SUSTAINABLE DEVELOPMENT
AND THE
CEMENT AND CONCRETE INDUSTRIES

DÉVELOPPEMENT DURABLE
ET LES INDUSTRIES DU CIMENT ET DU BÉTON

A dissertation submitted in partial fulfillment of
the requirements for the degree of
Doctor of Philosophy

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If it has been possible to build such an outstanding structure.......

Why it is not possible to build something better for them.........
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ABSTRACT

Sustainable development is an attempt to mitigate the environmental damages of the past, to adjust the present exacerbated superfluous pattern of consumption and the increasing social gaps between nations, in order to provide the future generations a fairer society living in a more healthy environment.

Up to now climate changes has been the focus of the discussion, but sustainable development is a much more broader issue. Just 20% of the world population has a high standard of living and consumes the greatest part of energy and raw materials and as a consequence generates the majority of CO₂ emissions, the main greenhouse responsible for climate change. At the same time, 50% of the population earns less than $ 2 US a day gasping for sanitation, hospitals, schools, houses just to satisfy the minimum of dignity.

In such a scenario the cement and concrete industries can play a key role either for solving social problems as for helping to mitigate the environment burden. Cement industry is often focused as a polluting industry, responsible for 6% of world CO₂ emissions, and concrete is frequently presented as a low technological added value product that generates around 1 billion tonnes of wastes per year. This is a common unfair perception that reveals a lack of information and adequate analysis.

The cement industry experienced an extraordinary reduction in gas and dust emissions as well as energy saving rooted in significant technological investments in the seventies and eighties. Its CO₂ emission is much lower than that of other industrial segments, such as transportation and progresses continue. At the same time millions of tonnes of industrial by-products and wastes generated by other industrial sectors are consumed and valorized by the cement and concrete industries every year.

As a construction material, concrete fulfils almost all the social and technological needs of societies. The spectrum of available concrete ranges from some MPa to 800 MPa, exhibiting high flowable properties or low noise when casting, showing good thermal performance at low cost, evidencing the immense technological progresses achieved in recent years.

With the current available technology a much longer life cycle of concrete structures should be achieved. An infrastructure lasting longer will contribute to reduce waste generation and alleviate budgets to invest in other social requirements instead of “indefinitely paying” for rebuilding or repairing structures in benefit primarily of contractors.

The sustainability in concrete industry can be reached by improving durability, even at somewhat higher initial costs, by conveniently enhancing the skills of labor force in the construction industry in order to reduce wasting, by using concrete in its whole potential such as a paving alternative, by disseminating the importance of quality concern, and finally by improving the recycling levels of concrete wastes. Pre-cast elements contribute also for reducing wasting, and the flexibility of the existing concrete technology allows good architectural projects
to be carried on, as well as a more pleasant environment to be created using colored interlocked concrete blocks for example, contributing to reduce the stress in big cities.

The cement industry has acquired enough development to reach in a short period a more sustainable production. The use of by products and waste derived fuel in the cement industry must increase worldwide, the optimization of industrial facilities is almost compulsory for the environment improvement and for the profit margin of companies. The gradual changing of old technology kilns into modern kilns with precalciner must be implemented. The main challenges for the cement industry are now how to face too stringent environmental regulations, the difficult and slow pace to get environmental permits and how to define a pragmatic and feasible program to upgrade cement kilns in some countries, mainly China and USA. This step involves significant financial investments and a delay of at least 3 years before the start up of a new plant. The CO₂ emissions can be substantially reduced by these already ongoing alternatives and they can be profitable for the cement industry. Moreover the possibility of CO₂ emission trading can reinforce the search for an even higher reduction of this type of emissions as well as accelerate the required changes.

Finally it must be taken into account that no progress will be achieved, despite all the available knowledge and technology, if ethic and volunteer commitment are not disseminated among authorities, companies and individuals. The recent emerging policy of social responsibility for companies is an encouraging step to reach a more fair society. Moreover the participation of associations, non governmental groups, media will synergistically contribute to the whole process of sustainability.
RÉSUMÉ

Le développement durable c’est un moyen d’atténuer les dommages à l’environnement du passé, d’ajuster le consumérisme frénétique actuel, de diminuer les écarts sociaux entre les nation dans le but de léguer aux générations futures une société plus juste dans un environnement plus salubre.

Jusqu’à présent seuls les changements climatiques ont attiré l’attention du public, mais le développement durable c’est beaucoup plus que cela. Seulement 20% de la population mondiale bénéficie d’un niveau de vie élevé et consomme la plus grande partie de l’énergie et des matériaux exploités, et par voie de conséquence, génère la majeure partie des émissions de CO₂, le gaz à effet de serre responsable des changements climatiques. En même temps 50% de la population mondiale gagne moins que $2 US par jour, cette population a un grand besoin d’hygiène, d’hôpitaux, d’écoles, de maisons juste pour vivre avec un minimum de dignité.

Dans un tel scénario les industries du ciment et du béton peuvent jouer un rôle primordial pour résoudre une partie des problèmes sociaux et atténuer le fardeau environnemental. L’industrie du ciment est souvent montré du doigt comme une industrie particulièrement polluante, même si elle n’est responsable que de 6% des émissions de CO₂ dans le monde, l’industrie du béton quant à elle est fréquemment présentée comme une industrie à très faible contenu technologique qui génère tous les ans 1 milliard de tonnes de déchets. Ce sont deux visions négatives peu méritées qui démontrent un manque d’information et une analyse inadéquate des effets de ces 2 industries sur l’environnement.

L’industrie du ciment a connu une réduction extraordinaire de ses émissions de gaz et de poussières et de consommation énergétique suite à des investissements technologiques massifs dans les années 70 et 80. Globalement, le volume des émissions de gaz de l’industrie cimentière est bien plus faible que celle d’autres industries lourdes comparables et de l’industrie des transports, mais des réductions additionnelles sont envisageables. En même temps l’industrie du ciment et du béton permet de valoriser des millions de tonnes de sous produits industriels et de déchets générés par d’autres secteurs industriels.

En tant que matériaux de construction le béton permet de satisfaire le plus part des besoins sociaux et technologiques des sociétés. La gamme des bétons actuels s’étend de bétons de quelques Mpa de résistance en compression jusqu’à celle de bétons de 800 Mpa. Les bétons modernes peuvent être fluides, silencieux, isolants acoustiques et thermiques. En outre, en n’utilisant que seulement la technologie déjà disponible il est possible d’augmenter de façon considérable la durée de vie des infrastructures en béton. Des infrastructures qui durent contribuent évidemment à réduire la génération de déchets et permettent d’investir l’argent des réparations, qu’il n’y a plus à faire, dans des investissements sociaux fondamentaux.

Le développement durable dans l’industrie du béton commence par l’amélioration de la durabilité du béton, même si cela entraîne des coûts initiaux un peu plus élevés, se poursuit
en améliorant la compétence de la main d’œuvre de façon à réduire le niveau de déchets générés dans l’industrie de la construction pour essayer d’exploiter le béton au meilleur de ses capacités comme dans les pavages en béton par exemple. L’utilisation d’éléments préfabriqués permet de réduire le volume de déchets et ajoute de la flexibilité à l’utilisation du béton, de mettre en valeur les qualités architecturales du béton, de créer un environnement plus agréable dans les villes en utilisant des pavés bloquants de couleurs variées, ce qui peut contribuer à diminuer le stress des populations urbaines.

L’industrie du ciment a acquis un niveau de développement tel qu’elle pourra dans un délai relativement court atteindre ses objectifs en matière de développement durable. L’utilisation de sous produits, de déchets industriels et de combustibles alternatifs augmente sans arrêt dans le monde, et les installations actuelles sont optimisées dans le but d’améliorer leur rendement environnemental, sans oublier les profits des compagnies. Il ne reste plus qu’à compléter le changement des vieux fours par voie humide en des fours modernes comprenant des précalcinateurs.

Le principal défi de l’industrie du ciment est maintenant de faire face à une législation environnementale très contraignante, d’obtenir des permis d’exploitation qui deviennent de plus en plus longs et coûteux à obtenir, et de définir de façon pragmatique comment améliorer la technologie cimentière dans des pays comme les Etats Unis et la Chine. Une telle transformation va exiger des efforts financiers significatifs sans compter des délais incompressibles puis qu’il faut au minimum 3 ans pour construire une cimenterie.

Les émissions de CO₂ peuvent être réduites en mettant en oeuvre différentes alternatives et devenir une source de profits pour l’industrie. Enfin la possibilité de commercialiser des droits d’émission de CO₂ peut inciter les cimentiers à faire des efforts supplémentaires pour réduire encore plus leurs émissions de CO₂ et accélérer le rythme des changements nécessaires.

Finalement, il faut bien se rendre compte qu’aucun progrès ne pourra être réalisé, malgré toute les connaissance acquises et la technologie disponible s’il n’y a pas de la part des autorités gouvernementales, des compagnies et des individus un désir profond de changement d’attitude. La notion émergente de responsabilité sociale d’une compagnie constitue un pas encourageant dans la bonne direction. Enfin, la participation d’associations et de groupes non gouvernementaux et des médias va contribuer à accélérer la mise en oeuvre du processus global de développement durable.
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1. **INTRODUCTION**

During the eighties the Bruntland Commission has defined Sustainable Development as “Development that meets the needs of the present generation without preventing the future generations from meeting their needs” [AMEUS 2001].

The 1992 Earth Summit in Rio de Janeiro-Brazil defined sustainable development as economic activity that is in harmony with the earth’s ecosystem [Metha 1998].

Sustainable development is a concept where “it is necessary to achieve economic progress while protecting the environment for the welfare of future generations” [Conseil Canadien du Ciment 1994].

Compatibility between production, consumption, national and international trade and environmental and social issues must be continuously searched. Establishing links between all these parameters is one of the greatest challenges of our times. Sustainability is more than simply seeking to decrease industrial polluting emissions or to save energy, it is also optimizing any activity so that its environmental impact is the lowest possible while its social added value the highest one.

More recently, the following issues started to be discussed once they had adversely impacted global environmental and economic scenarios, resulting in dangerous climate changes and in increasing social instability:

- Ozone depletion;
- Greenhouse effect;
- Acid rain;
- Scarcity of energy and raw materials;
- Increasing waste generation;
- Limited areas for landfilling;
- Ever-growing social needs.
However, climate change, due mainly to the emission of greenhouse gases, especially CO₂, became the main focus of decision makers and a key element for the industry in general, the cement and concrete industries in particular.

The cement and concrete industries play a key role in the development of any nation. Although impacting the environment, as any other industrial activity, the social and environmental benefits provided by both sectors largely overcome the impact they cause. Considering the enormous lack of infrastructure in developing countries, the use of concrete as a construction material will be more and more requested. It is necessary to find the sustainable ways of making its use even more advantageous for the community.

It is essential to understand the whole problem and integrate the different parameters, economical, social, industrial, and environmental, within a holistic vision in order to achieve pragmatic and fair solutions.

In chapter 2 the worldwide environmental degradation is discussed. Climate change, due mainly to the emission of greenhouse gases, is becoming a key element for the industry in general, the cement and concrete industries in particular. All industries are being asked to reduce their greenhouse gas emissions. The cement industry is responsible for nearly 6 percent of the CO₂ emissions, significantly under the 25 percent due to transportation. Moreover, it must not be forgotten that the majority of CO₂ emissions in a building are produced during the operation phase. Around 93% of the CO₂ is emitted during the service life of the building, while 7% is due to the materials used. Furthermore, in developed countries, waste generation has reached an unprecedented level, the landfilling alternative has become unacceptable, the high level of consumption of fossil fuels and non renewable raw materials is becoming alarming. In developing countries, the wasting of energy and materials, and further, irresponsible and unconscious practices placing a burden on the environment are also a source of concern. Scarcity of fossil fuel, non renewable raw materials and water will be a serious issue in a near future, together with the environmental burden due to emissions.
In chapter 3, the social scenario is taken into account. Presently, there are two billion people whose daily income is less than $2 US. The social requirements of these people are quite different from the remaining population. In the future, there will be an ever-growing need for infrastructure in order to improve the standard of living of these people. There are 3 billion other people living with less than $6 000 US per year and therefore with infrastructure needs as well as with expectations to be satisfied. The lack of sanitation infrastructure and housing, as well as the scarcity of drinking water, are alarming and unacceptable and require urgent solutions. Finally, the remaining 1 billion people with a high living standard have a very large environmental impact.

In chapter 4, the main issues concerning cement manufacturing are presented. The cement industry undoubtedly has an environmental impact through its extensive consumption of non-renewable raw material and fossil fuel. However, the progresses achieved in the reduction of the cement industry’s environmental impact over the last 20 years have been outstanding. The change from wet kilns to dry kilns with preheaters and precalciners made it possible to cut thermal energy consumption by half. Dust emission have been reduced by 90%, significant mitigation of emissions have been achieved, improvements in grinding technology have been remarkable. There has been a great change in the profile of fuels used by the cement sector, and alternative fuels have started to be used instead of fossil fuels. It is important, therefore, to understand the economic issues that led to this technological upgrading and that will lead to further ones.

In chapter 5, the macro scenario for the cement industry’s perspectives are discussed in order to understand certain policies adopted by the cement industry, as well as future perspectives. All over the world the process of globalization has completely changed the way we live. Company mergers, major changes in the communications systems networks, increasing competitiveness, international trade replacing national trade, increasing unemployment are some of the important issues. The cement industry underwent this process by implementing a strong policy of technological development and by updating its production equipment. The number of cement groups has been decreasing through acquisitions during the last 10 years. Aside from that, the main cement groups are developing an integrated market. Instead of increasing at any cost the
number of plants, cement companies are trying to buy well-located plants, in order to supply internal as well as export markets. Clinker grinding facilities increased in number, because it is the less expensive way to start developing a new market.

Concrete, discussed in chapter 6, is the most widely used material after water and its use is fundamental to promote the development of nations: it is used to build houses, schools, hospitals, dams, highways, airfields, etc. Concrete technology is very different today than it was some years ago. The versatility of concrete is extraordinary, its compressive strength now ranges from some MPa to 800 MPa, competing in compression with steel. Paving and dams can be built using roller compacted concrete, high-rise building or bridges using high performance concrete, self compacting concrete is used in numerous industrial applications, while lightweight concrete can be used to build low-cost housing. Admixtures play an essential role in improving durability. Despite the great progresses achieved, the main concern for sustainability remains the bad use of concrete, due to inadequate curing, unnecessary high water/cement ratio, lack of information, deficient labor force, bad management, and lack of better construction techniques.

In chapter 7, the efforts to mitigate emissions and save energy in the cement industry are discussed. These efforts have been successful, due mainly to technological progress in manufacturing, the use of by-products as supplementary cementitious materials and the burning of alternative fuels. The development of better filters, ecological burners, and stringent standards have contributed to a great reduction of further emissions such as NOx, SOx, and dust. Also examples of quarry restoration are shown in order to emphasize the feasibility of reaching good and sustainable alternatives for this industrial sector. Cements that require a low level of energy during their manufacturing process also constitute a remarkable progress, among them mineralized cements and belitic cements. Moreover, the progresses achieved in cement grinding have decreased the electrical energy used during cement production by at least 40%, but it remains a weakness in the cement manufacturing process from a sustainability point of view. Further evolution is expected to take place in the grinding process, which is more probable than any great revolution in thermal savings.
In chapter 8 the progress and search for sustainable uses of concrete are discussed. Undoubtedly, the key factor for sustainability will be to enhance concrete durability and avoid bad use of concrete. The recycling of concrete, an environmentally friendly material, is just starting, but the available technology requires further improvements. The extremely fragmented nature of the concrete industry, with small size operational units, is also a further challenge to achieve sustainability, since they cannot invest in quality and in quality assurance. However, with the new interest and greater involvement of international cement groups in the concrete market, the perspective of reaching the expected and required quality standards seems more promising.

In chapter 9, the main propositions to achieve a sustainable cement and concrete production are discussed, based on quantitative data and qualitative benefits for society. Also, the mechanisms to implement the proposed alternatives are explained. The key factors for sustainable cement production will be based on the optimization of cement plants and the increasing use of alternative fuels and by-products, while as a general rule, sustainable concrete production will be based on concrete durability, increasing the life span of structures, the social and environmental added value, the level of recycling and improving the labor force to reduce waste. CO₂ trading can be a turning point in the competitiveness of cement companies.

In Chapter 10, conclusions about the sustainability of the cement and concrete industries are presented, demonstrating that the cement industry is far from being a major source of concern for the environment, compared to other industrial sectors. Several policies that contribute to alleviate the environmental burden are being already implemented. Indeed the way to reach sustainability in the cement and concrete industries offers more possibilities for making profits rather than presenting future risks of additional financing loads for companies. Companies must focus on the importance of being socially responsible, while authorities and individuals must understand the real meaning and importance of ethics in order to promote the necessary changes.
2. ENVIRONMENTAL DEGRADATION

2.1 Introduction

The Rio de Janeiro-Brazil (1992) and Kyoto-Japan (1997) environmental conferences were historic moments, with governments volunteering their commitments. Climate change, mitigation of gas emissions responsible for the greenhouse effect and ozone layer depletion started to be widely discussed. Conservation of non-renewable natural resources, saving, recycling, life cycle and many other concepts were introduced in our daily life and in the routine of companies.

Sustainable consumption was declared a major concern at the Rio Earth Summit. Agenda 21 stated that “the major cause of the continued deterioration of the global environment is the unsustainable pattern of consumption and production, particularly in industrialized countries...” and called on developed countries to take the lead in promoting and achieving more sustainable consumption patterns [AMEUS 2001].

Consumption and production are undoubtedly the essence of economic activity. They involve the utilization of natural resources, their transformation into products and services and their ultimate disposal or dissipation into the environment as wastes. According to the Wuppertal Institute of Research [Boiral et al 2001], on average only 10 percent of the resources consumed in the different phases of a production process are actually integrated into a good that will be consumed. For instance, a 5 gram gold ring implies an ecological impact of 5 tonnes of ore. As well 32 kg of material and 8 000 liters of water are required to produce a 600 gram pair of jeans. The manufacturing of a car generates nearly 15 tonnes of wastes and requires 100 000 litres of water, aside from all the pollution generated during its life cycle. However, the production of concrete does not generate as much waste because over 90 percent of the resources are integrated into the final product.

On a global scale, nearly 25 million tonnes of fuel are consumed world-wide every day [Greco 1996]. Every year over 12 billion tonnes of wastes are generated, the majority being
landfilled, incinerated or dispersed in the environment, the generation of such a great quantity of wastes has the following effects [Boiral et al 2001]:

- Contamination of sites;
- Groundwater contamination;
- Release of toxic and inflammable gases;
- Illegal traffic of hazardous wastes;
- Increasing scarcity of landfill sites;
- Increasing costs due to landfilling and incineration;
- Loss of investments and income;
- Sanitation impact;
- Loss of materials and energy;
- Visual pollution.

The pressure for cleaner production processes and for serious environmental management and commitment is increasing dramatically. There is a worldwide trend in companies to take environmental policy into account when making investment decisions. The cost of prime real estate areas can be greatly affected by contaminated soils. An environmental accident or problem may lead to costly penalties that may adversely impact the position of a company on the stock exchange. The penalty imposed to Union Carbide ($5 billion US) following the death of 5,000 people in Bhopal, India due to the leakage of toxic gases, and that imposed on Esso ($10 billion US) as the result of an oil leak from the tanker Exxon Valdez along the Alaska coast are two examples showing how costly these penalties can be [Reis 1996]. Moreover, shareholders are much more sensitive to environmental policy and the risk to their investment, as well as their bad image as shareholders of a company that pollutes.

The ever-growing difficulties in getting permits to start new projects that may impact the environment (new plants, plant upgrading, etc.), and also the increasing number of ecologically protected areas are affecting general investment policies. Moreover, with the intensive urbanization process occurring in the last 20 years, many plants are virtually surrounded by invading suburbs, implying a drastic change in attitude related to communications with the neighborhood, and extra costs, due to the necessity to develop better environmental controls to
take into account more stringent regulations. In extreme cases, this situation has resulted in the shutdown of plants.

2.2 Greenhouse Gases

Presently, one of the greatest environmental challenges worldwide is to reduce the emission of greenhouse gases. The five main greenhouse gases are [Fondation Québécoise en Environnement 1999]:

- Carbon dioxide (CO₂). It is the main source of concern, since its concentration in the atmosphere has increased by 30 percent since the industrial revolution of 1850. CO₂ is generated by the decomposition of limestone, the breathing of animal, by plants, and the combustion of fuels, mainly from vehicles and power generation;

- Methane (CH₄) is the second most important greenhouse effect gas. Methane retains heat more effectively than CO₂. The decomposition of organic material is its main source. The decomposition of landfill materials together with an increase in the use of fossil fuels have resulted in a 145 percent increase in its concentration in the air over the last 150 years;

- Nitrogen oxide (NO₂) comes from oceans, from chemical fertilizers, nylon production due to high energy demand and from combustion of organic materials and fossil fuels;

- Ozone (O₃) results from the reaction between human pollution and sun light and it is found in the lower part of the atmosphere;

- Chlorinated halogens are generated essentially by domestic activities, mainly under the form of CFC (Chlorofluorocarbons) from aerosol forming agents and coolers as well as from industrial activities. CFCs are one of the most harmful gases for heat retention.

The Global Warming Potential (GWP) is a measure of the a gas’ reaction of over a certain period of time in relation to the same quantity of CO₂. With an assumed persistence rate of 100 years, this factor is 21 for CH₄, 310 for N₂O, 23 900 for SF₆, while for PFC (perfluorcarbons)
from aluminum production it varies between 6 500 for perfluoromethane to 9 200 for perfluorethane. In Germany these gases that have a high impact on the greenhouse effect represent almost 15 percent of the overall emissions [Hillebrand 1999].

Other emissions such as sulfur dioxide (SO₂), nitrogen oxides (NOₓ), hydrogen chloride (HCl) and hydrogen fluoride (HF) primarily cause acidification, another serious environmental problem.

The varying individual potential effects of the different emission components have to be taken into account when calculating the overall potential effect. For instance, the relative Acidification Potential of SO₂, the AP value, is given the value 1. AP value is 0.7 for NOₓ which means that this component only contributes 0.7 times to acidification as the same quantity of SO₂ [Kuhlman et al 1996].

The European Union’s (EU) negotiating mandate for the Kyoto Conference already included NO₂ and CH₄ emissions. The Kyoto resolutions stipulated an 8 percent reduction target, for the EU as a whole, with reference to the year 1990 [Hillebrand 1999].

2.3 Carbon Dioxide Emissions

Currently, the main environmental challenge worldwide is reducing the greenhouse effect generated mainly by CO₂ emissions. CO₂ is an important greenhouse gas which affects the temperature of the atmosphere by changing the current climatic system so quickly, that neither ecosystems nor mankind could adjust to it rapidly enough. In general an increase in atmospheric CO₂ concentrations from about 280 ppm to 355 ppm (about 27 percent) has been noticed since 1850. This increase in CO₂ has been associated with an additional greenhouse effect of 1.56 Watt/m², while other antropogenic gases, those gases that trap heat from sunlight [Yamamoto et al, 1997], such as methane, nitrogen, CFCs, etc result in a further greenhouse effect of 1.14 Watt/m² [Berner and Stahl 1999], therefore these other greenhouse gases should not be neglected.
A moderate increase in CO₂ was identified up to the end of the Second World War, but a very sharp rise in annual CO₂ emissions has been noticed since the fifties and this increase is being followed by decision makers. Climate factors that are presently decisive, such as changes in solar energy, which have mainly influenced the temperatures prevailing on Earth cannot be controlled by man. Impacts introduced by antropogenic influences, such as the input of climatically relevant gases into the atmosphere represent the only possibility for intervention. The BGR (German Federal Institute for Geosciences and Raw Materials) suggests that these findings should be incorporated in the arguments put forward by policy makers when taking decisions on industrial development and global warming prevention, so that the dialogue between economic and ecological interests can provide sensitive and environmentally compatible solutions at a reasonable cost.

Prevention costs, however, vary greatly from country to country, so that an exclusively nationally-oriented climate change policy is not only inappropriate but economically inefficient. Even stabilizing global CO₂ emissions at 1990 levels would, according to the Organisation for Economic Co-operation and Development (OECD) estimates, give rise to expenses of $120 billion US, not on a world-wide basis, but exclusively in OECD countries [Hillebrand, 1999].

2.3.1 Carbon dioxide sources

In December 1997 the Kyoto international conference identified the following principal sources of carbon dioxide emissions responsible for the greenhouse effect and climate change:

- plant gases;
- car exhaust;
- coal burning;
- forest burning.

In such a context, the OECD report [Vers une Nouvelle Ére, 1997] highlighted eight countries that play or will play an important role in CO₂ emissions and their environmental impact for various reasons, such as population and percentage of forests, as well as their participation in the world GNP and resulting consumption patterns (Table 1)
**TABLE 1: EIGHT IMPORTANT COUNTRIES FOR THE GLOBAL ENVIRONMENT**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>5</td>
<td>26</td>
<td>23</td>
<td>6</td>
</tr>
<tr>
<td>Russia</td>
<td>3</td>
<td>2</td>
<td>7</td>
<td>21</td>
</tr>
<tr>
<td>Japan</td>
<td>2</td>
<td>17</td>
<td>5</td>
<td>0.7</td>
</tr>
<tr>
<td>Germany</td>
<td>1</td>
<td>8</td>
<td>4</td>
<td>0.3</td>
</tr>
<tr>
<td>China</td>
<td>21</td>
<td>2</td>
<td>13</td>
<td>4</td>
</tr>
<tr>
<td>India</td>
<td>17</td>
<td>1</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Indonesia</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Brazil</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>16</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>56</strong></td>
<td><strong>59</strong></td>
<td><strong>58</strong></td>
<td><strong>53</strong></td>
</tr>
</tbody>
</table>

The scientific debate on global warming has shown that in addition to CO₂ there are several other trace gases affecting the Earth’s radiation balance. The political debate however and the definition of targets and reduction strategies has still concentrated almost exclusively on CO₂.

According to statistical data from Environment Canada, for 1995, 35 percent of CO₂ emissions come from industry, 27 percent from transportation, 17 percent from energy generation, 14 percent from offices and homes, and the rest from other sources such as agriculture and wastes [Canadian Portland Cement Association 1998].

Despite the wealth and technology available, CO₂ emission rose 18% between 1990 and 2000 [Gardner, 2002]. **Table 2** presents the different sources of CO₂ emissions in the U.S.A in 1995 [Cahn et al 1997]:

2-6
TABLE 2: SOURCES OF CO₂ EMISSIONS IN THE UNITED STATES (1995)

<table>
<thead>
<tr>
<th>Sector</th>
<th>CO₂ Emissions (Million tonnes) *</th>
<th>Percentage of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>1000</td>
<td>19.6</td>
</tr>
<tr>
<td>Commercial</td>
<td>800</td>
<td>15.7</td>
</tr>
<tr>
<td>Industrial</td>
<td>1700</td>
<td>33.5</td>
</tr>
<tr>
<td>Transportation</td>
<td>1550</td>
<td>30.5</td>
</tr>
<tr>
<td>U.S. territories</td>
<td>36</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5086</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

* These totals include electric utility emissions which have been distributed across the sectors based on their power consumption.

The CO₂ emissions of some countries, as well as the corresponding CO₂ emissions of the local cement industries, can be seen in Table 3 [OECD- Sustainable Development, 1997].

TABLE 3: GENERAL AND EVALUATED CO₂ EMISSIONS FOR THE CEMENT INDUSTRY (1996)

<table>
<thead>
<tr>
<th>Country</th>
<th>CO₂ Emissions (million of tonnes)</th>
<th>Specific CO₂ Emissions (tonne/head)</th>
<th>Cement Industry CO₂ Emissions (tonne/head)</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>5228</td>
<td>19.1</td>
<td>0.27 (1.4%)</td>
</tr>
<tr>
<td>China</td>
<td>3007</td>
<td>2.3</td>
<td>0.34 (14.8%)</td>
</tr>
<tr>
<td>Japan</td>
<td>1151</td>
<td>8.8</td>
<td>0.69 (7.8%)</td>
</tr>
<tr>
<td>Germany</td>
<td>884</td>
<td>10.9</td>
<td>0.41 (3.8%)</td>
</tr>
<tr>
<td>India</td>
<td>803</td>
<td>0.9</td>
<td>0.07 (8.0%)</td>
</tr>
<tr>
<td>England</td>
<td>565</td>
<td>9.8</td>
<td>0.23 (2.4%)</td>
</tr>
<tr>
<td>Canada</td>
<td>471</td>
<td>14.4</td>
<td>0.30 (2.1%)</td>
</tr>
<tr>
<td>Italy</td>
<td>424</td>
<td>7.2</td>
<td>0.57 (7.9%)</td>
</tr>
<tr>
<td>France</td>
<td>362</td>
<td>6.3</td>
<td>0.46 (7.3%)</td>
</tr>
<tr>
<td>Brazil</td>
<td>287</td>
<td>1.4</td>
<td>0.14 (7.1%)</td>
</tr>
</tbody>
</table>

2-7
CO₂ emissions in developed countries are much higher than in developing countries especially if specific emissions per head are considered. This fact suggests that aside from the exacerbated industrialized process, other parameters play a more significant role in the emissions level, especially if we consider that the greater part of infrastructures and building requirements are satisfied in these countries while developing countries are still providing minimum social requirements and therefore grasping for cement consumption.

The CO₂ contribution of the cement industry is not so high, excepted for the Chinese cement industry, when compared to the transportation sector and the heating and cooling CO₂ generation. If one considers that around 300 kg of cement/m³ concrete is used, or around 15 percent in weight, the corresponding CO₂/m³ concrete, is much smaller.

2.3.2 Effect of urbanization on carbon dioxide emissions

When implementing a sustainable development policy, the rate of urbanization is another parameter that must be considered. This issue is specially important for China and India, the two countries with the greatest population and potential highest rate of urbanization. Presently, around 30 percent of the population of these two giant countries lives in urban areas which can be considered as a very low percentage when compared to other developed and under-developed countries.

In urban areas, CO₂ emissions come from different sources. In the operation of a building for instance, energy consumption and CO₂ emissions derive mainly from operating the structure (heating and cooling) rather than from the materials that were used to build it. As developed countries are situated mainly in countries having rather cold weather, they are consuming more energy and causing more CO₂ emission. Buildings can account for half of a country’s consumption and half of its greenhouse gas emissions [Courtney 2000]. Some sky-scrapers in U.S.A for instance joined a governmental program aimed at energy saving. In the Empire State in New York, over 6,500 special windows were installed in order to improve the use of air conditioning. In the Sears Tower in Chicago, more efficient heating, cooling and lighting were installed as well. According to the EPA, if all commercial buildings took similar measures, the
energy consumption could be reduced by 30 percent, which would save $25 billion US annually in the operating costs of these buildings.

Urbanization is extremely important for energy patterns, emissions and waste generation. Not only is energy consumption in urban areas much higher than in rural areas, but the type of fuels and their quality also differ greatly from rural areas, where a larger amount of biomass is consumed [OECD – Sustainable Development, 1997]. The generation of domestic and industrial refuse, and mainly non biodegradable ones like polystyrene and polyethylene plastics, is a further serious issue.

2.3.3 Carbon dioxide emissions in transportation

With the growth of cities, the population is increasingly forced to live at a greater distance from their work due to: loss of purchasing power, soaring real estate prices, scarcity of housing facilities, or simply due to the search for a better quality of life in more pleasant and distant areas. The decentralization of employment, commercial activities, and housing is becoming more and more intense. This whole process results in an increasing number of trips, as well as longer ones.

The proportion of CO₂ emissions due to transportation ranges from 15 to 25 percent [OECD- Urban Travel and Sustainable Development 1995] for different cities. Reducing this emission is an essential commitment.

Transportation is the main driving force for business, service, industries and competitiveness, especially in a globalized scenario, but it is also a considerable source of costs due to casualties, health problems, pollution, and the degradation of ecosystems and landscapes.

In general terms the following more relevant environmental features regarding the impact of urban transportation are:
- local pollution;
- global pollution (greenhouse effect, acid rain, etc);
- noise pollution;
- consumption of non-renewable energy resources;
- health problems;
- degradation of bridges, monuments and buildings.

In spite of all the efforts done in several countries to promote mass transportation and implement policies aimed at reducing individual travel, a worldwide increase in vehicle transportation has been noticed.

The increasing participation of heavy vehicles in the daily scenario of cities due to the just-in-time policy, has also significantly increased the number of trucks in the streets, in spite of efforts to reduce their impact by means of better transportation logistics [Marciano Jr, 1999]. The already serious traffic problems can be also worsened by several other reasons such as floods, strikes, accidents, broken vehicles mainly in rush hours, etc. All these reasons are somewhat acceptable because it is difficult to do anything to prevent them, but what is not acceptable is traffic impaired by successive, and frequent pavement maintenance work, causing further jam problems for users that could be easily avoided.

The resulting traffic costs are extremely high, although they are often hardly, and sometimes subjectively, quantified. The following data are based on OECD member countries [OECD- Urban Travel and Sustainable Development 1995]:

- the cost of road congestion in OECD countries is estimated to be equivalent to 2 percent of the gross domestic product (GDP);
- the cost of road accidents, being 60 percent in urban areas, is estimated to be equivalent to 1.5 to 2 percent of the GDP;
- noise pollution accounts for about 0.3 percent of the GDP;
- local pollution is estimated to account for 0.4 percent of the GDP;
- non-local pollution costs are estimated at 1 to 10 percent of GDP.

From the point of view of air pollution, the main vehicle emissions are CO₂, CO, NOₓ, SO₂, volatile organic compounds (mostly hydrocarbons), Pb and particulates. Recent research also suggests that small particle emissions originating from diesel engines, tires and pavement wear are severe in urban areas. According to Swedish studies [OECD- Urban Travel and
Sustainable Development 1995], urban air pollution causes between 300 and 2,000 new cases of cancer annually. Traffic accounts for 70 percent of emissions of carcinogenic substances and substances that may affect the genes of people living in urban areas [OECD- Urban Travel and Sustainable Development 1995]. A study carried out for the British Government suggested that up to 10,000 people each year are killed by exhaust fumes in England and Wales [OECD- Urban Travel and Sustainable Development 1995].

The impact of urban pollution is not restricted to these problems and it can cause extensive damages to buildings, such as in Switzerland where it was evaluated at approximately $300 million US in 1988 [OECD- Urban Travel and Sustainable Development 1995]. Besides affecting forests, acid rain originating from pollution has been causing extensive damage to monuments and historical buildings made of limestone and marble.

Worldwide there is a tendency toward growth in the purchase and use of private cars, making it more accessible to the population as a whole, despite the drawbacks in owning and purchasing a car. In the last 40 years, there has been a ten-fold increase in the number of motor vehicles worldwide, reaching 700 million units [OECD-Road Transport Research Outlook 1997]. Over the next decade, it is expected that that number of vehicles and the number of trips, as well as trucking activity, will rise significantly. Over the last 20 years, overall car travel in OECD countries has been growing at 3.3 percent per year [OECD- Urban Travel and Sustainable Development 1995].

The need for upgrading the road network and improving public transportation is not often harmoniously integrated by authorities. New roads, streets, avenues, bridges, viaducts and tunnels must be be built more and more often.

Transportation causes a further serious environmental problem related to the huge amounts of scrap tires generated. Tires range in weight from as little as 5 kg for some automobiles to as much as 70 kg for trucks. In 1995, the U.S. alone generated 253 million scrap tires which corresponds to 1 tire/head/year [Terry, 1999]. When stored outside, due to its shape, a tire can retain up to 10 litres of water and constitute an ideal breeding ground for vermin,
mosquitoes, and rodents infestation. There are frequently no official storage site for these tires, mainly in developing countries, so that they are frequently dispersed around the country. The risk of spontaneous ignition is also an additional environmental issue.

Used oils represent also a further environmental impact. In Germany for instance, 1.2 million tonnes of oil per year are used as lubricants [Gaebel and Nachtwey, 2000].

2.3.4 Carbon dioxide emissions and energy consumption

Carbon dioxide emissions usually tend to closely reflect energy consumption, the main differences between CO₂ emissions being related to the use of a greater or smaller proportion of carbon rich fuels. This is why energy conservation is so important besides the fact that energy is usually provided from a non-renewable source.

From an energy point of view, it is important to mention some of the IEA’s key projections [OECD – Sustainable Development 1997] up to 2010 and beyond:

- world energy demand is likely to increase by 60 percent between 1994 and 2010;
- fossil-based fuels will account for more than 90 percent of primary energy demand in 2010 and probably at least 80 percent in 2020;
- the bulk of growth in demand will originate in the five largest non-OECD countries (Russia, China, India, Brazil, and Indonesia);
- CO₂ emissions will rise rapidly. More than a third of the increase will be in India and China.

These projections carry some important issues and political implications, such as:

- technology improvements, especially in the power generation sector, are extremely important for the long-term level of energy use and CO₂ emissions;
- great uncertainty surrounds future energy consumption in China and India, such as oil and gas production in the Middle East and potential production in Russia;
- while long-term energy supplies are perceived to be sufficient, their geographical distribution is highly uneven and there is a substantial scope for instability;
- the objectives of sustainable economic growth, energy security and environmental protection may lead to conflicting policy.

From an enviromental point of view, besides the concerns about emissions and energy issues, the increasing depletion of natural resources as well as the disposal of products at the end of their life cycle must be considered. It must be pointed out that the available resources of fossil energy carriers will come to an end in a foreseeable future as can be seen in Figure 1 [Gaebel and Nachtwey 2000]. The Gas reserves amount to 175 billion tonnes, lignite and oil reserves reach 200 billion tonnes and hard coal reserves amount to 480 billion tonnes.

![Figure 1: Forecasted availability of fossil fuels](image)

Assuming an annual increase in consumption of 2 percent, mineral oil will no longer be available in approximately 60 years, the situation for natural gas being similar. Only hard coal reserves will last for 150 years.
Coal burning however results in coal ash generation, a further ecological problem to be solved. The current annual generation of coal ash is estimated to be about 650 million tonnes worldwide [Metha, 1998]. China and India together generate about 200 million tonnes/year. European countries, mainly Russia, Poland, the former Czechoslovakia, Romania, Germany, Spain and the United Kingdom generates 250 million tonnes per year. Nearly 90 percent of the coal ashes produced currently end up either in low-value applications such as landfills and road bases, or are simply disposed off or stockpiled. The cost of disposal of fly ashes can play an important role fomenting their use. In Japan, coal ash disposal costs can be as high as $100 US per tonne [Komatsu 2000].

2.4 Indoor Environmental Degradation

The complexity of sustainability is remarkable because several parameters must be taken into account. Recently it has been noticed that it is not only the external environment which plays a fundamental role in civil construction, since the indoor environment was particularly focused upon in Agenda 21 on Sustainable Construction [CIB 2000]. As people spend more than 90 percent of their time in a closed environment, the indoor air quality therefore plays a more important role than outside air quality. This is a problem that affects mainly developed countries or highly populated urban areas.

Health issues in a closed environment are influenced by many factors, among them new construction materials and construction techniques, changes in indoor temperature, and light. Cleaning, cooking, painting, glues, perfumes, biological metabolism, construction material, hardware, furniture, etc., may also affect the environment.

It is well known that productivity in an office building greatly depends on a good indoor environment. This is the reason for changing the concept of Indoor Air Quality (IAQ) to Indoor Environment Quality (IEQ). The IEQ experienced a singular decrease in several countries, even in those countries that showed progress in the external environment. In the U.S., for instance, it is estimated that 50 percent of the buildings show serious problems in their indoor environment. In
Scandinavia, many buildings are showing problems with odor and their users presenting the so-called Sick Building Syndrome- SBS (stress, burnout, headaches, etc). The Environmental Protection Agency (EPA) estimates that the indoor environment may be ten times more contaminated than the outdoor environment. The environmental problem has somehow been transferred from outside to inside buildings [CIB 2000].

The decrease in IAQ is supposed to be the source of the high increase in allergy problems, from a few percents at the beginning of the 1950’s to almost half of the world population. The IAQ is also suspected to be at the source of lung cancer and other breathing diseases, mainly among children.

Therefore, from an environmental point of view, it would be more important to optimize the operation phase of a building unit and improve its indoor environment rather than simply evaluate the impact generated by the production of the construction material itself.

2.5 Construction Material Consumption

On the basis of weight, volume, and money, the construction industry is the largest consumer of materials. Moreover, several of these materials have a great impact on both the local and global environments.

The construction industry is also a major consumer of most of energy, thermal and electrical, used in the production and transportation of building materials, site assembling, and in the post-construction phase: use and operation, maintenance, and decommissioning. The U.K. government estimates that the operation and use of buildings consume from 40 to 50 percent of the total energy and the production and the transportation of building materials is responsible for consuming an additional 10 percent [John et al 2000]. The construction sector in U.S. consumes 40 percent of all extracted materials and accounts for 30 percent of national energy consumption for its operation [Kilbert et al 2000].
Based on evaluations made by Aifcin [2000], considering a dosage of 250 kg of cement per cubic metre of concrete and a world cement production of 1.5 billion tonnes, the concrete production amounts to 15 billion tonnes per year or nearly 2.5 tonnes/inhabitant. Raw material consumption, for cement manufacturing, mainly limestone, corresponds to approximately 2 billion tonnes. The mean consumption of natural aggregates corresponds to 5 to 10 tonnes/year/head in developed countries [Bitar 1999]. In the U.S., the consumption of aggregate per head in 1996 was 9 tonnes. In Europe, the consumption per head has been over 7 tonnes for many years already. In São Paulo-Brazil, for instance the consumption is about 3-4 tonnes/year/head but the national consumption per head is just 1.4 tonne [Valverde 1999].

It must also be considered that with increasing urbanization levels, existing quarries often became closer to urban areas, affecting local population while new quarries, located at further distances, will result in higher prices due to transportation costs.

Global construction and demolition waste (CDW) production is estimated at 2 billion tonnes per year [Torrin, 1998]. The major part of these quantities consists in concrete demolition waste or other rubble such as masonry, gypsum and wood. This means that a large quantity of natural resources is lost every year, further landfill sites must be sought and in some cases groundwater can be polluted. Moreover, it must be emphasized that landfilling, one of the most common alternatives for waste disposal, no longer represents a sustainable alternative.

The total generation of CDW in the EU is about 450 million tonnes. Excluding earth and excavated road materials, the amount of core CDW is estimated at 180 million tonnes per year, that is around 0.5 tonnes/head [Dorsthurst et al 2000]. The CDW makes up between 25 to 50 percent of all municipal waste. This figure is probably representative for most of the industrialized world. Usually CDW is considered chemically inert from an environmental point of view.

Concrete waste consists of huge masses of materials, which often invite its illegal disposal. Reinforced concrete may be regarded as slightly harmful due to the risk of reinforcement bar corrosion [Torrin 1998]. In the U.S., the amount of waste concrete is roughly 40 to 50 million
tonnes per year. The proportion of the total waste stream that is recycled varies from place to place but it lies in the range of 0 to 35 percent [Chan et al 1998]. According to Uchikawa and Obana [1995] the quantity of construction waste materials in Japan in 1992 was around 86 million tonnes being 29 million tonnes of it (34 percent) waste concrete. Twelve million tonnes of waste concrete has been used as roadbed materials, the remaining 17 million tonnes being disposed of.

2.6 Water Consumption

Water is also another natural key issue for sustainability, industrial development and environmental stability. Consumption by the concrete industry is around 1 billion m³/year. Although the Earth is constituted by 2/3 water, it is forecast that the availability of fresh water will be soon scarce. The potential impact of climate change on hydrological systems and food production adds an additional element of uncertainty to future projections [OECD Sustainable Consumption and Production 1997]. Even the possibility of more frequent disputes over water between countries must be considered. Therefore any alternative to save and optimize the use of water must be considered.

The demand in freshwater for human consumption has increased more than fourfold in the last 50 years while the world population has roughly doubled in the same period. Water for irrigation and industrial production is the major reason of this increase, but the demand for water in municipal areas is also increasing, particularly in countries undergoing rapid urbanization. The projection regarding the number of people living in water-scarce countries (less than 1,000 m³/head/year) will be 13 to 20 percent of the global population by 2050, and most of these countries will be in the Middle East and Africa [OECD-Sustainable Consumption and Production, 1997].

In at least 5 countries China, India, Pakistan, Yemen and Mexico, there are already problems in agricultural production with insufficient availability of surface water. It is necessary to drill to reach groundwater but the amount of water that has been removed from the groundwater is higher than natural reposition. International agencies consider a 2500
m³/inhabitant/year level as reasonable availability, while below 1 500 m³/inhabitant/year is considered critical [OECD-Sustainable Consumption and Production, 1997].

There will be areas affected by drought and restricted supply, this will be the case of U.S., China, India, Pakistan, and Mexico for instance.

Available freshwater represents 3%, with a great part of it being of difficult access, located in glaciers or as groundwater of difficult access [Thame 2000]. Another important issue is that the availability of water is not homogeneous, with some regions having higher levels of availability while others show levels under the minimum required amount. Water consumption can vary from 10 l/day/person in some African countries to 600 l/day/person in the U.S. On a world basis agriculture represents 70% of the water consumption, industry 20%, and household use 10% [Deléage, 2002]

The volume of worldwide unreplaced water, due to the higher demand without the corresponding replacement (related to water loss in buildings, industrial facilities and water pipes, clima change and mainly pollution of natural resources), evaluated by aerial photos, is nearly 160 billion m³ [Thame 2000]. In order to evaluate the magnitude of this process, it can be mentioned that from an agricultural point of view it is necessary to use one tonne of water to produce one kilogram of grain during its whole production cycle, with one tonne of grain being required to feed three persons. Therefore 160 million tonnes of food could be produced using this unreplaced water which could be enough to feed 480 million people.

Water management must drive the forces for more ecological behavior. Industrial pollution, diffused pollution brought by rain water and that due to lack of sanitation, not as toxic but in high volume, are sources of water degradation and consumption.

The construction of dams however has been criticized for its impact on people and ecosystems, and in the last century approximately 60 million people have been displaced by large dam construction projects worldwide, and around 250 small dams, for instance, were removed or descommissioned in the U.S. in the 1990s [Gardner, 2002]. Environmental issues must be taken
into account in dam construction and though they may be a limiting factor in reducing the number of further large projects, this is often an actual need.

Improvements in recovering water from rivers, based on sanitation works as well as dam construction in order to provide a better flow and regulation of water throughout the year, have to continue. Concrete plays an essential role in this sanitation process and in dam construction.

2.7 Conclusion

Both, outdoor and indoor environment have been experiencing degradation recently due to the uncontroled generation of greenhouse gases. The sources of these greenhouse gases are now well identified as well as future trends. Among the greenhouse gases emitted presently, CO$_2$ emissions have a great impact on environmental changes. In spite of the fact that the cement and concrete industries are not the major source of CO$_2$ emissions, they still represent 6 percent of total CO$_2$ emission and some efforts must be done to decrease this amount.

From the more general point of view of sustainable development, further points must be considered: how to reduce fossil fuel and raw material consumption when making cement and concrete and how to foment concrete recycling at the end of the life cycle of a structure. Indoor environment is also experiencing significant degradation, resulting in evergrowing deseases.

It can be noticed therefore, that sustainability is a highly complex subject and, once again, it must be emphasized that it can not be treated separately. Without a holistic approach there can be no success in trying to reach a pragmatic sustainable policy.
3. SOCIAL IMPACT AND SUSTAINABLE DEVELOPMENT

3.1- Introduction

The issue of sustainability is of major relevance, with increasing economic development producing social gaps between and within several countries. The current social, economic and environmental conditions at the beginning of the millennium are so alarming that it will be necessary to replace the present vision of institutions involved in orthodox economic policies, such as the IMF- The International Monetary Fund, into a more pragmatic proposal, less economic and more human focused. According to World Bank data, 2 billion people earn less than $2 US a day.

There are approximately 6 billion people in the world, of which about 80 percent live in under-developed or developing countries, with some areas experiencing unequal demographic growth, such as Africa, whose population increased threefold in the last 40 years or Asia which population increased twofold in the same period. The needs of developing and developed countries are different. The financial resources required to promote the development and environmental protection of developing countries are under the control of a minority that may dictate the way of leading with these questions according to their own interest.

The gap in the standard of living is identified by Metha [1998], who mentions that the developed world, composed of North America, Western Europe and Japan, account for 12 percent of the world population but for 60 percent of total energy consumption. Moreover these countries enjoy a high standard of living, with their economies dictated by consumption and the generation of considerable amounts of waste and pollution per capita. However, poverty and wealth gaps are similarly identified as one of the key drivers of unsustainable environmental degradation. According to the Worldwatch Institute, “people at either end of the income spectrum are far more likely than those in the middle to damage the earth’s ecological health: the rich, because of their high consumption of energy, raw materials and manufactured goods, and the poor, because they must often cut trees, grow crops, or graze cattle in ways harmful to Earth, merely to survive from one day to the next” [OECD-Sustainable Consumption 1997].
According to the World Bank [Gardner, 2002] "poverty is not simply a lack of income, but a lack of access to food, clean water, education and other services that have a marked impact on the opportunities for the poor".

Among the factors adversely pressing society and leading to the present scenario, the following can be mentioned:

- Different demographic growth;
- Significant increase in the rate of urbanization;
- Fast deterioration of the environment impacting the weather and health world-wide, mainly in urban areas;
- Change in consumption pattern;
- Growth in speculative investments instead of productive investments;
- Search for excessive profit margin by industries;
- Lack of synergy and integrated management among macroeconomic industrial, technological, commercial, social and environmental policies;
- Gaps in the concentration of wealth among and within countries;
- Progressive shortage of raw materials and fossil fuels.

Although being one of the most obvious needs for society, improvement of the compatibility between industrial, social, and environmental development has been conducted at a very slow pace considering the technological progresses presently achieved. The challenge for developing countries is difficult, since they have to promote their development and solve their social debts, without impacting the environment with scarce economic resources.

3.2 Social Issues

The lack of housing facilities, infrastructure, and social services is a problem that must be urgently solved. Since governmental budgetary constraints are becoming increasingly severe, this
constitutes a bottleneck for economic and social developments. The following data emphasize the dramatic current scenario [Gélinas 2000]:

- 1.4 billion people have no access to safe drinking water;
- 2.6 billion people have no convenient sanitation services;
- 1.1 billion people have no satisfactory dwelling;

The second highest source of death of children worldwide, causing approximately 1 million deaths per year, is diarrhea, which could be so easily prevented by easier access to water for washing, better health education and oral rehydration therapy [The Economist 2002]. It is estimated that about 20 000 people die each day from water-related diseases [Gardner 2002].

About 75 percent of the population of OECD member countries live or work in urban areas, and worldwide it is foreseen that the great majority will be living in urban areas after the year 2005. In the next two decades, the volume of urban agglomerations will be boosted. The highest increase will occur in cities in which the population ranges between 1 and 5 million inhabitants [OECD- Sustainable Development- OECD Policy Approaches for the 21st Century 1997]. With accelerated urban development, the need for infrastructure will be growing, especially in developing countries, where the highest population growth and urbanization rates will be found.

Based on the GNP/head data provided by The Economist [1999], the following worldwide scenario can be stated:

- 3.6 billion potential consumers have a low income (less than $3 000 US/year). This huge amount of people will be demanding basic infrastructure services (schools, hospitals, houses, etc.) and therefore they will be future customers for the cement and concrete industries. It will be absolutely necessary to develop new low cost construction, with low wasting and fast execution time. Improving labor force qualifications is a key issue for these people and the cement and concrete sectors can provide some support in training. Sanitation is another potential market for cement and concrete industries. The main sustainable alternative for these people is not high-tech
products, but rather low cost and environmentally adequate technology, such as lightweight concrete, roller compacted concrete, mortar blocks and precast units;

- 1.4 billion consumers have a medium purchasing capacity (between $3,000 to 10,000 US). They represent the largest spectrum regarding demand in goods. The demand varies from sky-scrappers and malls to low cost housing and sanitation infrastructure. Concrete road paving and precast elements are the main option for the demand in cement. The main challenge will come from competition with steel structures and asphalt. It is desirable to improve existing concrete production technology (better curing, use of water reducers, low W/C ratio, etc.) in order to avoid premature degradation of concrete structures;

- 1 billion consumers have a high purchasing power (over $10,000 US). The type of cement consumption these people will require is quite different. Since their basic needs are already satisfied, their consumption pattern is basically concentrated in trips, cars, etc. These people are concentrated mainly in Europe, North America and some Asian countries. The cement market specially in Europe will be mainly focused on rebuilding old structures, build leisure areas etc. The market is therefore focused, or should be focusing, on higher performance products such as High Performance Concrete and Self Consolidating Concrete aimed at improving durability, fast execution and space saving due to elevated cost of real state. Recycling of construction and demolition material is a major concern and must reach higher levels.

The following issues must furthermore be considered:

- The urbanization rate has been increasing steadily;
- Road transportation is still fundamental for economic development;
- Public transportation has been often neglected and it is expensive and it requires time to be implemented;
- Governmental economic resources are becoming scarce and too often badly allocated;
- The worldwide economic crisis will greatly affect the availability of financial resources for new projects;
- Environmental and health issues have an ever-growing impact on direct and indirect national costs;
- In a globalized market, competitiveness is a key component;
- Globalization has brought new consumption patterns and work relationships.

An efficient management of infrastructure investments is a key component for sustainable mobility and also to improve the quality of life. However, since the second half of the eighties many countries have instead experienced cutbacks in infrastructure investments with many development programs being seriously affected.

### 3.3 Economic Perspectives

The crises experienced by some countries such as Russia, Brazil, Argentina, and other Asian countries such as Korea, Thailand, strongly affected the macroeconomic scenario and their consequences affected companies and countries. The high level of interest rates have been a parameter impairing a sustainable economical growth. The reduction of interest rate is a further attempt to promote a reinforcement of economic health.

World GNP (Figure 2) has been showing a decreasing trend [Alternatives Economiques 1999] and it should be pointed out that the general situation has not worsened due to the emerging needs of China and the previous good health of the U.S. economy.
Figure 2: Decreasing trend in world GNP

The current American economic situation, however, must be seriously taken into account. The events of September-2001 at the World Trade Center towers have impacted the world economy and could accentuate a recession scenario. The recent corporate scandals have also strongly affected the stock market and economy as a whole. Any forecast is difficult to make. However, compared to several other industrial sectors, the construction industry will be less affected. In a recession scenario, civil construction is still an easy way to generate employment and to make the jump start of the economy.

The construction industry is a basic sector in a nation’s growth, and particularly, a key component in developing countries regarding employment generation for poorly qualified or unqualified workers. From a social point of view, this component cannot be neglected; however, from an economic and environmental point of view, it has serious consequences as the costs derived from waste and repairs are significant. In this sense, it is important to look for alternatives to minimize the resulting environmental impact of wasting and, at the same time, fulfill social needs.

Due to its own characteristics, the cement and concrete industries contribute socially and economically to world assets since its investments are long-term productive ones. Certainly, the use of cement and concrete meets the needs of rich and mainly poor people all over the world. Cement and concrete materials help to build the infrastructures necessary to all social classes.

The cement and concrete industries play an important role in the world-wide economy and have a high social development implication. Civil construction has a high impact on the economy of any country, it represents approximately 10 to 11 percent of the European Union GNP [John et alli 2000] and 14 to 15 percent of the GNP in developing countries. In some countries the
construction sector can at times share 25 percent of GNP. With some 30 million employees in the European Union construction is the largest industrial sector [Sjöström 2000].

In the years to come, cement consumption, for instance, will largely increase in developing countries, as can be seen in Figure 3 [Scheubel & Nachtwey 1997]

![Cement use vs GDP per capita](image)

**Figure 3**: Cement consumption and the GNP per capita

It can be seen that the cement consumption increases until $10,000 US, and that over this value, there is a decreasing trend in the consumption pattern. Cement consumption will be used in developing countries to build houses, schools, hospitals, dams, and even a more durable road network.

In all countries, and in particular due to globalization, transportation is an essential factor in economic activity, industrial competitiveness, and trade. The asset value of the road network is estimated at 1.5 to 3 times the GNP of a country and the costs of transportation in the economy ranges from 2 percent to as high as 17 percent of the GDP for less-developed countries [OECD-Road Transport Research Outlook 2000, 1997]. The value of this asset and the need to maintain its functionality coupled with both an aging road network and increased traffic loads has inevitably meant higher investments on maintenance and rehabilitation. OECD member countries
spend approximately 23 percent of their road budgets on maintenance activities [OECD-Road Transport Research Outlook 2000, 1997].

Although being the main driving force for business, service, industries and competitiveness, especially in a globalized scenario, road transportation is also a considerable source of costs due to casualties, health problems, pollution, and the degradation of ecosystems and landscapes. Overall costs of road casualties and collisions in OECD countries are estimated to be roughly 2 percent of GDP and accidents in the UK account for about 60 percent of this cost [OECD- Urban Travel and Sustainable Development 1995]. The largest of all estimated costs is in the United States where the figure is equivalent to about 8 percent of GDP, however, nearly two-thirds of this represents the cost of pain, suffering and loss of quality of life, which is not included to the same extent in the other estimates. Road death rates are unacceptably high particularly for pedestrians and cyclists in urban areas. Road accidents kill about 500,000 people and causes injuries to about 1.9 million worldwide [OECD- Urban Travel and Sustainable Development 1995].

Undoubtedly there are countless and obvious costs, such as lost hours in traffic, stress and decrease in productivity of employees, increased fuel consumption, accelerated wear on vehicles, greater emission levels, impact of pollution on the health of the population, delays on the delivery of goods with significant material damage, lost deals and business, casualties, real estate devaluation, etc. Many of these costs can be easily calculated, but some can only barely be evaluated.

In this context, the low emphasis that has been given to urban paving as an alternative to reduce these costs, and the lack of synergy between the people concerned, including authorities, community, industry and transportation companies, seems amazing. Urban paving should be more judiciously considered, and not only in terms of material selection, such as rigid or flexible pavement, but also in terms of the strategy and criteria for selecting them. In each case it would be necessary to provide the best cost/benefit performance, including: maintenance and its impact on local traffic, cost and budget availability, traffic volume and characteristics, available technology, durability, local pollution levels and dispersion, improved safety for users
(pedestrians and drivers), extension and localization of the stretch, etc. The maximization of financial resources, the improvement of labor force allocations and the reduction of the environmental impact must be optimized.

A contradictory issue to be considered in evaluating pollution impact and economic issues concerns subsidies. Before imposing taxes, it should be more carefully considered whether governmental subsidies will not induce pollution. Taxes related to pollution have been adopted in many industrialized countries aiming to force companies and individuals to respect the environment, but, at the same time, governments still support specific industrial sectors that may have an opposite effect, contributing in an increase of pollution. According to Lévéque et al [1999], there are many public subsidies that induce pollution and that may frequently exceed the gain achieved by enforcing environmental taxes. In 1999 in France, ecotaxes generated about $300 million US while financial aid to polluting activities amounted to $8 billion US in eight sectors examined, inducing a production of 30 million tonnes of CO₂.

In this evaluation three types of subsidies were considered:

- Direct subsidy which is the most current, consisting in a direct payment from the State to support the production or, selling or buying of a good, covering, for instance, losses in exploitation or investment subvention. In this case, the impact is due to the government’s decision to support certain sectors of the economy whose activities are unfavorable to the environment;

- Tax assistance which is the second form of subvention considered. Fiscal aid is based on exemptions regarding general fiscal rules. Tax assistance is devoted to a particular sector, activity or a user category, it can consist in a tax deduction on revenue and profits, in an extension in payment delays, in credits or local tax exemption, etc. In the case where a tax assistance benefits a manufacturing process or a product that is more polluting than another, it must be considered as a support to pollution;

- Incomplete payment by the user of certain public services of a polluting nature (such as road infrastructure, rural electricity, public transportation) is the third form of subsidy. It
consists in charging prices below their real cost, so that the difference of cost must be covered by further taxes or by other sources.

Subsidies inflate the costs of government, add to deficits, and raise taxes, moreover they are an incentive for inefficiency and consumption rather than productivity and conservation. The total of these forms of support can vary from $7 billion US for Ruhr Valley coal in Germany to $300 billion US for agriculture in OECD country members. In the U.S., for instance, subsidies to fossil fuel industries exceed $20 billion US per year with fifteen different and direct subsidies to virgin resource extraction and waste disposal in effect within 5 years. Worldwide subsidies exceed $1.5 trillion US annually [Hawken et al 1999] Agriculture, energy, transportation, water, forestry and fisheries are the most frequently supported sectors worldwide.

Productivity is becoming a very serious issue from an economic point of view. Entrepreneurs are slowly noticing the importance of providing a good environment and working conditions for their employees as an advantage for both sides. Based on Figure 4, it can be evaluated that an improvement of 1% in productivity of workers, which would correspond to a $1.30 US would be almost enough to pay the entire energy consumption of a company ($1.53 US) [Hawken et al 1999].
3.4 Impact of Globalization

The worldwide economy has been experiencing great changes, mainly in its economic scenario, but also in its social and technological scenarios. A great part of these changes is related to so called globalization.

Globalization is presently characterized basically by massive company mergers and acquisitions, by the development of a strong network in the communications field.

With globalization, many trade barriers have been broken. The structural and political fragility of some countries and companies has been exposed by the oscillations of the world economy, and by the absence of consistent criteria in loan concession policies. Protectionism and chronic problems with high inflation rates in some countries should also be considered in such a scenario.
At the beginning of the 70’s approximately 90 percent of foreign exchange transactions concerned financing commerce/trade and long term investments, while the remaining 10 percent consisted in speculative investment, whereas the opposite trend is observed today, creating great uncertainty in the labor markets and volatile currency exchange rates [OECD- Economic Globalization and the Environment 1997].

The exacerbated industrial growth was related, among other factors, to the increase in the restraint good’s demand in developing countries as well as to the search for improved welfare in developed countries which results in a strong adverse impact on the environment. Meanwhile, the rapid worldwide deterioration of environmental conditions awakened in society, especially in the last 10 years, a great concern for environmentally related issues. This is one of the most important characteristics of globalization, and, probably the one with the highest synergetic effects.

Although it multiplies business, opens formerly protected markets, drops tariff barriers, and increases the volume and freedom for worldwide money circulation, globalization does not promote a better distribution of wealth, the rapid increase in the number of jobless people being the crudest and most notorious side of it. The following new geopolitical and social parameters brought about by globalization will certainly impact the profile of future consumption and market behavior as well as new investments and business:

- increase in unemployment rates;
- increase in layoffs and service providers;
- aging of world population;
- national welfare systems facing collapse in the next 2 decades;
- overall tightening in monetary policy;
- decrease in investments available for infrastructure;
- dismantling of subsidies;
- getting out of political and economic crisis and grasping for consumption in some countries;
- difficult economic recession in some countries.
The number and proportion of people having long-term full-time employment is decreasing everywhere, whereas non-standard working conditions such as part-time work and peripheral employment, are increasing. The change in traditional employment is due to two trend shifts: globalization and the transfer from a property-based society to a knowledge-based society [Dumez and Jeunemaître 2000].

Globalization promoted a new type of relationship in the job/work pattern with a great increase in informal activities and service providers that have certainly been affecting the economic activity of countries. In such saturated markets, it will not be possible to absorb all of the labor force and ensure the survival of small businesses.

In Figure 5 typical movements of labor forces during the period of globalization for OECD member countries are presented [OECD- Vers Une Nouvelle Ère Mondiale- Défis et Oppotunités, 1997].

![Figure 5: Movement of the labor force](image-url)
Early in the sixties a migration process took place from rural areas toward cities in search of better work opportunities and incomes. Moreover, until 1971 the distribution of labor force remained almost the same between industry and services. Mainly during the 80’s, when in broad general terms the first effects of globalization started to be felt, there was a remarkable increase in the services area, which resulted in the incorporation into the market of a great proportion of workers laid off by the industrial sector. It can be presumed that in developing countries, where the labor force is less qualified and therefore more vulnerable to unemployment, this scenario must be somewhat more critical, especially due to the absence of satisfactory welfare mechanisms that could potentially temporarily counteract this situation.

At the same time, in many countries, a large part of the population is aging and the economic active share is decreasing putting even more stress on welfare systems worldwide, generating internal deficits, reducing the economic availability for urgent investments in infrastructure. On the other hand the population in developing countries is young and grasping for education, employment generation in a scenario of scarce or badly allocated budgets.

3.5 Basis for Sustainability

In order to achieve sustainability there are some specific goals that must be harmoniously fulfilled and integrated [Yevdokimov, 2001]:

1- Economic
   • Economic growth;
   • Economic efficiency;
   • Economic stability.

2- Social
   • Preservation of cultural heritage;
   • Elimination of poverty;
• Equal access to education;
• Equal access to healthcare.

3- Ecological
• Biodiversity
• Resilience to pollution;
• Clean environment;
• Optimal management of natural resources.

There are three key issues with significant implication for defining a sustainable policy [OECD-Sustainable Consumption and Production 1997]:

- Population growth: The global population has more than doubled since 1950 and is projected to increase from 5.5 billion to 8.5 billion by 2025. Growth is occurring disproportionately fast in developing countries where institutional/economical/social systems are currently less able to provide the population’s welfare;
- Economic growth. Global economic output has increased five-fold since 1950. World commercial energy consumption rose by 45 percent between 1971-1991. Improvements in energy and materials efficiency have been more than offset by increases in volume output;
- Poverty and global inequity. There is an enormous wealth and income disparity between developed and developing countries. Average 1991 GDP per capita was $19000 US in OECD (Organization for Economic Cooperation and Development) countries, compared to $2 400 US for developing countries. Disparities within countries can be equally great, creating social tension and encouraging dissatisfaction with living standards. Despite faster percentage economic growth in developing countries, the share of global income going to the richest 20% of the world’s population rose from 70 percent in 1960 to 83 percent in 1989.

In the present scenario, the HDI (Human Development Index) of a country should be more seriously considered, because it is a way to evaluate the degree of the quality of life as well as a
helpful tool in deciding market needs and perspectives. Contrarily to the traditional way of evaluation of welfare, that takes into account the GNP/head, the HDI takes into account several parameters such as the own GNP per head, profile of age distribution of the population, degree of education, social stresses, unemployment rate (exacerbated by globalization), as well as the uncertainty among employed people. This could provide investors a better idea of labor quality, costs with security, risk of violence, infrastructure availability, perspectives of market, etc. In the same way, cultural heritage and urbanization rate have a high impact on the needs and desires of potential customers as well as in the nature of the products to be offered on the market.

Further requirements of sustainability involves ethics and partnership with clients and suppliers as well as a good working environment for employees in order to achieve their maximum productivity and develop a relation based on confidence. All of the parameters to be considered in sustainability are presented in Figure 6 [Ashley et al 2002].
3.6 Conclusion

Environment is a very important issue in the context of sustainability, but is not the only one, economic issues have still been the priority for decision makers. In a world where half of the inhabitants lives in poverty, with enormous lack of infrastructures and where the GNP is highly concentrated, sustainability must have a much deeper meaning, with higher social added value. One should not simply wonder about the new generation’s future, but also about providing dignity to the present generation.

Sustainable development is therefore a serious commitment to the future. It is almost the answer to the exacerbated process of consumption we are currently experiencing. The highest socio-economic output at the lowest environmental impact has to be systematically sought in any human activity.

Sustainability will mean, in a few words, to make in a better way, to make more with less, to optimize natural resources, and to use economic resources with sensitivity. Market demands
for developed countries are quite different from that of developing countries, as well as social pressures and the availability of natural resources.

In such a scenario, the cement and concrete industries undoubtedly play an essential role in the development of our society, keeping in view that concrete is the most widely used material after water, and it will continue to be so in this new century. Both industries, specially the concrete one, provide, directly and indirectly, a great quantity of jobs, having an enormous importance for achieving social welfare by means of building, roads, bridges, dams, schools, houses, hospitals, offshore platform, malls, airfields, etc. From a social and economic point of view the advantages brought by the cement and concrete industries are clear for society as a whole, but it does not mean that they have reached an optimal use and production of these materials according to sustainability.

The discussion cannot be restricted solely to the intrinsic features of the materials in environmental terms, since an ecologically adequate material, when poorly employed, still poses a problem to the environment. In this process, a broad user-guidance and awareness-raising work is equally necessary as well as stimulating the development of new building techniques that maximize energy gain and minimize losses in the site.
4. PORTLAND CEMENT MANUFACTURING

4.1 Introduction

The manufacturing of Portland cement requires high quantities of raw material and thermal and electrical energy.

Limestone is the most important raw material used for the production of cement as a source of CaO. It is largely found in nature worldwide. Secondary raw materials are clay, sand, and bauxite or hematite used as corrective materials to provide the required SiO₂, Al₂O₃, and Fe₂O₃ contents. These components are conveniently dosed, ground and homogenized, and fed to the kiln where they are burned at about 1,450°C and subsequently cooled. The resulting clinker is ground together with calcium sulfate, and eventually, other supplementary cementitious materials in order to obtain cement.

The main thermal energy consumption occurs during the burning process, while electrical energy is essentially used for cement grinding. The fossil fuels most used are fuel oil and coal. The search for ever-increasing energy savings occurred mainly after the first oil crisis in the seventies and became a major concern due to its impact on production costs. As a result cement manufacturing technology experienced great progress, with the development of dry kilns equipped with preheater and precalciner replacing old kilns in which the raw meals were homogenized in a wet system consuming a high level of energy during burning. Also new developments in grinding technology were achieved allowing a reduction in electrical energy consumption.

The most important emissions of the cement industry is CO₂, due to the decomposition of limestone and to fuel burning. CO₂ is the most important greenhouse gas and its mitigation is a worldwide concern. The cement industry is reducing its emission as well as its dependence on fossil fuel. In the last 30 years, the cement industry has also achieved a remarkable reduction in dust emissions and NOx in the exhausted gases.
All these technological advances contribute greatly to alleviate the environmental burden, to obtaining a better product and to improve the competitiveness of cement plants. Technology upgrading and quality assurance as a follow up to the process, as well as quality of the product, are more than just environmental concerns, they also constitute a major step toward ensuring the participation of the plant in the market share.

4.2 Raw Materials

The basis for any cement production is an existing market and the availability of suitable raw materials.

In order to evaluate the feasibility of installing a cement plant and also the profitability of the venture, some issues regarding raw materials must be considered. Among these issues the following can be mentioned:

- localization of the deposit with regard to the potential market;
- life-cycle of the quarry;
- quality of the available calcium carbonate;
- minor elements;
- raw meal burnability and impact on energy consumption;
- local quarrying requirements from an environmental point of view.

As a general rule, the main steps in cement manufacturing are:

- raw material exploitation;
- raw meal crushing;
- raw meal grinding;
- raw meal homogenization;
- raw meal burning in a rotary kiln at about 1450°C;
- clinker storage;
- clinker and gypsum grinding plus supplementary cementitious materials (slag, fly ash, limestone filler etc).

Limestone is the source of CaO and is therefore the main component used in Portland cement manufacturing. Calcium carbonate of any geological formation qualifies for the production of Portland cement. The most common forms of calcium carbonate used to make Portland cement are limestone, chalk and marl. Usually, clay provides the SiO₂, Al₂O₃ and Fe₂O₃ necessary to make Portland cement clinker. When the clay does not contain enough of these components corrective materials have to be added, among others, sand (source of SiO₂), iron ore (source of Fe₂O₃) or bauxite (source of Al₂O₃).

Limestone is one of most frequent minerals present in most countries throughout the world. About 7 percent of the Earth’s crust consists of this material. The world output of limestone and other materials containing calcium carbonate, such as dolomite, is estimated at between 2 and 4 billion tonnes per year [Merker 2000]. Limestone usually has a predominantly fine-grained crystalline structure The hardness of limestone depends on its geological age usually, the older the geological formation, the harder the limestone [Duda 1977].

Chalk is a relatively recent sedimentary rock formed during the Cretaceous period. Chalk is characterized by a soft earthy texture qualifying it as a raw material especially for the wet process of cement manufacturing, since blasting is not required for quarrying. Moreover, as crushing can also be omitted, the production cost of cement is considerably lowered. The calcium carbonate content of a chalk can be as high as 98-99 percent in some deposits.

Marl is a sedimentary rock generated by simultaneous sedimentation of calcium carbonate and clay. It is an excellent raw material to make Portland cement because it contains lime and clay in already homogenized conditions, with a very low hardness compared to limestone. Marls sometimes contain bituminous constituents that may contribute to energy savings.

In the manufacturing process certain chemical parameters are used to reach the required cement properties and kiln operation feasibility. The main parameters are the Lime Saturation
Factor (LSF), the Silica Ratio (SR) and the Aluminum Ratio (AR), which are calculated as follows from the chemical composition of the raw meal:

**LSF**: \( 100 \text{CaO}/2.8 \text{SiO}_2 + 1.18 \text{Al}_2\text{O}_3 + 0.65 \text{Fe}_2\text{O}_3 \)

**SR**: \( \text{SiO}_2/\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 \)

**AR**: \( \text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3 \)

In the cement industry, there is a traditional terminology used to simplify the mineralogical phase designation where C corresponds to CaO, S to SiO\(_2\), A to Al\(_2\)O\(_3\) and F to Fe\(_2\)O\(_3\), N refers to Na\(_2\)O, K for K\(_2\)O and S designates SO\(_3\). The main Portland clinker phases (**Figures 7 and 8**) are:

- C\(_3\)S an abbreviated and conventional way of referring to pure tricalcium silicate in the cement industry (in practice, as this phase contains impurities it is rather called alite);
- C\(_2\)S or dicalcium silicate (belite is the corresponding impure industrial form);
- C\(_3\)A or tricalcium aluminate;
- C\(_4\)AF or iron tetracalcium aluminate.

**Figure 7**: Photomicrograph of a clinker showing C\(_3\)S (A), C\(_3\)A (D) and C\(_4\)AF (F)
Figure 8: Photomicrograph of a clinker showing C₂S (B), C₃S (A), and interstitial phase (I)

The proportion of C₃S/C₂S depends on the LSF. C₃S and C₂S are the main hydraulic binders of Portland cement. C₃S being more reactive than C₂S, it responds for the initial strength development (basically up to 7 days) for a given water/cement ratio. C₂S is responsible for late strength development.

The LSF usually varies between 90 and 100 depending on the required characteristics of the cement as well as those of the fuel used. The higher the LSF, the higher the thermal energy consumption, but the lower the electrical energy consumption during cement grinding, because it is easier to grind C₃S than C₂S to reach a certain fineness since C₂S has a higher elasticity modulus than C₃S.

The total silicate phases content (C₃S+C₂S) in the clinker depends on the SR (Silica Ratio) as well as the amount of the liquid phase necessary to promote the reactions during clinkerization. If the SR is too low, the amount of liquid phase will be too high. This may cause accelerated wear of the lining or result in the formation of an intensive coating that can lead to a kiln shutdown. On the other hand, if the SR is too high the resulting raw meal will be hard to burn, increasing the thermal energy consumption, decreasing clinker granulation and making it difficult to grind. Moreover, energy losses through the kiln wall will increase due to the absence
of a protective coating. The SR may vary from 1.9 to 3.2, but it usually varies in the range between 2.2 to 2.6.

The AR (Alumina Ratio) defines the respective proportion of C₃A and C₄AF in the clinker. This proportion is very important for hydration heat and for early age strength development in high water/cement ratio mixtures. The behavior of concrete exposed to sulfate and chloride-aggressive environments also depends largely on this proportion, the lower this ratio the better the sulfate resistance.

The AR influences the liquid phase viscosity in the sintering zone which affects clinker granulation and the formation of a convenient coating in the sintering zone. Usually, the AR ranges from 1.5 to 2.5, but its value depends largely on the desired final properties of the cement. Usually, the higher the SR the lower the AR, and vice versa. This adjustment in SR and AR values is made in order to compensate and adjust the quantity and viscosity of the liquid phase.

Minor elements found in the raw materials can affect either the kiln operation or the final performance of Portland cement. The main minor elements and their corresponding effects are:

- MgO- It is usually found associated to CaO in methamophic limestone. When its content in the clinker is lower than 2 percent, it is mainly incorporated in C₃S, and does not form periclase crystals that react with water and can cause expansion due to the formation of brucite Mg(OH)₂. ASTM C-150 standard requires that the MgO content of Portland cement be lower than 5 percent to avoid any expansion. It is however a fluxing agent that is beneficial for the burning.;

- P₂O₅- It can impair the final properties of the cement by lowering cement strength when its content is higher than 0.6 percent. It is mainly found in limestone and carbonatite, the latter being an igneous geological rock that is rarely used as raw material for cement manufacturing. The Cimpor group’s Jacupiranga plant in Brazil, is a rare example of a cement plant using carbonatite;
- Fluorine- At a low content and well-controlled level (between 0.3 to 0.5 percent) it is an excellent fluxing agent that improves raw meal burnability and allows energy savings. However, higher contents of fluorine delay setting and can cause operational problems with buildup occurring in the preheater. Fluorine comes from limestone;

- Alkalis (K₂O and Na₂O) usually come from the clay. Alkalis affect the manufacturing process due to the development of buildup (K₂O being worse than Na₂O) that may lead to kiln shutdown. Alkalis affect the rheological behavior of concrete paste, increase the initial strength of cement, but decrease its long term strength. Alkalis, when present in too high an amount, greater than 0.6 percent Na₂O equivalent, can cause alkali-aggregate reaction, a serious phenomenon leading to concrete deterioration when reactive aggregates are used. Alkalis are usually expressed as Na₂O equivalent which corresponds to: \((\text{Na}_2\text{O}) + 0.658 (\text{K}_2\text{O})\);

- Chloride- is an extremely deleterious element for the manufacturing process and may lead to severe buildup problems in the preheater. The maximum content of Cl⁻ in the raw meal should not exceed 0.03 percent;

- Sulfur- comes mainly from fuel and secondarily from the raw or corrective materials. The sulfur content must have a good stoechiometric ratio with alkalis in order to combine with them. Usually the sulfur is incorporated in the clinker as arcanite (K₂SO₄) or as calcium langbeinite (K₂Ca₂(SO₄)₃) or is entrapped mainly in the belite phase (C₂S). When there is an excess of SO₃ with regard to the alkalis content or vice-versa, buildup or rings will develop in the kiln and lead to kiln shutdowns, besides causing a premature wear of the lining.

Other minor elements, mainly, zinc, barium, lead and cadmium, must be very carefully controlled, since even low quantities can result in serious problems regarding setting and strength as well as operational and environmental concerns.
4.3 Energy Issues

Over the past decades, the cement industry has made major progress in reducing its energy consumption. This has been achieved primarily by replacing wet production facilities by new modern dry-processing plants and by moving away from petroleum-based fuels.

The cement industry traditionally used mineral coal, fuel oil, and to a lesser extent, natural gas and charcoal as energy sources. In the 1890’s, pulverized coal firing achieved its first real commercial success in the cement industry in the United States. Thereafter, pulverized coal firing has largely developed as an empirical art. [Duda 1977]. The profile in the use of these fuels did not change until 1973 when the first oil crisis occurred. Initially this crisis had an adverse impact on the cement industry, but it later led to extraordinary progress from a technological development point of view.

The oil crisis resulted in the search for alternatives that minimized the dependence of countries on oil imports. More economical kilns were developed, fuel oil was replaced by mineral coal and charcoal, new energetically alternative sources were sought, among them rice husks, tires, etc. In parallel, an increased amount of supplementary cementitious materials (blast furnace slag, fly ash, calcined clay, limestone filler) started to be used.

From a technical point of view burning fuel oil or natural gas is much simpler than burning coal. Coal contains a variable amount of ash that must be considered when calculating the chemical composition of the raw meal. While a good quality coal can have an ash content of 8 percent, a medium grade coal can have an ash content around 12 percent. Some coals used during the oil crisis had an ash content of up to 35 to 40 percent [Marciano & Kihara 1997]. In India, the available coals have a high ash content while in other countries, such as Brazil, for instance, the high quality low ash coal, is used by the steel industry. In any case, the cement industry will depend on coal as a source of energy in the long term, since, if an annual increase of 2 percent in consumption is assumed, petroleum oil will no longer be available in approximately 60 years. The situation for natural gas is similar. Only the reserves of both, hard coal and lignite will last for over 200 years. Alternative fuels must be found.
Since the eighties, petroleum coke or “pet coke”, as it is usually called, has become one of the most commonly used alternative fuels in the cement industry worldwide. Pet coke is a black solid residue from the petrochemical industry, obtained mainly by cracking and carbonizing residue feedstock, tars and pitches in processes such as delayed coking or fluid coking [MacEachern 1998].

Presently, the market dictates that refiners produce more valuable light ends, causing a reduction in the amount of heavy fuel oil that could be available for the cement industry. For approximately two or three tonnes of heavy fuel oil, about one tonne of petcoke becomes available. There are two types of pet coke the delayed and fluid coke. Fluid coke is produced continuously in drop form at 600°C. It is a quite hard and fine material composed of particles of 0.5 to 4 mm. Typically, it has a very low ash and volatile matter content. Delayed coke is softer than fluid coke. Moreover it is somewhat coarser with a particle diameter in the 0-300 mm range. It also has a relatively low ash content, but can contain up to 15 percent volatile matter. Delayed coke is more readily available and, due to its easier grindability, suitable for both main burner and precalciner firing [Terry 1999].

From a sustainability point of view, it is easy to see that each country will have to find the best option to conciliate fuel availability and economic and environmental issues. The U.S. cement industry’s fuel mix, for instance, shows a trend, driven by economics and policies, away from natural gas and petroleum products to coal and coke. In 1972, natural gas represented 45 percent of the fuel mix, while coal and coke represented 36 percent. By 1994, gas consumption had dropped to 7 percent and coal and coke totaled 73 percent [Cahn et al 1998].
4.4 Kiln Development

The rotary kiln concept was introduced in the cement industry by Frederik Ransome, in 1885 in England [Duda 1977]. The first rotary kiln was gas fired, since the firing of a powdered coal was not known at that time. The diameter of the first cement rotary kilns was approximately 1.8m - 2.0m. It was approximately 20m - 25m long, with output capacities of about 30 - 50 tonnes per day. Since Ransome’s kiln was introduced its evolution has steadily targeted production increase and energy savings.

Among the main determining criteria for the selection of a kiln system the following can be mentioned [Carstensen 1993]:

- **Market Scenario**
  - Production output in tonnes/day;
  - Product quality;
  - Future demand capacity.

- **Raw material characteristics.**
  - Minor elements;
  - Moisture content;
  - Volatile component circulation.

- **Type of Fuel.**
  - Availability;
  - Quality;
  - Cost.

- **Environmental protection and legislation.**
  - Allowed maximum powder emission;
  - Limit of NOx emission;
  - Limit of SOx emission;
- Waste co-firing and alternative fuels burning: Limits of heavy metals, dioxins, organic components and inorganic halogens emissions.

**Profitability**

- Current and future cement price perspectives;
- Production costs (thermal and electrical energy, labor, etc);
- Investment cost.

Two fundamental methods are used to manufacture Portland cement, based mainly on the preparation of the raw feed before its introduction in the rotary kiln.

The first is the wet process, where a slurry is used for raw meal preparation. If the physical properties of the raw material components (plastic clay, chalk with high moisture content, etc) do not allow economical preparation of a dry raw mix, its application is essential.

The second is the dry process, where the dry state of the raw material components is exploited to prepare the raw mix. **Figure 9** schematically represents both processes [Cembureau 1997].

**Figure 9:** Wet and dry processes for clinker manufacturing
In the wet process, the feed material is prepared by wet homogenization and grinding. The resulting slurry, whose water content ranges from 18-45 percent is fed directly into the upper end of the kiln. Wet kilns can have different configurations. They are usually very long with internal heat exchangers performing inside the drying, decarbonation and burning of the raw meal. They can be shorter, when preliminary dewatering of the slurry by suction or filter press is done, resulting in a lower moisture content feed.

Keeping in view that for each percent water reduction of the raw meal paste (with 30 to 45 percent water) the economy is evaluated at 120 MJ/ tonne of clinker [Perez et al, 1995] further developments to reduce the water content in cement manufacturing have been achieved.

Semi-dry or semi-wet kilns were developed to remove 10 to 20 percent of the water from the slurry, through the use of filter presses, for instance. The resulting raw feed material contains about 15 to 20 percent moisture. Pellets of the feed material are loaded onto a travelling grate where they are preheated by the rotary kiln’s hot exit gases.

In the dry process, the feed material enters the kiln in a dry powdered form. Dry kilns can be long without internal installations or with internal heat exchangers such as chains and, refractory bridges or they can be short when preheater and precalciners are used.

Shaft kilns were another alternative technology, used in the sixties and seventies, and that gradually started to decline. These kilns present a low rate of production, usually under 300 tonnes/day, and were popular in countries of large geographical size with different local demands. Therefore, vertical kilns could be built to supply a limited market demand with a lower investment. The system is based on feeding pellets into a vertical kiln, and letting them go through the kiln by gravity under the effect of counter-current hot gases from the flame.

Modern dry kiln systems comprises a heat exchange tower composed of cyclones in which the dry feed is preheated by the kiln’s gases prior entering the rotary kiln. The calcination process can nearly be completed before the raw material enters the kiln if fuel is added in a special combustion chamber called precalciner.
Dry kilns equipped with a preheater and precalciner show great advantages over wet kilns due to their much lower specific heat consumption.

The mean energy consumption of a wet kiln is 6 000 MJ per tonne of clinker while the dry kilns previously mentioned show an average consumption of around 3 300 MJ per tonne of clinker with a minimum of 2 900 MJ per tonne of clinker [personal experience].

The usual output of a wet kiln varies from 500 to 2 000 tonnes/day, while long dry kilns vary from 500 to 1 500 tonnes/day. More recent dry kilns equipped with preheaters and precalciners have an average production of 2 000 – 4 000 tonnes/day and a maximum of 8 000 tonnes/day [personal experience].

Table 4 shows the typical heat balance for the wet and dry processes for the same kiln capacity [Gouda in Yamamoto et al 1997]:

**TABLE 4: TYPICAL HEAT BALANCE FOR WET AND DRY PROCESSES**

<table>
<thead>
<tr>
<th>Energy use</th>
<th>Wet Process (MJ/ tonne clinker)</th>
<th>Dry Process SP (MJ/ tonne clinker)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clinker Formation</td>
<td>1 800</td>
<td>1 800</td>
</tr>
<tr>
<td>Evaporation of Water</td>
<td>2 445</td>
<td>25</td>
</tr>
<tr>
<td>Radiation and Convection</td>
<td>1 130</td>
<td>600</td>
</tr>
<tr>
<td>Exit gas loss</td>
<td>630</td>
<td>730</td>
</tr>
<tr>
<td>Clinker discharge loss</td>
<td>170</td>
<td>130</td>
</tr>
<tr>
<td>Loss on calcination and superheating</td>
<td>190</td>
<td>105</td>
</tr>
<tr>
<td>Dust sensitive heating</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Total</td>
<td>6 385</td>
<td>3 420</td>
</tr>
<tr>
<td>Thermal efficiency</td>
<td>28 %</td>
<td>52 %</td>
</tr>
</tbody>
</table>

SP: Suspension Preheater
Finally Figure 10 schematically presents the energy consumption of different types of kilns and the progress achieved by the cement industry [Grosse-Daldrup et al 1996].

![Energy consumption for different types of kilns](image)

**Figure 10**: Energy consumption for different types of kilns.

### 4.5 Grinding

Grinding is a very important step in Portland cement manufacturing not only due to its high impact on manufacturing costs but also due to its ever-growing importance in the final performance and quality of cement.

Ball mill was introduced in the cement industry in 1892. At that time, it was composed of a single chamber having a diameter of 1.2 m and a length of 5-6 m. Its production rate was about 3 tonnes of cement per hour. Presently, a modern grinding mill can have a diameter of 6.0 m, and a length of 18 m. The output of such a ball mill can be as high as 250 tonnes/h of cement with a specific energy consumption of 30 kWh/tonne (110 MJ/tonne) of cement [Bucher 1996].

Cylindrical mills or ball mills waste about 80-90% of the energy just to drive the charge, without any comminution process, clearly showing its low efficiency [Bucher 1996]. The ball mill is a low efficiency equipment with the majority of the energy being lost or dissipated as heat and noise and a low quantity being in fact used for the grinding process. The energy converted
into size reduction work lies between 2 and 20% of the total energy supplied to the mill, the remaining energy is lost as [Duda 1977]:

- Friction between particles;
- Friction between particles and mill elements;
- Generation of sound;
- Heat and vibration;
- Material turbulence inside the mill;
- Loss of mechanical efficiency from motor to mill.

In the last years a remarkable evolution in grinding systems occurred in order to improve their performance and simultaneously reduce energy consumption. The first was the changing from open to closed ball mills.

The older open circuit is just a tumbling mill with two or three chambers to promote a mechanical separation, without a further more efficient pneumatic grain size separation. As both the coarse and the fine particles are ground simultaneously unnecessary further work occurs. The cement grain size distribution in an open circuit is broader while in a closed circuit it is much narrower with a smaller mean size.

Closed-circuit grinding plants consist of a tube mill, elevators and separators. These auxiliary units require additional energy which amounts to 10-20 percent of the mill’s energy requirement, but at higher fineness values (over 350 m²/kg) the energy requirement for a closed circuit grinding mill is lower. Closed-circuit systems allow an energy saving of 20 percent [Rawle 1996].

When grinding in a closed circuit, only the coarser particles pass through the mill several times until the requested fineness is reached. In the separator, the fine particles are separated and removed as finished product and do not return to the mill [Duda 1977]. As a consequence, cement produced in a closed circuit has a more uniform grain size distribution.
The ball mill is still the most common grinding equipment for cement production worldwide and is also frequently used for blended cement grinding although the risk of overgrinding the softer components such as clinker and limestone (unnecessary energy consumption without further fineness gain). The development of a new generation of separators has however been impressive and contributes to reducing energy consumption and final product performance. Despite its accepted advantages such as easy maintenance, simple operation and maximum availability, ball mill has a decisive disadvantage when considering its still high specific energy consumption.

As a result another further and remarkable step in cement grinding improvement occurred recently with the development of vertical mills. The working principle is based on two to four grinding rollers with shafts hinged and riding on a horizontal table or a grinding bowl, with the grinding pressure of the rollers upon the mill feed [Duda 1977]. Roller press mills have a lower specific energy consumption than tumbling mills and require less space per unit and output at a substantially lower investment cost. Roller press mills started to be used mainly in the eighties. Initially they were almost exclusively used for raw meal grinding.

The specific energy requirements of vertical mills are about 70 percent of those required by a ball mill, but the most energy efficient grinding process for cement without supplementary cementitious materials is a high pressure grinding roll used for the finishing grinding. Compared to the ball mill system, the specific energy requirements of a high pressure grinding roll system is only 50 to 60 percent [Galvão 1996].

Roller mills however are progressing and are also well adapted to the modern concept of separate grinding/mixing technology (Figure 11) [Bittner 2000]. This technology, using units specifically optimized with regard to the material for grinding, can save energy by separate grinding and produce material with adjustable properties.
Figure 11: Development of grinding systems

The use of grinding aids is another usual alternative used by the cement industry to improve the performance of cement grinding. Grinding aids are chemical products that improve the efficiency of the grinding process when added in small amounts to cement. These admixtures allow [Massazza 1981]:

- an increase in mill production for the same energy consumption rate and product fineness or grinding duration;
- an increase in cement fineness at the same energy consumption rate and mill production;
- a reduction in reagglomeration of the ground material originated by the kinetic energy of the grinding media (pack set).

Grinding aids are products that are adsorbed by the ground particles, reducing the bonds that attract other particles and that are causing agglomeration. Grinding aids prevent ball coating and therefore increase mill efficiency and also increase the efficiency of air separators by dispersing the particles so that the smaller ones are not carried along by the larger ones. The elimination of the surface forces causing interparticle attraction also contributes to the flowability of the cement.
The more widely used products are surfactants, such as amines and related salts, polyols, alcohols, lignosulphonates, fatty acids and related salts.

Usually, all the grinding aids are introduced in the grinding system in very small amounts, generally between 0.01 percent and 0.1 percent by mass of cement.

Grinding aid technology has not made much remarkable changes and progress. In the early 1990’s a new generation of additives, amine-based grinding aids, was developed in order to enhance the strength performance of clinker. They solubilize the normally slow reactive ferrite phase, which partially coats the silicate phases. As the ferrite phase gradually dissolves, more silicate surface becomes available for strength-giving hydration [Sandberg 1999].

The grinding step can influence the type of gypsum added to the cement to control its setting time and also to optimize its mechanical strength. Through the combined effect of temperature and residence time in the mill gypsum (CaSO₄. 2H₂O) can be partially dehydrated and transformed into hemihydrate (CaSO₄. 0.5H₂O) which is a more rapidly soluble phase. This may lead to a change in the rheological behavior of the cement paste. It can also increases the risk of false set in blended and in ordinary cements having a low C₃A content that have been submitted to a fast cooling.

The fineness developed by different materials and grinding equipment will not be the same, and therefore the grain size distribution of the cement produced will present some variations. Supplementary cementitious materials demand a certain fineness in order to develop their properties but the same can also be said for clinker although particles finer than 3 μm do not bring great benefit to strength development. Strength development depends essentially on the more reactive particles found in the range of 3μm - 40μm approximately. Cement grain size distribution is fundamental in order to achieve the required properties.
4.6 Emissions in the Cement Industry

The main constituents of the gases that exit from a cement kiln are nitrogen from the combustion air, CO₂ from calcination and combustion, water from the combustion process and the raw materials, and excess oxygen. The exit gases also contain very small quantities of dust, chlorides, fluorides, sulfur dioxide, NOₓ, carbon monoxide, and still smaller quantities of organic compounds and heavy metal. NOₓ gases are released mainly because of the very high temperature reached in the kiln. Finally some SO₂ can be generated, due mainly to the sulfur contained in the fuel used in the kiln. The exit gases are dedusted in filters (electrostatic precipitators). Cement plants are usually liquid effluent-free, since any water used in the process is evaporated though the chimney. Mitigation of CO₂ emission is the main concern of the cement industry but not the only one.

Dust emission, mainly related to fugitive dust, was mitigated by the extraordinary progresses in air bag filters, dust collectors, etc. Cement Kiln Dust-CKD is the discharged dust that can not be reintroduced in the kiln in order to comply with chemical requirements of standards or due to process problems that it can cause (chloride, alkali and sulfur cycles that lead to buildups and to kiln shutdown). CKD is not a major concern worldwide, and it is a problem mainly in few countries, among them USA. This problem is essentially related to old technology cement kilns (wet kilns for instance) or focused in countries where blended cement is not often used. By using blended cement it is possible to reintroduce the CKD in the process and control their negative impact by using convenient amount of supplementary cementitious material. The cement industry is penalized in countries where blended cement is not used since they waste energy to bypass gases and looses production. The society is penalized because it must be found costly environmental solutions for this CKD. The problem therefore is of local nature, not a main concern for sustainability in worldwide basis, and could be easily counteracted, from technical point of view if there was not some specific standard limitation.
Over the last few decades the European cement industry has demonstrated an impressive and continuous environmental improvement within the context of the sustainable manufacture and use of cement. Some examples are [Cembureau 1997]:

- Dust emissions have been reduced by 90 percent over the last 20 years, as a result of refinements in the production process and substantial investments in modern product handling methods and air pollution control equipment;
- The specific energy consumption for the production of cement clinker has been reduced by approximately 30 percent since 1970. This reduction in primary energy requirements is equivalent to approximately 11 million tonnes of coal per year with corresponding benefits in the reduction of CO₂ emissions.

However, it must be kept in mind that isolated improvements in the industrial processes presently used are nearing physical and engineering limits. Improvements in energy efficiency seem unlikely to be achieved on a short-term basis and will result in increasing costs, without promoting any further high CO₂ mitigation. The reduction in CO₂ will have to come from another source than the process, such as from the use of supplementary cementitious materials, for instance, as it will be discussed later. Moreover, any consistent strategy to improve sustainability must not only focus on mitigating CO₂ emissions, but also on raw material savings, as well as the type of fuel used on the corresponding emission pattern and levels, as can be seen in the Figure 12 [Berner et al 1999]. Gas emits 43 percent less CO₂ per unit of energy than coal and 48% less than petroleum coke. If it were possible to replace all the coal and coke in the American cement industry with natural gas, it would promote a 15 percent drop in CO₂ emissions. This objective however, depends of the availability and cost of the fuels and the policy adopted by each country and company.
Among the proposed alternatives for the American cement industry to reduce its \( \text{CO}_2 \) emission the following can be mentioned [Cahn et al, 1997]:

- Replacement of old clinker capacity by precalciner kilns;
- Cooler modifications;
- Direct firing systems;
- Upgrading of milling systems;
- Installation of high efficiency electric motors;
- Use of waste-derived fuel;
- Burning energy-bearing hazardous waste as kiln fuel. Such substitution results in great \( \text{CO}_2 \) mitigation because incinerators cannot recover any energy.

Moreover cement plants in the U.S. are currently subject to tightening air emission regulations as part of an ongoing effort to reduce ozone levels. Indeed, nitrogen oxides and volatile organic compounds are the primary precursors of ozone. \( \text{NO}_x \) is formed in any combustion process by two primary mechanisms. Thermal \( \text{NO}_x \) is formed when nitrogen and oxygen from the combustion air react at temperatures in excess of approximately 1450°C. \( \text{NO}_x \) is also formed by oxidation at lower temperature of nitrogen compounds contained in the fuel.
There is a strong dependence between the amount of NOx emissions and the type of the kiln and the fuel used, as can be seen in Table 5 [Klein et al 1998].

**TABLE 5: NO\textsubscript{2} EMISSIONS FROM CEMENT KILNS IN KG/TONNE OF CLINKER**

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Wet kiln</th>
<th>Dry kiln</th>
<th>Long</th>
<th>With Preheater</th>
<th>With Precalcer</th>
<th>With Precalcer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas</td>
<td>9.0</td>
<td>7.0 - 9.5</td>
<td>5.7</td>
<td>1.7 - 3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td>Nda</td>
<td>3.3 - 4.6</td>
<td>Nda</td>
<td>Nda</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>1.5 - 4.3</td>
<td>2.4 - 4.6</td>
<td>1.5 - 2.9</td>
<td>1.4 - 2.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

nda: no data available

Modern preheater/precalciner kilns usually generate lower NOx emissions than older and less energy efficient kilns, when using the same type of fuel. For the same type of kiln process, coal generates substantially less NOx than both natural gas and bunker oil. There is a strong indication that use of some waste-derived fuels have a beneficial effect on reducing NOx emissions [Klein et al, 1998].

Any step in the modification of operations leading to a reduced fuel consumption and to an improved process stability contributes to minimize NOx emissions. Presently, potential reductions can be estimated at 15 to 30 percent. Kiln operating parameters, such as the burning zone temperature, the amount of excess air and flame shape affects NOx emission.

Among the available NOx control technologies, low NOx burners appear to be the most widely used, at least for applications in indirectly coal-fired long dry, preheater and precalciner kilns. Low NOx burners limit both NO\textsubscript{x} formation mechanisms by slowing the mixing rate of fuel and air. Low NO\textsubscript{x} burners actually reduce the flame temperature, reduces local oxygen concentration in the flame envelope, and ensure that nitrogen from fuel is released into an oxygen-deficient environment where it is more likely to stay as harmless N\textsubscript{2} [Johnson 1999].
The EPA, the U.S. Environmental Protection Agency, prescribe low-NOx burners, mid-kiln firing or alternate control techniques. Low NOx burners are considered a Reasonably Available Control Technology (RACT), meaning that the EPA believes them to be a cost-effective choice for most cement kilns. These burners bring further advantages, such as lower CKD (Cement Kiln Dust) generation.

Sulfur is another important component in cement manufacturing. It can be introduced in the kiln system by the presence of pyrite in the raw material, or mainly and more frequently, by the fuel. If the amount of sulfur is too low compared to alkalis, it will cause build-up formation which affects the operation of the kiln. If the sulfur content is too high, it will cause an even worst build-up problem and will increase SOx emissions. Therefore, the SO3/alkalis ratio must be adjusted as close as possible to one.

Sulfur is oxidized in the form of gaseous SO2. A great part of this SO2 combines with or condenses on the raw meal particles and is reintroduced into the kiln process until the particles reach a higher temperature, then they evaporated again and they condensate again creating a cycle of volatilization and condensation. Part of the sulfur leaves the kiln trapped in the clinker as alkali sulfates or in the kiln gas outlet mainly as SO2.

The sulfur which is released by the fuel or volatilized from the raw meal tends to condense onto the preheater walls at temperatures around 800 to 1 150°C. It does not contribute in any great measure to SOx emissions from the system.

By now, cement plants have become highly efficient in controlling trouble-free uniform production operations using various substitute raw materials and fuel, while, of course, maintaining product quality and uniformity and staying within the emissions limits.

Technological progress in process engineering in the areas of storage and metering equipment, burners, and preheater and calciner modifications for the control and improvement of emissions are impressive in terms of the goals achieved as can be seen in Figure 13 [Bittner 2000].
Figure 13: Emissions profile in the cement industry

In many countries, a distinction is made between emission limits for existing kilns and for new kilns, and, differential regulations and transition periods exist to improve the process. The use of the Best Available Techniques (BAT) will also be required regarding production and environmental issues. This approach seems very reasonable and pragmatic.

4.7 Further Technological Considerations

The cement industry is a highly capital-intensive industry. The huge investments and long payback periods for process modifications make the cement industry very careful in selecting and developing new technologies [Cembureau 1997] but at the same time it is very sensitive and receptive to developments that may improve its efficiency.
Efforts to save further energy and protect the environment have been achieved due to the continuous search for up-to-date technologies such as [Marciano & Kihara 1997]:

- automation increase in the plants (about 3 percent energy savings) [Votorantim 1994];
- electronic packing systems (less pollution and 25 percent less electrical power) [Cauê 1994];
- hybrid grinding using roller and ball mills;
- vertical mills (lower noise levels and 20% energy savings);
- last-generation dynamic separators use;
- modern silos (up to 50 percent energy savings) [Paraíso 1994];
- new coolers (up to 15 percent energy savings) [Rio Branco 1995];
- new burners and burning systems.

In the same way, in the early 1980s when energy costs began to rise again, efforts were made to improve preheater cyclones. The objective was to design a preheater that would result in reduced pressure drop and increased collection efficiency. The result of these developments was the so-called Low Pressure Cyclone.

Preheaters and clinker coolers installed at that time had rather low thermal efficiencies, resulting in greater fuel consumption and higher NOx emissions [Jepsen et al, 1998]. The first few generations of precalciners also had operational difficulties resulting in retention times that were too low to ensure complete combustion of fuels such as coal and natural gas. This caused elevated fuel consumption and maintenance problems.

The fresh air used in the clinker cooler is heated to temperatures of up to 1 000°C through contact with the clinker, so it can be supplied to the kiln as combustion air. This extensive preheating of the air is essential for achieving high burning temperatures. Therefore, in order to optimize thermal energy consumption to reach values of 3 000 MJ/tonne of clinker, it is necessary to optimize the thermal efficiency of coolers.
Modern cooler technology results in fuel saving for the kiln system and power savings for the cooler ventilation system that may amount to 250-330 MJ/tonne clinker, which represents approximately 9 percent of the total energy consumption [Jepsen et al, 1998].

Another very important and sometimes neglected energy-saving issue is linked to the role played by the refractory lining and coating of the kiln [Marciano 1987]. In order to adjust the economical and technical requirements of clinker manufacturing the refractory lining must provide two main fundamental requirements: durability and ability to retain heat.

Any kiln shutdown for the purposes of changing or repairing the lining results in an irreversible loss of production of thousands of tonnes of clinker. Aside from this, the heat loss through the kiln wall depends significantly on the residual thickness of the brick and on its ability to retain a stable coating on the brick lining. It has already been seen that even in a period of time as short as 100 days the thickness of the brick lining can be reduced to 50 percent of its initial thickness [Personal experience]. The equivalent fuel loss due to this reduction can represent 2-3 percent [Duda,1977].

4.8 Manufacturing Costs

Cement manufacturing costs vary widely from country to country, depending on many factors. Manufacturing costs are presented in Figure 14 [Kassau 2000]:
Figure 14: Manufacturing costs

Given that it can produce immediate economic benefits, the use of substitute or alternative fuels is going to be of increasing importance, reducing costs particularly in countries, or companies with burning systems with very high specific energy consumption, in which fuel costs are clearly greater than electrical energy costs. [Grosse Daldrup et al, 1996]

The distribution between thermal and electrical energy varies due to the use of different burning processes, use of supplementary cementitious material, etc. In some countries or regions, the cost of electrical energy is becoming higher than the cost of thermal energy [Grosse Daldrup & Scheubel 1996]. In Germany, indicators show that energy costs are approximately 40 to 45 percent of the total cost of the production of the clinker. Electrical energy is used primarily to drive the extensive grinding equipment (62%) and to operate the kiln systems (22%).

There are various factors in routine operation which influence the productivity of the industry [Saxena 1995]:

- Age of the plant;
- Quality of inputs e.g. coal and power;
- Quality of raw material;
- Technology level;
- Government regulations;
- Labor productivity;
- Energy costs;
- Management aspects.

However, one very important issue in cement manufacturing is kiln shutdowns that consume time, money and energy. Surveys about cement industry report that 35 to 52 percent of maintenance budgets are spent in individual areas or plant shutdowns, not as a consequence of a
global and expected routine or preventive maintenance and could therefore be prevented. These data only reflect the price of maintenance and do not consider the costs of production loses [Lefebvre 2001]. A kiln shutdown represents a time of accelerated activity, with numerous vendors, contractors, and heavy equipment engaged in multiple tasks in close quarters. For the period between 1995 to 2000, the Mine Safety and Health Administration (MSHA) recorded that 23 percent of fatal accidents for any given year occur during shutdown periods, for US cement plants alone. [Lowel 2001].

A good strategy program must be defined, in order to be successful at reducing shutdown costs, downtime, rework and safety incidents, as well as improving start-up response and equipment reliability.

Anti-pollution regulations also have increased the cost of investment in the industry, with dust collecting facilities currently representing 10 to 15 percent of the construction cost of a plant.

Given the large investment costs required to set up a plant, fixed costs in the industry are particularly high and significant compared to variable costs. Fixed costs are said to generally account for more than 50 percent of overall production costs [Lefebvre personal comunication]. With the automation of the production process, labor costs decreased, most of the variable costs of production now come from energy consumption.

As cement is a low economic added value product, freight has a high impact in the final cost and in competitiveness. The industry is strongly influenced by transportation costs relative to production costs. In the U.S., average transportation and distribution costs account for almost 25 percent of the price of cement. As a result, most cement plants sell their production close by or within a radius of 300 km from the cement plant [Dumez & Jeunemaître 2000].

4.9 CONCLUSION
The progress achieved by the cement industry in the last 25 years is remarkable. Thermal energy consumption has been reduced by 30-40 percent, emissions mitigation has been impressive, achieving a 90 percent value for dust and almost 50 percent for NO\textsubscript{x} and SO\textsubscript{2} emissions. With the specific thermal energy saving previously mentioned a CO\textsubscript{2} mitigation around 20 percent has been achieved, only due to process improvement. It must be considered however that is not an absolutely value and to define a worldwide percent is hard. Although improving manufacturing process by reducing specific thermal energy consumption, there was a substantial increase in cement demand and therefore in the CO\textsubscript{2} generation and these progresses were not the same worldwide. Besides, many countries use different amounts of by products to the manufacturing of blended cement as well as the replacement of fossil fuel by waste derived fuel, with 5-10 percent replacement, a further contribution for CO\textsubscript{2} mitigation. Some countries also experienced cement production decrease due to local economic crisis that impaired the consumption. All these issues must be taken into account for a correct reduction of CO\textsubscript{2} in worldwide basis. The cement industry also has a serious commitment to raw meal savings as well as to improvements in the performance of the final product, while also reducing costs.

Progress has also been achieved in grinding technology but not as expected and there are still expectations for improving this important step in cement manufacturing. This progress has to be achieved mainly through the improvement of energy consumption, since quality has experienced a significant progress. Grinding aids technology has also not progressed as could be expected, creating a field that should be more deeply researched.

Engineering technology is reaching its limit and further advances to improve sustainable cement production will surely be highly expensive, however, many alternatives can be implemented according to the particular characteristics of the plant.

Cement producers must ensure uniform and high quality products at the lowest possible cost and, independently of the kiln type the following basic steps must be ensured:

- Raw meal burnability improvement (minor element control, fineness, homogenization, dosing, etc);
- Good stable coating development in the burning zone;
- Adjustment of the SO$_2$/alkalis ratio
- Control and reduction of false air sources in the kiln;
- Control of burner conditions regarding wear;
- Secondary air recovery optimization aimed at the maximum temperature;
- Convenient adjustment of secondary air quantity;
- Convenient atomization of oil or coal fineness;
- Good mechanical maintenance (kiln ovality, ring backlash, etc) and preventive programs;
- Ball mill control (charge, wearing, lining, moisture, etc).

These single and essential measures can be stated as the minimal requirements to optimize energy consumption and produce a good product without further investment while saving money.
5. PORTLAND CEMENT ECONOMIC ISSUES

5.1 Introduction

Exacerbated industrial growth has been related, among other factors, to an increase in the restraint demand in developing countries as well as to the search of improving the welfare of developed countries, which has resulted in an adverse impact on the environment. Meanwhile, the rapid deterioration of environmental conditions worldwide has awakened in society, especially in the last 10 years, a great feeling of concern over environmental issues.

The cement industry has been strongly affected by globalization, leading to mergers, takeovers and production adjustments which affect investment and management policies as well as environmental issues. The greater share of cement production has shifted from Europe to Asia and the ten major cement groups are responsible for 40 percent of the world production. In such a scenario, global management may impact the environment and cement market strategy, leading to the closing of old cement kilns in order to be more competitive, and increasing cement trade.

The possibility of making business with CO₂ emissions is also a future parameter that may impact the competitiveness of cement groups, contributing to a better and more pragmatic solution for greenhouse gas mitigation on a global basis.

The macro scenario for production in the cement industry must be discussed in order to understand the trends and the effects it may have on the market and on environmental issues.

5.2 Economic Issues in the Cement Industry

The cement industry has, by its own characteristics, a highly valuable social and economic contribution to world assets since its investments are long term and productive. The cement industry is a mature industry, essentially in the hands of highly capitalized multinational companies already involved in a global basis.
Cement is a simple product typified by complex economics. It is a capital-intensive industry and the payback period for a new 1 million-tonne plant is approximately three years of turnover [Chandelle 2001]. However, the investment return of a cement plant today is much more vulnerable, due to unexpected changes in the world economic scenario.

The cement industry is not a labor intensive industry, representing only 50 000 direct jobs in the European Union (EU) and contributing only 0.2 percent of the European GDP, while the construction industry represents around 11 percent of the GDP.

In the last 20 years, the demand for cement experienced periods of great and low euphoria as a consequence of economic crises, sometimes of a regional nature and at other times of a global nature. However, as a general rule, cement production has increased in global terms, as can be seen in Figure 15 [Scheubel & Nachtwey 1997]

![Figure 15: Evolution of world cement production](image)

The increase in cement production is closely related, however, to the growing demand for cement in China and secondarily in other Asian countries. In Figure 16, the evolution of world production during the period of 1987-1997 for China alone, and also for the rest of world except China, is presented.
Figure 16 - Cement production

The increase in China’s production during the nineties is the main reason for the world increase in cement consumption. In the rest of the world, the growth rate varied over the years from −1.7 percent to 4.6 percent, with some peaks and drops, while in China the growth rate varied from 0.6 percent to 41 percent with a slight tendency to be situated around 10-13 percent. Worldwide cement consumption increased more slowly in the last three years than in comparable cycles. The usual strong growth rates of previous years, particularly in Asia and recently in Latin America, failed to occur and the resulting over-capacity changed the market structure, and not only on a local basis.

The geographical production profile has significantly changed, with the most remarkable shift in cement production being from Europe to Asia after 1990, as can be seen in Table 6.
TABLE 6: PRODUCTION SHARE OF CEMENT BY CONTINENT

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>54.2</td>
<td>47.2</td>
<td>35.4</td>
<td>19.3</td>
</tr>
<tr>
<td>Asia</td>
<td>22.4</td>
<td>30.9</td>
<td>44.8</td>
<td>62.0</td>
</tr>
<tr>
<td>America</td>
<td>18.8</td>
<td>17.5</td>
<td>14.5</td>
<td>13.9</td>
</tr>
<tr>
<td>Africa</td>
<td>3.4</td>
<td>3.6</td>
<td>4.7</td>
<td>4.2</td>
</tr>
<tr>
<td>Oceania</td>
<td>1.2</td>
<td>0.8</td>
<td>0.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

The specific investments required per tonne and per year were somewhat lowered, but great investments were needed, and therefore they were more frequently supplied to countries with a previous high economic growth, such as Thailand, Indonesia, Korea and Mexico, among others [Scheubel and Nachtwey 1997].

Only a few new plants were built, some producing more than 5 000 tonnes/day. Instead, a reduced number of new kiln lines of moderate capacity were installed and there was a strong trend towards modification or modernization of existing production lines. In weak markets, many projects were postponed or simply cancelled [Tabbert 2000].

The technological advances also had direct consequences on the work force necessary to produce cement and improve competitiveness. The cement industry currently produces much more cement than it did 10-20 years ago using approximately 50 percent less staff, and in some cases 70 percent less. Figure 17 presents the evolution of the average time spent to produce one tonne of cement [Scheubel, 1993].
Cement has become a global commodity product, with its production being concentrated in fewer plants and groups due to intensive technological development in manufacturing and distribution resulting in higher performance and lower costs. Globalization, of course, is also a subject with many facets. Cement was traditionally seen as a local product dependent on local transportation frame conditions. A cement plant’s actual market is located 200-400 km away at a maximum. In the EU, where around 95 percent of the cement production is delivered by truck or rail, the previously mentioned sales radius is justified, since cement is a low economic added-value product very sensitive to freight costs. This situation occurs essentially worldwide. However, cement produced in the Far East can now be found in Central Europe, for instance.

The main causes that had favored an increase in international cement trade in the last years, estimated at 45 million tonnes in 1995 (3 percent of production at that time), can be summarized as follows [Miller 1995]:

- difficulties in supplying the internal demand due to variations in the market, wrong forecasts, unexpected economical factors, etc.;
- collapse in internal demand forcing local manufacturers to search for export market means of compensation;
- competition between national and international suppliers;
- promotion of exports as a source of foreign currency;
shutdown of older plants;
cement price anomalies in different markets.

Large cement plants have been built where the output could be loaded onto ocean-going vessels. The resulting shipments have transformed cement into a globalized industry. The coherence of the local price system was disrupted by changes that occurred in distant markets. International trade increased and great investments were made by traders in silo ships and in cement loading and unloading systems.

The end of the 20th century was highly impacted by globalization. In 1981, just about 200 general mergers occurred worldwide, corresponding to an amount of $200 billion US involved in these business. The number of mergers increased to 4,300 in 1995 and 6,300 in 1999 representing $720 billion US [Andreff 2002]. Mergers and takeovers also occurred within the cement industry, particularly in Asia, Eastern Europe and North America. Local cement manufacturers increasingly became part of multi-regional or global groups [Tabbert 2000].

In 1988, the top 10 cement producers represented just 9 percent of global cement production, while in 2000 they represented 34 percent and only one year later they reached 40 percent [Chandelle 2001]. These 10 largest cement companies control, however, considerably more by means of their indirect shareholder investments, which stand at approximately 630 million tonnes. The takeovers and mergers have been occurring so rapidly that in a short period of 2 years, the scenario has significantly changed, as can be seen in Figure 18 [Scheubel 2000] and in Figure 19 (based on information provided by magazines and companies).
Figure 18: Cement capacity controlled by 10 companies in 1999 (in million tonnes)

Figure 19: Cement capacity controlled by 10 companies in 2001 (in million tonnes)
According to Chandelle [2001], the prevailing acquisition logic has shifted from industrial to access to capital for the cement industry. In order to have access to global markets, and also to obtain access to cheaper capital as a borrower, the cement groups had to increase for competing against chemical and other capital intensive industries. A certain critical size in market share had to be reached, and therefore many decisions were linked to the cost of capital [Chandelle, 2001].

Low global growth rate of 3.5 percent, make it difficult, however, to attract investors. Developing countries provide better growth rates, but also higher risks. In order to diversify and be able to take advantage of the high growth in certain areas, a group must be big enough to balance its investments and have stakes not only in one region or country, but rather across a broad spectrum of investments [Chandelle 2001].

The result of this development has been price wars in many areas, often beyond the survival capacity of many undertakings [Scheubel et al, 2001].

Keeping in view that the main cement groups are located in Europe, and that they have significant participation overseas in countries that need to import cement, as well as exporting potential, it is expected that a global cement production will result in a more integrated management. In such a scenario, with high cash flow [Goodfellow 1997] and without perspectives for an increase in cement consumption on the continent, European cement producers have in effect turned, in the last 5 years, to the overseas market with frequent acquisitions and the promotion of exports in case of a swing in demand.

European countries show favorable competitiveness conditions, with highly updated facilities, well-structured environmental issues, a good geographical position due to their proximity to potential consumer markets, availability of cement, and convenient harbor facilities. The local markets have adjusted the balance between offer and demand some years ago, and the situation suggests an even greater decrease in consumption in the already limited market. In Eastern Europe, with the political and economic openings, many plants have been acquired by Western multinational groups and there is still a potential market for further increase in demand.
The 1973 world oil crisis transferred enormous amounts of money to Arabian countries who invested in economic development, mainly infrastructure and cities. Between 1974 and 1979, world cement consumption increased by 20 percent and doubled in the Arabian peninsula. Arabian countries needed to import cement in order to carry out their construction program. As a result, international cement trade rose sharply, accounting for 3.6 percent of world cement consumption in 1960, 4 percent in 1970, 5.4 percent in 1975 and 7.6 percent in 1980. In response to this increase in international trade, some countries decided to start exporting cement. Spain was the first country to do so, followed by Japan and then later by Greece [Duméz & Jeunemaître 2000]. In recent years, North America has become a new export-oriented market for these countries.

In Asia, the 1997 regional financial crisis facilitated foreign investments and changed the local cement market profile. Currency devaluation and high debts were the main reasons for this process. Since 1994, 27 deals, mergers and acquisitions have been made, corresponding to $ 5.3 billion US and 103 million tonnes [Carrillo, 1999]. The Philippines, Indonesia, Malaysia and Thailand were the main target markets for Blue Circle, Holderbank, Lafarge and Cemex. These companies put a lot of financial resources into buying, and eventually improving, the operations and profitability of these cement plants by implementing modern cement production technology and by developing an international integrated distribution network.

Over-capacity in markets with reduced turnover resulted in considerable efforts to export and changed the market situation far beyond the crisis area. At times, clinker or cement could be bought below cost. As a result, even outside Asia, cement units with a traditionally high export ratio came under strong competitive pressure, forcing some plants to close down.

With the economic crisis in Asia due to the indebtedness of several countries, many with short term obligations and banks with doubtful loans, cement demand decreased. Therefore, some of these Asian countries could not absorb their total cement production, and in a world crisis scenario, they will probably become even more aggressive in the export market. This scenario is stimulated by currency devaluation and the squeezing of profit margins.
It must be taken into account, however, that China and India, with a total population of approximately 2.2 billion people, have an urbanisation rate of nearly 30 percent [The Economist, 1999]. If the process of urbanisation is accelerated in these countries, cement consumption will increase dramatically, as will the environmental burden. China’s cement industry has a great number of production lines dependent on old technology and high energy consumption, contrasting with some large-sized technically advanced modern enterprises. Some of the modern Chinese plants had dry process cement production lines in operation by the end of 1998 ranging from 700 to 7,200 tonnes/day. The Chinese production is sufficient for domestic consumption as well as for exporting, mainly in the Asian market. Chinese exports are on the order of 9 to 10 million tonnes per year. The Chinese industrial policies to be implemented will, or at least should, encourage the establishment of new dry process production lines, replacing or shutting down about 4,000 mini-cement plants with shaft kilns. More precalcining kiln production lines, with a daily capacity of 2000 to 4000 tonnes, will be built using foreign investments, so as to enhance the ratio of high-quality cement in the total nationwide output of the cement industry [personal communication].

In Latin America, between 1994 and 1999, many mergers and acquisitions occurred equivalent to $5.6 billion US and 60 million tonnes in 31 deals. This means that about one third of the regional production was transferred in 5 years [Carrillo 1999]. The most remarkable growth in the region, and perhaps world-wide, belongs to the CEMEX group. After some internal acquisitions in the seventies and eighties and promoting exports in the eighties, the CEMEX group reached the top ten largest cement producers in 1989 and increased its international share, mainly after 1995, leading to its current third place among world cement producers. The Votorantim cement group, from Brazil, started its internationalisation process more recently, crossing its local borders by acquiring two cement plants in Canada, besides a grinding unit, some concrete operations, and terminals in the Great Lakes market in the U.S. Despite an economy permanently under suspicion and usually submitted to extremely high inflation and interest rates, some advances in political stability have occurred in South America, as well as an opening up of the economy with the drop of trade barriers, less protectionism and several privatization moves, and the formation of an economic block—Mercosur— which have promoted a return to productive investments.
Latin American countries have a good potential for supplying their own markets with updated industrial facilities, but they still often show some economic uncertainty. The collapse of demand in Mexico and Argentina in 1995 due to a currency crisis at the end of 1994 [Goodfellow, S., 1997], high internal financial costs (multiple and high taxes, lack of adequate infrastructures, lower qualification of the labor force, etc.) have adversely affected production costs, making these countries less competitive and more vulnerable to an integrated import/export market.

In the U.S. and Canada, an intensive transfer in production from local to multinational cement companies of European origin has occurred. This fact had, and will have, an impact on the profile of cement manufacturing as well as in cement standardization, to take into account the increasing use of supplementary cementitious materials. The use of SCM in blended cement is just a matter of time and adjustments in the whole interest of the cement groups. The foreign groups, specially European ones, have large experience in the use of SMC and have been using SMC for more than 50 years in some cases. They know the advantages SMC can bring, from life cycle of quarry to environmental mitigation without major investments. With the possibility of CO₂ trading there will be a higher trend to use more SCM. The trend of moving toward more economical dry kilns rather than remaining with wet kilns such as in the U.S., for instance, has been also highly influenced and consolidated by the ever-growing participation of foreign groups in the local market. International cement groups accounted for 22 percent of North American production in 1980, and for 65 percent in 1995. Over 70 percent of North American production capacity, including 95 percent of Canadian capacity, is at least partially owned by Cembureau members [Chandelle 2001]. Moreover, the competitiveness of the cement industry will be improved. Companies could increase their capitalization and reinvest in their producing units. By adopting the use of SCM and more modern kilns, it will be possible to reduce the traditional market regulatory import, with a mean value of 8 percent, used in high demand periods. Imports already accounted for 19 percent in 1987 [International Cement Review 1996]. In the year 2000, however, total U.S. imports of cement and clinker reached 29 million tonnes or 26 percent of the total consumed with imports coming from 28 different countries [Holland 2002].
Globalization has resulted also in the construction of a great number of grinding units, strategically located in order to competitively satisfy specific markets. The construction of a grinding unit represents a lower investment, but requires the development of a much more coherent distribution network.

Since specialized river barges and large ocean-going floating silos have been developed, it is possible to economically ship cement thousands of kilometers from its production site, at very competitive prices. Although coastal markets are much more sensitive to imports, central regions can frequently be reached by river, favoring an integrated management of imports. The trend of building terminals and cement grinding units can continue, since the cost of a new mid-size plant of 1 million tonne/year capacity is presently about $150-170 million US or more, depending on the environmental investments required. It takes 2-3 years to put it in production (a long time in an unstable world in transition), while the investment for a good deepwater cement terminal (when not existing and leased) is below $20 million US [International Cement Review 1996]. Moreover, the environmental requirements and license to operate such a facility are usually much easier to obtain than the ones necessary to operate a new plant.

In a more global perspective, many determining facts influence, and will continue to influence, world cement market:

- Level of updating of industrial facilities;
- Production costs, taxes, competitiveness, profit margin;
- Energy-related and environmental issues and adopted policies;
- Impact of environmental issues on manufacturing costs;
- Quality and environmental accreditation;
- Pragmatism of environmental standards;
- Cement offer on the international market;
- Geographical potential for exportation;
- Freight costs and good harbor facilities;
- Presence of international groups and their share in local markets;
- Long term rather than short term profit maximization
- Capital allocation and cost;
- Currency needs, pressures on the commercial balance and foreign exchange policy;
- Unemployment rate and social stress.

According to Dumez and Jeunemaître [2000], in periods of recession, competition will be less likely to be important. Cement producers will do their best to avoid price wars that put their market share at risk, they will rather focus on efficiency gains and cost conditions, in order to have an edge over their competitors during the upturn of the business cycle. When the economy is booming, competition at the fringes of natural markets is more pronounced, with pre-emptive moves and the gradual erosion of market shares, changing the balance of power between producers.

Competition primarily refers to situations where producers focus on price and volume in order to gain or defend market share. Rivalry refers to competition based on other factors, such as customer service, product quality, the preemption of the best production sites, the search for cost advantages over competitors, and improvements in distribution network [Dumez & Jeunemaître 2000].

However, producers have also often mobilized institutional strategies, trying in particular, to get antidumping sanctions, state aid and import quotas, in order to slow down and regulate the importation and eventual price dispute. These mechanisms were used worldwide, the main question now is how to deal with this situation, now that great parts of the market are globalized and distributed among fewer competitors.

5.3 Impact of Environmental Issues

For a long time, the construction industry and research community have underestimated environmental issues in marketing and product development as well as in the general information made available to the public. This may prove to become harmful if environmental directives are to be drawn based on irrational principles [Penttala 1997].
As mentioned by Chandelle [2002] “you are not what you really are, but what you are perceived to be”. The cement industry is perceived as an industry with a high environmental impact, even though it reduced its dust emissions by 98 percent in the last 30 years, and also as a rich industry. This strong industry was built world wide mainly without state subsidies, whereas other industries have used them. The cement industry’s environmental performance needs to be better publicized and communicated.

Environmental policies worldwide may affect the cement industry in several ways. In Europe, labor costs tend to be much higher than elsewhere, especially compared to U.S., due to the incidence of social taxes on income. In order to regain competitiveness, there is a strategy in the EU to reduce non-wage labor costs, by shifting the burden of taxation from labor to another alternative, probably energy. The problem is that the cement industry uses a lot of energy, and little manpower [Chandelle 2002]. There is also the idea of imposing a tax on virgin raw materials, with the aim of creating and developing a market for recycled aggregates. The effectiveness of such an alternative is doubtful. The main issue concerns the impact of taxes on competitiveness, although energy intensive producers are a natural target for most governments around the world. Any taxation in the use of coal, for instance, can be questioned because it will put pressure on natural gas consumption, a fuel of limited availability that will increase NOx emission levels [Canadian Portland Cement Association 1998].

Access to material is a further issue. The Habitats Directive in the EU has defined as much as 12 percent of the entire area of the EU as reservation areas where it will not be possible to start new plants or extend existing operations. This will make it increasingly difficult for the cement industry to gain access to raw materials for cement production [Chandelle 2002].

Environmental issues, mainly greenhouse gas mitigation, will have an economic impact on the cement industry. The alternatives to be implemented to improve the environment must be pragmatic and there will also be a possibility of making profits with emissions trades.

Discussion on strategies to reduce CO2 emissions are economically based on two approaches: quota controls with certificates and price controls through levies [Hillebrand 1999].
Whereas the certification model means that reduction goals are achieved clearly and unequivocally because of quantitative limits set, the ecological effectiveness of levies is unknown a priori. Conversely, in the case of levies, the economic consequences (reflected in additional costs and price changes) can be determined with relative precision, but the price of certificates, and thus the effects on cost and price structures in the economy, cannot be predicted.

A key issue will be how to regulate, on a global basis, a new market for a product for which no market previously existed, i.e. emissions of greenhouse gases. The basic questions are: what is the price and taxes on emissions, or, what is the ability to trade permits internationally or domestically, because there are simply different ways of applying a price to this particular product. One proposed scenario suggests that permits might be available at around $30 US/tonne [Chandelle 2002]. Some initial deals suggest a price around $10-15/tonne US, but the scenario is still not clear. Depending on the possibility of selling or buying these permits, this may represent a good possibility for making profit or a great concern for the cement industry. The cement industry contributes about 6 percent of the total worldwide anthropogenic emissions of CO₂. In the EU, it corresponds to 3 percent, while the industry as a whole generates 18 percent of the total. It must be remembered that 40 percent of CO₂ emissions originate from the operation of buildings, much more than the CO₂ generated by the material production itself [Chandelle 2002].

It has been widely argued that, in principle, a trading scheme is more efficient and effective than a tax system. Indeed, it is already possible to do business with brokers in the U.S. who are prepared to put together bilateral trade agreements on the basis of willing parties. The process of trading allows participants to indicate their willingness to buy and sell at particular prices and thus estimate the value they place on the product concerned.

A tax is only an effective way of approaching the problem if we know, with some precision, the elasticity of both supply and demand for the emission of greenhouse gases. This implies knowing not just how consumers react to different prices (and differences between different consumer groups), but also the different costs of reductions of these emissions in different companies and industries.
Cement, for instance, has a relatively high elasticity of substitution, meaning that a change in the relative price of cement from two sources can cause a significant change in the relative share of cement purchased from the two sources. U.S. government data suggests that a 1 percent drop in the relative foreign price compared to the cement produced in the U.S. could lead to a 5 to 10 percent increase in the relative share of imported cement [Cahn et al, 1997].

The increase in the quantity of waste burned in cement kilns, that would otherwise have been incinerated, is an effective alternative for reducing global CO₂ emissions and reducing the environmental burden as a whole, by providing more affordable waste management for society. The average rate of waste burning in Europe today is about 12 percent. By 2010, cement kilns in the EU will have an average fossil fuel substitution of about 17 percent. With stronger support at national levels, it could reach close to 30 percent. In Switzerland, the substitution rate is already 40 percent, in France it is more than 26 percent and in Belgium it stands at 33 percent [Chandelle 2002].

Moreover, cement plants are by now becoming highly efficient in controlling trouble-free uniform production operations using various substitute raw materials and fuel, while of course maintaining product quality and uniformity and staying within emissions limits.

In many countries, a distinction is made between emissions limits for existing and new kilns, and there are various regulations and transition periods. The use of the Best Available Techniques (BAT) will also be required regarding production and environmental issues. BAT means essentially that implementation of environmental improvement must be fully justified in any cost/benefit analysis. It must take full account of specific site considerations. BAT is a development of Best Available Techniques Not Entailing Excessive Cost (BATNEEC). Strictly speaking, BATNEEC are U.K. terms, while BAT is a term that originated in Europe [Osborne 1999].

In the current scenario, the investments necessary to fulfil ever-growing environmental requirements in some countries are already high, therefore environmental legislation must be pragmatic, otherwise, if it is too severe, there will be a natural trend to move cement production
to countries where the laws are not so stringent and production costs are lower, causing unemployment without solving the global environmental problem.

The impact of governmental economic policies affecting the environment must be carefully taken into account too. The impact of grants at the production level for different sectors of activity is one of them. Grants change profit margins and relative prices resulting in a new production composition in the whole economic scenario [Rosewell 1999].

Further more effective and homogeneous mechanisms must be adopted in order to promote technological development and environmental alternatives, conciliating different interests into a pragmatic solution.

5.4 Conclusion

In order to achieve sustainability in the cement industry, it is necessary to understand the macroeconomic scenario affecting this sector. The cement industry produces a low added-value product from an economic point of view and is very sensitive to changing scenarios. The search for low cost capital, the need to diversify markets and the establishment of a strategic network have contributed, in the last years, to the mergers that occurred in the cement industry. These mergers led to a concentration of cement production, with approximately 50% of this production belonging to the 20 main cement producers. The impact of these mergers has resulted in a worldwide technological transfer, in improved competitiveness, in global management instead of local management and in a higher participation of the cement industry in the concrete business.

The resulting main advantages for the environment will be a better use of energy and a lower rate of gas and dust emissions, a higher use of by-products and waste-derived fuels, reducing the environmental burden. With upgraded technology, it will also be possible to produce better cements for use in concrete with enhanced durability. With the new developments in cement production, specially new generation separators in grinding step, it is possible, for instance, to counteract the “potential weakness” of blended cement that is the lower initial
strength (compared to ordinary cement) by a better cement grain size distribution, one of the keys for a good cement quality.

The shift in cement production from Europe to Asia, after the nineties, and the increasing participation of foreign cement groups represent an advantage for the environment since many new low energy consumption kilns were built in Asia, where they often replaced smaller old technology kilns. This process of technological transfer must continue and will also contribute to foment the change from old to up-to-date technologies and the production of more market-oriented cements, with better performance. If it is considered that the two main countries in the region, China and India, presently represent almost 2.5 billion people with an urbanization rate of only 30 percent, a quite low figure when compared to the majority of industrialized countries (around 80 percent), the potential for a high urbanization rate must be supported by production of good quality cement and concrete in order to reduce the damages to the environment.

The restrained cement demand in some areas, associated to local economic crises, may increase worldwide cement trade volumes and the development of new grinding units and harbor facilities, in order to satisfy a global management in the cement industry.

Environmental issues can be used either as a competitive tool or as a local disadvantage for cement production and even as a barrier for importation. Very strict environmental regulations may increase anti-pollution costs or impair the use of waste-derived fuels, affecting plant competitiveness compared to other cement plants located in countries where environmental legislation is not so rigid. This can lead to plant shutdown or production transfer to the latter countries.

It can be predicted that CO₂ emissions trade will play an important role in the competitiveness of the cement industry. The multinational cement groups will contribute to the development of a better emissions trading process, regulating the market and contributing to the mitigation of CO₂ emissions worldwide.
Finally, the increasing participation of well-structured and highly-capitalized cement groups in the concrete market will contribute to improve concrete production, implementing quality standards and increasing investments in higher technological added-value products. There will also be a contribution to the dissemination of knowledge and transfer of good practices, and of more uniform and integrated environmental policies.
6. THE CONCRETE INDUSTRY

6.1 Introduction

Concrete is a mixture of hydraulic binder, water, aggregates, air and, increasingly, chemical admixtures. Concrete binder also contains increasing amounts of industrial by-products, either incorporated at the cement plant to produce blended cements or in the concrete mixer during concrete production. The content of industrial by-products in the binder can vary from 5 to 80 percent.

With the remarkable progress achieved in the last 30 years, the spectrum of available concrete has become quite large. Higher strength and durability, improved workability and enhanced flowability, less cement consumption and better thermal and acoustic properties are among some of the improvements that have been achieved. However, despite the availability of this technology, quite often this development is harmed by poor workmanship and lack of quality control on the site. Therefore, the discussion cannot be restricted solely to the intrinsic features of the materials in environmental terms, since an ecologically adequate material, when poorly employed, still poses a problem to the environment.

In the different types of concrete presently produced, the hydraulic binder dosage can vary from as low as 50 kg/m$^3$ in a backfill without shrinkage, to 100 to 160 kg/m$^3$ in mass concretes used in dams, to up to 850 kg/m$^3$ in Reactive Powder Concrete. However, in the majority of conventional concretes, the amount of cement ranges from 200 to 350 kg/m$^3$. Figure 20 illustrates the binder content in different types of concrete.
Concrete strength does not depend directly on the cement content, but rather on the water/binder ratio (w/b) of the concrete, as it will be discussed later.

6.2 The Commercialization of Concrete

While the cement industry is well structured, controlled by big multinational companies with worldwide distribution, the concrete industry on the contrary is still a local industry that supplies local markets with the concrete market being controlled essentially by small or very small companies. A few multinational concrete companies from Australia and England, such as Pionneer and RMC, respectively, started operating in the market over the last 20 to 30 years and are operating in different countries on different continents. These concrete companies have even started buying cement plants recently, while cement companies are currently getting involved in the concrete distribution business.

A second important characteristic of the concrete industry is its market approach. In the industrialized countries, concrete is more and more a product that is delivered on site. The cement to be used in concrete production is delivered in bulk by truck or railcars to the concrete plant, while in developing countries concrete is produced in situ, handmade or in low capacity mixers. In these countries, cement is mainly sold in bags. In countries with higher GNP/head, there is a trend toward a higher use of ready-mix and precast concrete, while in countries with low purchasing power there is a normal trend for using large quantities of cement in bags in order to build simpler houses with low technology. In Table 7, the profile of cement consumption in
some countries illustrating the previously mentioned trends is shown [Personal communication Aitcin-2002].

Table 7: CEMENT USE IN SOME COUNTRIES

<table>
<thead>
<tr>
<th>Country</th>
<th>Bulk cement (%)</th>
<th>GNP/head (US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada and USA</td>
<td>95</td>
<td>24 000 - 30 000</td>
</tr>
<tr>
<td>France</td>
<td>70</td>
<td>21 000</td>
</tr>
<tr>
<td>Brazil</td>
<td>15</td>
<td>4 500</td>
</tr>
<tr>
<td>Morocco</td>
<td>8</td>
<td>3 300</td>
</tr>
<tr>
<td>Sri Lanka</td>
<td>2</td>
<td>2 900</td>
</tr>
</tbody>
</table>

A certain quantity of concrete is produced in precast concrete plants that manufacture concrete products such as concrete blocks, interlocking paving blocks, artificial stones, structural elements or even architectural elements having a structural or/and decorative function. The concrete precast industry is strong in Europe, representing around 20 to 25 percent of the concrete market, but is not so developed in North America where it represents 3 to 5 percent of the market.

Another source of variation in the concrete industry worldwide is the use of admixtures. The North American and Japanese concrete industries use, in general, admixtures in the majority of their concretes, while the European industry is slowly starting to use admixtures, particularly the precast industry. In developing countries, admixtures are still used very little or not at all.

It is important to go back to basic chemical principles that govern cement hydration to explain why, in the near future, admixtures will play a key role in the development of the concrete market as well as on its environmental performance.
6.3 Hydration Reactions

When cement anhydrous compounds come into contact with water, their hydration starts to take place through a dissolution-precipitation process. The liquid phase becomes saturated with various ions, which combine to form different hydration products that start filling the space originally occupied by water. The unfilled space between cement particles will consist of voids or capillary pores [Aïtcin 1998].

The rate of hydration of the main cement compounds in the first days of hydration can be briefly described as $C_3A > C_3S > C_4AF > C_2S$. The rate of hydration of these compounds depends on the size of the crystals in the clinker, impurities in the crystal network, rate of cooling, surface area, particle size distribution, temperature, etc.

Calcium silicate hydration is responsible for the development of concrete strength at different ages. The main products that are generated from the reaction of the cement silicates and water are: Calcium Silicate Hydrates having an approximate composition sometimes written as $C_3S_2H_3$, though due to its wide variation in composition the general formula $C-S-H$ is more commonly used, and Portlandite ($Ca(OH)_2$ or just CH). The reactions can be briefly described as:

\[ \begin{align*}
2 \, C_3S + 6H & \rightarrow C_3S_2H_3 + 3CH \\
2 \, C_2S + 4H & \rightarrow C_3S_2H_3 + CH
\end{align*} \]

The hydration rate of $C_2S$ is much slower than the corresponding rate of $C_3S$. $C_2S$ is therefore responsible for long term strength development, mainly after 28 days, while $C_3S$ is responsible for short term strength. On the other hand, the amount of CH released by the $C_2S$ is much less than the amount released by the hydrated $C_3S$, which is advantageous for concrete durability.

The hydration of $C_3A$, the compound responsible for cement setting, is very rapid, and, it releases much heat. In order to control the hydration of $C_3A$ some calcium sulfate, about 5%, is
added in the ball mill during the final grinding of cement. C₃A reacts with calcium sulfate to form ettringite (C₆Å₃H₃₂) according to the following chemical reaction:

\[ \text{C}_3\text{A} + 3\text{CSH}_2 + 26\text{H} \rightarrow \text{C}_6\text{Å}_3\text{H}_{32} \]

Ettringite is a stable hydrated product only when there is enough calcium sulfate. When gypsum is consumed and all the C₃A is not hydrated (generally between 8 and 16 h) after the first contact between cement and water, ettringite is transformed into tetracalcium monosulfoaluminate C₄Å₃H₁₂ (AFm) according to the following reaction:

\[ 2\text{C}_3\text{A} + \text{C}_6\text{ÅH}_{32} + 4\text{H} \rightarrow 3\text{C}_4\text{ÅH}_{12} \]

Ettringite formation reduces the C₃A hydration rate due to the development of a coating surrounding the C₃A (dormant period) this is how cement setting is controlled. Once this barrier is broken, due to AFm formation, the C₃A can react faster.

The hydration reaction of the ferrite phase is quite similar to that of C₃A but proceeds at a much slower pace. The reaction can be described as follows:

\[ \text{C}_2\text{A}_{0.5}\text{F}_{0.5} + \text{CH} + 3\text{CSH}_2 + 25\text{H} \rightarrow \text{C}_3\text{A}_{0.5}\text{F}_{0.5}.\text{CÅH}_{32} \]

According to Vernet [Aitcin, 1998], the main steps in cement hydration can be summarized

- Mixing period: different ions are released by the various phases into solution. The dissolution is quite rapid and exothermic, and reacting hydrates germinate. The surface of the cement particles becomes partially covered with C-S-H and ettringite. There is an intense release of heat for some minutes, the so called pre-induction period;

- Dormant period: the rapid increase in both the pH and Ca ions content in the interstitial water further slows down the dissolution of the clinker phase. The thermal flux slows down considerably, but it never stops. A small amount of C-S-H is formed during this period and eventually small amounts of ettringite or hydrogarnet (C₄ÅH₁₃) are also formed. Some flocculation of cement particles can also occur during this period;
- Initial setting: the hydration reaction is suddenly activated when lime starts to precipitate, this occurs when there is practically no more silicate in the aqueous phase. The thermal flux increases slowly, because the precipitation of portlandite is endothermic, at the beginning, and it increases at a later age. Usually initial set falls within this period, except when some stiffening of the mortar occurs due to the development of ettringite needles and some C-S-H. The hydrated silicate and aluminate phases start to create interparticle bonding resulting in a progressive stiffening of the paste;

- Hardening: During setting, $\text{SO}_4^{2-}$ ions are totally consumed by the formation of ettringite. This usually occurs between 9 and 15 hours after the initial mixing. At that time, ettringite becomes the source of sulfate to form monosulfoaluminate with the remaining aluminate phase. This reaction generates heat and results in the acceleration of the hydration of the silicate phases;

- Slowdown: The cement grains are covered by a layer of hydrates which becomes thicker, it is progressively more difficult for water molecules to reach the remaining unhydrated part of the cement particles through this thick layer. Hydration slows down because it is mostly controlled by the rate of diffusion of water molecules through the hydrated layer, and the hydrated cement paste appears as a very compact “amorphous” massive paste. Portland cement hydration stops either when there is no more anhydrous phase (well-cured high water/binder ratio concrete), or when water cannot reach the unhydrated phases (very dense and highly deflocculated systems) or when there is no more water available, if that happens (very low water/cement ratio).

Finally, at the end of its hydration the hydrated cement paste consists mainly of C-S-H and CH (Portlandite). The C-S-H represents around 50-60% of the solid volume in a cement paste, while CH represents around 20-25% of the cement paste, depending on the cement type [Khayat, course 1999]. Calcium sulfoaluminate represents about 15 to 20% of the solid volume of a cement paste. The C-S-H phase is the main binding hydrate in Portland cement pastes. At the initial set of cement paste, the hydration of $\text{C}_3\text{S}$ has just started and therefore the crystallization of ettringite will be the major contributing factor of the initial set.
Furthermore, it is interesting to notice that C₃S and C₃A are the main cement compounds responsible for the release of heat during the cement hydration process and this heat release is highly important for concrete performance, especially for mass concrete and for huge structural elements, since it can lead to lower concrete durability due to the development of cracks. The heat of hydration of C₃A is higher than the heat of hydration of C₃S. As the C₃S content of a cement is much higher than its C₃A content, the amount of C₃S will have a greater influence on the final heat released by the cement.

The heat of hydration of the main cement phases are presented in Table 8 [in Tagnit-Hamou 1995]:

Table 8: HEAT OF HYDRATION OF THE MAIN COMPONENTS OF CEMENT

<table>
<thead>
<tr>
<th>Component</th>
<th>Heat of Hydration (J/g)</th>
<th>Average Content in Type-I Cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₃S</td>
<td>500</td>
<td>55-60</td>
</tr>
<tr>
<td>C₂S</td>
<td>250</td>
<td>25-30</td>
</tr>
<tr>
<td>C₃A</td>
<td>1150</td>
<td>8</td>
</tr>
<tr>
<td>C₄AF</td>
<td>420</td>
<td>8</td>
</tr>
</tbody>
</table>

6.4 The Role of the Water-Cement Ratio

One of the most important parameter to control concrete quality is its water/cement ratio (w/c) which has a major influence on concrete properties such as strength, workability, durability and deformation. The water content, expressed by the w/c ratio, is referred to cement weight. Ideally, the water introduced in a mixer should be equal to the amount necessary to promote cement hydration and a convenient flowability of the mix, therefore the lower the water/cement ratio the more durable and the stronger the concrete. Therefore, from a concrete performance point of view, the lowest w/c ratio should be used, however concrete must be transported and placed using conventional construction procedures. It must also be considered that some water can be lost due to evaporation, local segregation, the influence of cement grain size distribution,
cement flocculation entrapped water, etc. This water linked to cement flocculation has almost no benefit for cement hydration and causes problem for concrete durability and this problem can be counteracted by using a water reducer (8-10%), or a mid range water reducer (10-15%) or a high range water reducer (15-25%), that will prevent this problem and provide the effective necessary water for the cement hydration.

Conventional concrete is basically characterized by a high w/c ratio, usually between 0.60 and 0.70, while some special concrete, such as High Performance Concrete, usually have a w/c ratio concrete below 0.40.

The porosity of the hardened cement paste is also influenced by the w/c ratio as well as by cement fineness, the use of dispersing agents, etc., and the evolution of the hydration process. The higher the w/c ratio, the higher the initial volume of capillary pores since the distance between the cement particles is large.

The w/c ratio is traditionally correlated to the strength, as expressed by Feret’s and Abrams’ laws [in Aïtcin and Neville 2002]. The main factor influencing the compressive strength is the amount of porosity developed as a function of the w/c ratio. The higher the w/c, the higher the porosity and the lower the strength. However, the experiments of Abrams were based on circumstances particular to the time, they were performed, for instance, using no admixtures and coarser cements than we have today, etc. The reactivity of cements was lower, with different grain size distribution and clinker composition and the workability of the cement paste was mainly determined by the water content in the mix. The water in the mix had to hydrate cement as well as provide fluidity to the mix in order to allow the concrete to be placed.

Strength also depends on the required amount of water for cement hydration, taking into account that some water will be consumed to fill around 30 percent of very fine pores (gel pores) of the hydrated cement paste. The progress of hydration also leads to a decrease in porosity and to an increase of strength [Aitcin and Neville 2002].
The presence of silica fume, for instance, can have not only a chemical effect but also a physical effect at early ages, affecting the packing of particles, the forces controlling the proximity of cement particles and therefore the hydration process and the corresponding strength. The pores diameter is another parameter to be considered, since under a certain size, the pores will not influence strength.

The cement particles also show electrical charges at their surface and consequently tend to flocculate, impairing workability as well as early hydration. However, the neutralization of the charges present on the surface of cement particles can be achieved with admixtures and the excess water previously trapped in cement flocs is no longer required to promote workability. Without the need for this excess water, cement particles are closer to each other. The lower the w/c, the closer the distance for the products of hydration to develop inter-particle bonds and therefore strength [Aitcin and Neville 2002].

C-S-H is basically a layered poorly crystallized hydrated product constituted by malformed tobermorite or by a layered mixture of tobermorite and jennite, two hydrated calcium silicate [Beaudoin et al, 1992]. Pores in the cement paste can occur in the C-S-H crystals. These pores correspond to the voids due to the adsorbed water at the hydrated crystals’ surface. As the space between the C-S-H layers corresponds to 18 Å, these pores will be too thin to influence cement paste strength and permeability. The loss of such water can however increase shrinkage and creep. The pores can also be of a capillary nature. The space that is not occupied by the unhydrated cement and the hydrated products corresponds to the capillary pores, with the porosity of the paste corresponding to the total volume of the capillary pores. The capillary pores contain water that has not already been chemically combined. If the paste is kept humid, these pores remain filled with water. [Khayat 1999, course].

For low w/c ratio concrete, the capillary pores of the cement paste can have a diameter of about 0.01 to 0.05 μm. On the other hand, in a cement paste with a high w/c ratio that was not well hydrated, capillary pores can reach a diameter of about 3 to 5 μm. Metha [Khayat 1999, course] suggests that the capillary pores coarser than 0.05 μm have a deleterious influence over the strength and the permeability of concrete, decreasing durability, while capillary pores finer
than 0.05 µm mainly have an influence on shrinkage and creep. To ensure a good strength and low permeability, it is essential that the capillary pores be discontinuous, a consequence of the w/c ratio and the evolution of hydration.

The water can be chemically bonded when incorporated in the hydrated products. It can also be found in the capillary pores, the so-called free water, when these capillary pores have a diameter over 0.05 µm. If the relative humidity becomes less than 100%, then this water starts to evaporate without causing any volumetric change since it is not chemically or physically bonded. On the other hand, if the water is in pores with a diameter lower than 0.05 µm it cannot be considered as free water and its release depends on the relative humidity. If the relative humidity is under 80% this water can evaporate and will influence the shrinkage of the cement paste. The adsorbed water is on the solid surfaces and its release can result in an additional drying shrinkage if relative humidity is lower than 30%. Finally, zeolitic water occurs between the C-S-H layers and it can be released only if the relative humidity is under 11%, causing hard shrinkage in the cement paste [Khayat 1999, course].

Water absorption causes an expansion of concrete due to the release of capillary stresses. Capillary stress release is a reversible phenomenon, with capillary pores being filled or emptied according to the relative humidity, however material changes during cement hydration reduce this reversibility.

Another issue affecting strength that must be considered is the development of a transition zone between the cement paste and the aggregates, representing a weakness in concrete and a region of potential failure.

During consolidation, coarse aggregate, depending on their size, shape and surface texture may prevent a homogeneous distribution of water in fresh concrete due to a so-called localized “wall effect”. Because of this localized wall effect, some bleed water tends to accumulate at the surface of coarse aggregate particles [Neville, in Aitcin 1998]. As a result, the local w/c ratio in the cement paste next to coarse aggregates, called the transition zone, becomes substantially higher than the w/c ratio some distance away. Compared with the bulk cement paste, the
microstructure of the transition zone is characterized by the presence of large pores and large crystalline hydration products (CH, ettringite, etc.). The transition zone is typically 0.05 to 0.1 mm in usual concrete. When concrete is subjected to a given stress, the cracks first begin to develop in the transition zone. The use of a lower w/c ratio and silica fume reduce the thickness and weakness of the transition zone contributing to an increase in the strength and durability of concrete.

When discussing the influence of the w/c ratio in concrete strength, the different hydration behavior of supplementary cementitious materials compared to conventional clinker components must also be considered. The rate of hydration and the reaction mechanisms are distinct. This issue is particularly important if it is considered that worldwide there is a trend toward the use of blended cement containing increasing amounts of supplementary cementitious materials or even the use of these materials to replace cement directly in concrete plants.

Slag has a similar behavior as clinker components, reacting with water but at a much slower rate compared to clinker components. This reaction however is accelerated by the presence of CH, sulfate and soda that catalyze this reaction. Pozzolans, mainly fly ash, metakaolin, silica fume and volcanic rocks, cannot react alone with water to produce hydraulic products. In order to produce hydraulic binders they must react with the CH that is liberated by C₃S and C₅S hydration. In both cases, for slag and fly ash, the resulting main binder is C-S-H with different Ca/Si ratios and hydraulic properties. Therefore, instead of a release of CH in both systems, pozzolanic reactions consume CH; this phenomenon results in an improvement in concrete durability. These secondary hydration products fill the capillary pores and increase concrete impermeability by reducing the capillary pore size, besides transforming the coarser CH crystals into very small crystallized hydraulic products.

Although generating binding products, supplementary cementitious materials do not react at the same rate as cement. This difference should be considered by defining a water/binder ratio instead of a water/cement ratio and taking into account the type and amount of supplementary cementitious material present in the mix, in order to achieve an optimized amount of water, thereby optimizing strength and workability.
The w/c ratio undoubtedly has a decisive influence on concrete performance, and the permanent search for improving concrete durability is a necessary for sustainability.

Ideally, a crack-free HPC will be more durable, as well as better from an aesthetic point of view, however many people still believe that it is almost impossible to build virtually crack-free HPC structures [Morin et al, 2002]. As HPC does not bleed, it is highly sensitive to plastic shrinkage, and if not properly cured, it can develop, in a few hours, significant autogenous shrinkage.

Full hydration cannot be achieved in a closed system, closed system meaning that neither water loss nor water gain occurs, unless the w/c is higher than 0.42, but although more water than required to hydrate cement is used in many cases, a certain gas-filled porosity is always present, whatever the degree of hydration and the w/c ratio. However, according to Jensen and Hansen [Morin et al, 2002], if an external source of water is available, it is possible to obtain a non-porous cement paste when the w/c is less than 0.36.

In Figure 21 the schematic representation of hydration reaction in a closed system can be seen, while in Figure 22 the representation with an external source of water can be seen.

In a closed system, with the evolution of the hydration degree $\alpha$, the amount of capillary water decreases with the decrease of the w/c.

In an open system with an external source, once hydration is completed, which means $\alpha=1$, there will be no capillary water for the w/c ratio corresponding to 0.36, while there will be a lot for the w/c of 0.60. In both cases, no autogenous shrinkage will occur.

Comparing both cases, the importance of providing good curing for concrete, especially HPC can be noticed. Good curing reduces autogenous shrinkage and therefore the appearance of cracks. It is interesting also to observe that concrete with a w/c of 0.36 associated to good curing conditions will have a better performance than concrete with lower w/c without curing.
### Figure 21: Schematic representation of hydration reaction in a closed system

### Figure 22: Schematic representation of hydration reaction with an external source of water

#### 6.5 Rheology

Rheology is the study of changes in the form and the flow characteristics of materials, taking into account elasticity, plasticity and viscosity behaviors [Khayat 1999].
The quality of fresh concrete is determined by its suitability to be mixed, transported, compacted and finished. It has also been defined as the amount of internal work necessary to produce full compaction. Concrete rheology is essentially governed by physical and chemical factors. The rheology of concrete is related to the plasticity and the visco-elasticity of cement paste, that determines the flow behavior of the concrete [Ramachandran et al 1998]. The factors that affect workability include quantities of paste and aggregates, plasticity of the cement paste, maximum size and grading of the aggregates, and their shape and surface characteristics.

Among the chemical factors influencing the rheology of fresh concrete, the initial reactivity of the cement and supplementary cementitious materials, when in contact with water, and the duration of the dormant period can be mentioned [Aitcin 1998]. Among the physical factors, the grain size distribution and shape of the aggregates can be mentioned. In very low water/binder ratio systems, the grain size distribution and shape of cement particles can also play an important role in determining the rheology of fresh concrete.

At high w/c ratios, the presence of high contents of C₃A in cement is desirable in order to ensure early strength development without impairing workability. For low w/c ratios, strength development is ensured by the hydration products from C₃S and C₂S while workability can be achieved by the use of superplasticizers. Therefore, a low C₃A content is preferable when making a low w/c concrete, contributing to a higher durability of concrete due to lower porosity and lower sensitivity to sulfate attack [Aitcin and Neville, 2002].

Concrete production has been increasingly carried out using high-speed, high-shear batching systems, with addition of chemical admixtures in the batching process. Ideally, fresh concrete properties (slump, homogeneity, air entrained, air void system) should remain constant to provide sufficient time to eliminate on-site adjustments [Jolicoeur and Spiratos, 1999]. The required workability for casting concrete depends on the type of construction, placement method, consolidation efforts, shape of formwork, and congestion of the reinforcement. A good workable concrete should not exhibit excessive bleeding or segregation. Thus workability includes properties such as flowability, moldability, cohesiveness, and compactability. Of course, one of the main factors affecting workability is the water content in the concrete mixture.
[Ramachandran et al 1998], but in modern concrete it is not the only one, specific admixtures can be used to modify this characteristic.

In a freshly placed concrete which is still plastic, settlement of solid particles is followed by the formation of a layer of water on the surface, known as bleeding. In lean mixes localized channels develop and the seepage of water transports some very fine particles to the surface. Bleeding may thus give rise to laitance, a layer of weak, non durable material containing diluted cement paste and fines from the aggregate. External bleeding is not damageable, because it helps to prevent plastic shrinkage, but internal bleeding is very damageable to concrete durability and strength. A part of the bleeding water is trapped under the coarse aggregates and the reinforcing steel, which finally weaken the concrete. As a result bleeding must be avoided. The amount of bleeding can be reduced by using proper amounts of fines, increasing cement content and using admixtures such as pozzolans or air-entraining admixtures and colloidal agents [Ramachandran et al 1998].

During the handling of concrete, some separation of coarse aggregates from the mixture can occur resulting in a non uniform concrete mass. This phenomenon is known as segregation. Segregation may lead to flaws in the final product and honeycombing can occur in some instances. Segregation can occur during handling, placing, vibrating or finishing operations. The primary cause of segregation is the differences in the size of the particles and specific gravity of the mixture, and a too low viscosity of the cement paste that cannot support the aggregate in suspension. The tendency to segregate increases with slump, reduction in cement content and increase in the maximum size and amount of coarse aggregate. By proper grading of the constituents and handling, this problem can be controlled [Ramachandran et al 1998].

Replacing some of the cement by a supplementary cementitious material, for instance, simplifies the control of the rheology of any given concrete mixture, provided that the grain size distribution and shape of the particles of the supplementary cementitious material are similar to those of the cement replaced. Moreover, economical savings can be obtained from the reduction in superplasticizer dosage necessary to achieve the desired workability [Aitcin 1998].
The stiffening times of cement paste or mortar fraction are determined by measuring their setting times. Setting times are assessed by initial and final set. When a concrete reaches the stage of initial set it can no longer be properly handled and placed. The final set corresponds to the stage at which hardening begins [Ramachandran et al 1998]. Concrete can also exhibit false or flash set. When stiffening occurs due to the presence of partially dehydrated gypsum, false set is noticed, in such a case workability can be restored by remixing.

From a rheological point of view, the extreme cases of concrete behaviors are roller-compact ed concrete and self-consolidating concrete, with both showing quite different fluidity.

Roller compacted concrete is a dry concrete, having no measurable slump, obtained by adding a relatively small proportion of cement paste to a mix of coarse and fine aggregates, typically 1 300 kg/m³ of coarse aggregate instead of 1 050 kg/m³ in conventional concrete. It has the consistency of uncompacted damp soil and therefore external compaction energy is required to move the aggregate particles closer to each other until the paste coats the surfaces and fills all the interstices in the granular skeleton [Gagné, 1998]. Workability in this case describes the amount of compaction energy required to reach full compaction of the material or its maximum density. Two types of roller-compact ed concrete are presently used, roller-compact ed concrete for mass concrete and for thick slabs. Roller compacted concrete for the construction of dams has a compressive strength typically ranging from 10 to 25 MPa. It is made with around 70 kg/m³ of cement and usually about 30 to 70 kg/m³ of fly ash. In the case of thick slabs, with the current technology, 40 to 60 MPa concrete can be reached by a proper adjustment of the aggregate size used, by using a high quality cement paste with low water-binder ratio, and a cement dosage of no more than 300 kg of cement [Gagné 1998].

On the contrary, self-consolidating concrete is a highly flowable concrete that can spread readily and fill the formwork without any consolidation and without undergoing significant separation of material constituents. It requires less vibration and sometimes none at all [Khayat 1999]. Self-consolidating concrete is a new type of high-performance concrete that exhibits a low flow resistance or yield stress and a moderate viscosity to maintain homogeneous deformation, even through closely-spaced obstacles. In order to ensure adequate balance between flowability
and stability, it is important to limit inter-particle friction among solid particles, especially for coarse aggregates and sand particles. In general, it is important to limit the coarse aggregate volume to a maximum of 50% of the total volume of solids and sand volume to 40% of the mortar volume. The reduction in aggregate content requires the use of a higher volume of binder with increasing cost and temperature rise. Therefore, self-consolidating concrete often contains high volume replacements of fly ash, blast furnace slag, limestone filler or stone dust to enhance fluidity and cohesiveness and limit heat generation. Such materials are generally less reactive than cement and can reduce problems resulting from fluidity loss observed in richer concrete. The incorporation of one or more types of powder material having different morphology and grain-size distribution can improve particle-size distribution and reduce inter-particle friction, thus enhancing deformability, self-compactability and stability [Khayat 1999].

The w/b of self-consolidating concrete mixtures is typically on the order of 0.30 to 0.50, with approximately 600kg/m³ of fines smaller than 80 µm. A viscosity-enhancing admixture (commonly cellulose derivatives and polysaccharides of microbial sources) along with a superplasticizer can ensure both high deformability and adequate stability of the fresh concrete, resulting in greater filling capacity of the formwork and uniformity of in-situ hardened properties. The resulting combination can secure a mixture with a low yield value and moderate viscosity necessary for producing high-performance self-consolidating concrete [Khayat 1999]

6.6 Influence of Admixtures on Hydration

Admixtures are chemical products used to improve specific concrete properties. They are added in the concrete batch during mixing.

Admixtures play a central role in modern concrete. Organic admixtures are used more frequently now than they once were, and are used essentially in liquid form. The amount (on a solid basis) varies with the type and does not usually exceed 2% of the weight of cement. Above all, it has been possible to improve workability of the fresh concrete in such a way that concrete with w/c ratios as low as 0.25 can be made almost fluid and cast on site with the usual equipment used to place traditional concrete.
According to Dodson [in Aitcin & Baalbaki 1998], admixtures can function according to several mechanisms and can be classified according to what they do. Such a point of view simplifies their perception and comprehension. Admixtures can be used to:

- Disperse cement particles in the aqueous phase of concrete;
- Alter the normal rate of hydration of the cement, in particular, of the hydration of the tricalcium silicate phase;
- React with the by-products developed during hydration, such as alkalis and calcium hydroxide;
- Improve some physical or chemical aspect of the cement paste or concrete.

With improvements in admixtures, considerable progress has been achieved in the control of concrete properties. Some of the most significant challenges that have been successfully met include [Jolicoeur and Spiratos 1999]:

- Increase of compressive strength and reduction of concrete permeability through reduction of pore volume, which was made possible by water reducers and superplasticizers, and the addition of ultrafine supplementary or pozzolanic materials (silica fume for instance);
- Improvement in the freeze-thaw resistance of concrete through the introduction of a controlled air void system using air entraining agents;
- Reduction of the corrosion of concrete steel reinforcement through the addition of corrosion inhibitors;
- Minimization of microcracking due to drying shrinkage through curing compounds, more appropriate curing methods and the use of shrinkage-reducing admixtures;
- Minimization of early thermal micro-cracking in large concrete elements by improved control of the reaction rate and the generation of the heat of hydration, using both supplementary materials and chemical admixtures;
- Increase in concrete service life resulting from enhanced durability, corrosion resistance and freeze-thaw resistance.
Water reducing agents are among the most used admixtures. Water reducers are organic substances or a mix of organic and inorganic substances that allows, for the same slump, to decrease the water demand of concrete or that provides a better workability for the same amount of water. Water reducers are used at dosages of about 0.1 to 0.4 percent of the cement weight. Water-reducing admixtures usually reduce by approximately 8 to 10 percent the amount of water required to obtain a given workability [Ramachandran et al 1998]. The main advantages for concrete are an increase in strength and improved workability.

Among water reducers, the most commonly used are calcium and sodium lignosulphonates, sugar acids, etc. Lignosulphonates are produced during lignin degradation in the bisulphite cellulose extraction process in the paper industry. Since lignosulphonates are the by-product of an industrial process, their chemical structure and molecular structure is not expected to be optimized to obtain the higher water reduction in concrete. Lignosulphonates are effective water reducers, but their dosage cannot be increased, because they also produce secondary effects that can become a problem, mainly set-retardation and excessive air entrainment of large air bubbles [Ramachandran et al 1998].

The main flowing effect of water reducers is due to their adsorption in the surface of cement grains. The flowing effect is also partially a consequence of the retarding effect of the admixture that leads to an excess of available water that allows the cement paste to flow. The rheological behavior of the cement paste depends on the characteristics of the cement particles (composition, size, electrical charge, etc) and of the type of electrolyte in the solution. Cement grains can exhibit different electrical charges due to different chemical compositions. In the absence of a water reducer, opposite charges will attract each other, leading to flocculation and increasing the viscosity of the paste. Water reducers work according to two mechanisms; electrostatic repulsion and steric hindrance. When working by electrostatic repulsion, water reducer molecules are adsorbed into the surface of cement grain, providing each grain the same electrostatic charge and creating repulsive forces. Such action results in a flowing effect with enhanced plasticity of the mix. When working by steric hindrance, the tail of water reducer molecules repulse the tails of water reducer adsorbed in adjacent cement particles.
Superplasticizers are very efficient water reducers, they are chemical admixtures which can maintain an adequate workability of fresh concrete at low w/c ratio, for a reasonable period of time, without affecting the setting and hardening of the cementitious system. Superplasticizers have been characterized as high-range water reducers to distinguish them from other less effective chemical admixtures [Ramachandran et al 1998]. They are able to reduce water requirements by up to 30%, in the best cases.

From a chemical point of view, some superplasticizers are organic polyelectrolytes, which belong to the category of polymeric dispersants. Their usual dosage is around 1% of the weight of cement. Sometimes their dosage is 3 to 5 times that of regular water reducers without, however, promoting any undesirable effects [Ramachandran et al 1998].

Sulphonate-based superplasticizers are the most important group of high-range water reducers. The most widely accepted compounds of this group are the polynaphthalene sulphonates (PNS). Polynaphthalene sulphonates were the first type of synthetic high-range water reducers to be introduced in concrete [Ramachandran et all 1998]. A second family of sulphonate-based superplasticizers is polymelamine sulphonates (PMS), representing a continuous single chain polymers with sulphonate groups on each melamine sub-unit. Polysulphonates act essentially by developing electrostatic repulsive forces.

Synthetic organic polymers bearing carboxylic acid groups can also act as highly effective dispersants. Indeed polycarboxilates are broadly used as dispersing agents in detergents and in various aqueous-based industrial formulation processes. The carboxylic group (COOH) being a weaker acid than the sulphonic group (SO$_3$H), polycarboxylates are highly ionized even in alkaline environments, whereas polysulphonates are highly ionized even in moderately acidic solutions. Several polycarboxylate polymers, particularly polyacrilates derived from a combination of acrylic and substituted acrylic monomers have been proposed as concrete superplasticizers since the 80’s [Ramachandran et al 1998]. Polycarboxylates essentially develop steric hindrance.
Setting accelerators are added to concrete in order to reduce the setting time or to accelerate the hardening of concrete. They promote a quick hardening of concrete under normal temperature or a normal hardening under low temperature. The two main accelerator admixtures used are calcium chloride and calcium formiate, some nitrates are also used as accelerators. This type of admixture has no major effect on the cement paste at very early age. The quick setting of the paste, however, will enhance viscosity at a later age [Tagnit-Hamou 1995].

The highest strength gains are achieved between the first and third day of curing, which is very important in the case of low temperatures. Chlorides have a flowing effect in the cement paste. Accelerators contribute to reducing segregation in the fresh paste, however, they can eventually lead to the corrosion of steel bars [Tagnit-Hamou 1995], but new alternatives such as NCA will not lead to corrosion.

Retarders are used when a longer setting time than usual is required. Cement setting usually occurs around 2 to 5 hours after the first contact with water and hardening between 3 to 7 hours. Sometimes it is necessary to prevent concrete hardening for 24 to 48 hours, for instance in order to avoid cold joints in certain construction work. It must also be emphasized that concrete mixing in warm tropical climates or concrete transportation over long distances, among other reasons, can require the use of retarding admixtures. Certain retarding admixtures can be of an inorganic nature such as boric acid, phosphoric acid, and their corresponding salts, zinc oxide being the most typical. Organic retarders are the most widely used, and among them the lignosulphonates, carboxylic acid, amines, gluconates [in Tagnit-Hamou 1995].

With this type of admixture, the initial hydration of aluminates and silicates is retarded since the admixture has an effect over the crystal nucleation and germination of the hydrated phases. Once the admixture leaves the solution by adsorption in the hydrated aluminate phases, silicate hydration becomes stronger. The initial strength, at early ages, is lower while the longer age strengths, 28 days and later, are higher when compared to a paste without retarder [Tagnit-Hamou 1995].
Air-entraining admixtures are organic products that stabilize a certain amount of air in the form of microscopic bubbles, 90 percent of which measure less than 100 μm in diameter. Air entraining agents are used in concrete to improve freeze-thaw durability and, cohesion. Air entraining agent dosage is approximately 0.05% of the weight of cement. With the development of such a network of fine bubbles, concrete resistance against freezing and thawing is enhanced, as well as against chloride deterioration, since the bubbles prevent crack propagation. The presence of 2 to 4 percent of air in a concrete improves its cohesion and minimizes the occurrence of segregation and bleeding. Its use can also contribute to reduce the required quantity of sand or to correct sand that is too coarse. The main commercial products used are abietic and pimaric acids, fatty acid salts, ethoxy phenol, etc [Tagnit-Hamou 1995]. Air-entraining agents are long chain molecules that have a polar group at one extremity. These molecules are concentrated in the interface air liquid, with the polar group in the liquid while the non polar extremity stays out of the liquid. The internal surface of the bubbles will be composed of the hydrophobic part of the admixture, which plays the role of barrier against water penetration during and after concrete mixing [Tagnit-Hamou 1995]. The air bubbles are developed by entrapping air during concrete mixing.

By using other types of chemical products, up to 30% of air can be entrapped in the concrete with the aim of reducing its density, improving its thermal insulating properties and producing lightweight concrete with lightweight aggregates.

6.7 Main Causes of Concrete Deterioration

Hardened concrete has to conform to several requirements from a mechanical point of view: compressive and flexural strength, static modulus of elasticity, creep under compression, abrasion resistance, bond development with steel, penetration resistance, pullout strength, etc. Concrete must also be conveniently made in order to prevent premature deterioration when facing aggressive environments. A good concrete must therefore satisfy many requirements to reach a good performance.

The most common causes of concrete failure are [Aitcin and Baalbaki 1998]:

6-22
- Shrinkage (drying or autogenous);
- Thermal contraction;
- Thermal gradient;
- Overloading;
- Internal-alkali-aggregate reaction or AAR;
- Delayed ettringite formation (DEF);
- Corrosion of embedded steel;
- External attack: carbonation, freezing and thawing;
- Physical attack: abrasion, freezing and thawing, expansion, etc;
- Chemical attack: acid attack, carbonation, sulfate attack;
- Biological attack: bacterial attack.

Prevention is a key element. In order to improve concrete durability when dealing with the main causes resulting in concrete deterioration, it is important to consider the environment that the concrete will be facing during its service life, in order to select the appropriate cement, aggregates, admixtures and water-cement ratio. The previously mentioned deleterious mechanisms are facilitated when using high w/c ratios, with their corresponding higher porosity, and bad curing conditions. Improper placing and curing can prevent potentially durable fresh concrete from performing adequately once hardened. Water curing not only promotes hydration, it minimizes autogenous shrinkage and fosters the late hydration of C2S as well as that of supplementary cementitious materials, when used. Autogenous shrinkage, can be drastically reduced if water curing starts as soon as hydration is initiated.

The knowledge of the 28-d compressive strength of a concrete is, of course, fundamental to make calculations that will allow the construction of a safe structure, but it is necessary to be sure that this 28-d compressive strength will not be altered during the whole life cycle of the structure. Unfortunately, many examples demonstrate that concrete that had an adequate initial 28-d compressive strength have lost most of their structural functionality because they were facing environments for which they were not conceived, or because they were not placed or cured
correctly. Such situations have often resulted in repair or demolition prior to half of their life cycle. [Marciano Jr. and Aïtcin,1999].

Several codes now emphasize concrete durability rather than strength when selecting the concrete to be used to build a structure. This is step forward from a sustainable development point of view. The European Standard EN 206 on concrete is a good attempt at achieving these goals by dealing with environmental aggressiveness, life cycle of structures, curing, and further requirements to be fulfilled by constructions [Gonçalves, 2000].

From a durability perspective, it is also important to understand concrete deformations in order to minimize these deleterious mechanisms. Concrete deformations, shrinkage or expansion can be classified, according to their origin, as follows[Bonneau 2001]:

- Topo-chemical deformation (Le Chatelier Shrinkage, ettringite expansion, free lime hydration, etc);
- Water transfer-related deformation;
- Thermal deformation;
- Deformation under load

The initial absolute volume (cement plus water) is higher than the final absolute volume (hydrates plus fluid phase), however, when hydration occurs in the presence of an external source of water, the volume balance is positive, since the formation of C-S-H from the anhydrous cement is expansive.

Plastic shrinkage occurs during the fresh state of concrete, before setting, by water evaporation or by drainage through the support for instance (soil or old concrete). Plastic shrinkage increases with wind speed, temperature and sun exposure. For a fixed w/c ratio, plastic shrinkage increases with increasing cement content or when the w/c decreases since the capillary pores are finer and therefore more sensitive to water departure.
Autogenous shrinkage, caused by self-desiccation, is a deformation occurring at constant mass and temperature. It is a consequence of cement hydration. Autogenous shrinkage increases when the w/c ratio decreases due to the reduction of the diameter of menisci. For the same reason, it also increases with cement fineness. It increases as well with larger replacements of cement by silica fume. Silica fume reduces the diameter of the initial capillary pores, leading to higher capillary stresses, and consumes CH by pozzolanic reaction. CH works like a rigid inclusion, and when it disappears, it allows shrinkage.

Drying shrinkage is a consequence of superficial water evaporation from the hardened cement paste. This deformation occurs with a mass loss.

Carbonation shrinkage occurs due to the carbonation of CH and release of some water by evaporation according to the chemical equation: Ca(OH)$_2$ + CO$_2$ → CaCO$_3$ + H$_2$O. This shrinkage is associated with a gain in mass.

Drying shrinkage due to water release can be minimized by the use of expansive cement, the use of a shrinkage reducing agent, the use of a barrier against evaporation such as a curing membrane or by providing an external source of water or by the incorporation of saturated lightweight aggregate, whose water can act as an external source of water (external in this case is related to the cement paste).

Thermal deformations are proportional to temperature variations and to the relative humidity of the concrete. In fact, the internal relative humidity is a function of temperature. Capillary tension will amplify the initial thermal dilation. The thermal dilation coefficient of the concrete also varies during cement hydration.

Concrete is also subjected to deformation under load. Contraction is proportional to the load. Microcracks lead to deformations that are not elastic but rather permanent. This phenomenon is more striking in the interfacial zone, the transition zone between the aggregates and the cement paste.
Creep of concrete is related to an increase of the deformations over time under a constant charge or load. The cement paste is considered a rigid gel with a viscous phase (water) and an elastic skeleton. Under load, the water is drained out of the pores of the rigid skeleton, this phenomenon is similar to shrinkage since it is a water movement. Concrete is composed of a viscous phase (cement paste) and an inert phase (aggregate). During load, the paste progressively transmits the stresses to the aggregates. The development of microfissures starts at the interface between the aggregate and the paste when a certain load limit is reached, and above this load, the opening of a microfissure explains the irreversible part of creep.

Aggregates occupy 60 to 80% of the volume of concrete, therefore they influence the unit weight, the elastic modulus and the dimensional stability of concrete as well as its durability. Usually, aggregates are stronger than the matrix. By convention in North America, coarse aggregates are larger than 5 mm and fine aggregates smaller than 5 mm. Typically, fine aggregates are made up of particles ranging from 75 μm to 5 mm in size whereas coarse aggregates have a size varying from 5 to 40 mm. In mass concrete, the size of coarse aggregates can reach a value of 150 mm [Ramachandran et al. 1998]. Some minor constituents of fine or coarse aggregates such as clay lumps, friable particles, coal, chert, etc., may adversely affect workability, setting and durability characteristics [Ramachandran et al 1998]. The shape of the aggregates can also play a very important role, especially in high strength concrete - flat and elongated aggregate particles are detrimental for strength and workability, while cubic or spherical aggregates produce better workability.

One of the most common causes of concrete deterioration is related to the alkali-aggregate reaction (AAR). AAR was first noticed in the U.S. in 1940, but it has been reported all over the world, affecting dams, bridges, buildings, etc., since then. The timeframe for the appearance of AAR is variable, it usually starts to be noticed between 2 and 10 years [Tagnit-Hamou 1995]. The deterioration mechanism demands three basic conditions: humidity, the availability of alkalis in the cement and a reactive aggregate. The main reactive aggregates are those that show a structural instability (or disorganization of their crystalline structure). The main potentially reactive aggregates are chalcedony, volcanic rocks, etc. Limestone and some quartz under geological stress can be also potentially reactive. The resulting reaction between alkalis and silica
is expansive by nature, due to the formation of a swelling gel, leading to the appearance of cracks in the concrete, usually in a dendritic pattern. The development of AAR results in the rapid deterioration of concrete once the process has started. The selection of non reactive aggregates, the use of low alkali cement, or the use of blended cement containing some pozzolan are the main alternatives to counteract such a problem.

A further concrete deterioration frequently noticed is linked to the cracking of concrete due to the corrosion of reinforcing steel. Steel corrosion can be related to the penetration of Cl ions or can be due to carbonation. A good quality concrete offers a good protection against the corrosion of steel rebars, due to a low permeability and high alkalinity of the concrete, with the interstitial liquid showing a pH of around 13. The carbonation process transforms Ca(OH)₂ into CaCO₃, thereby reducing the pH of the internal environment from 13 to 8. If such a low pH reaches the vicinity of a rebar due to the presence of large cracks (over 0.4 mm) or a high porosity then the steel will rust causing the formation of iron hydroxide and corresponding degradation [Tagnit-Hamou 1995].

The deterioration of concrete by Cl⁻ ions is an electrochemical process which requires a high porosity (size and distribution of the pores play an essential role) allowing the diffusion of these ions. The steel reinforcement will be attacked by Cl⁻ ions developing an anode and a cathode with a resulting eletrochemical potential in the steel bar. The metallic iron of the steel bar will lose electrons and will react with the hydroxide generated in the cathode, leading to the formation of rust with an increase in volume of as much as six times the initial volume of metallic iron, depending on the level of oxidation [Tagnit-Hamou 1995].

The deterioration of concrete by penetration of SO₄²⁻ ions leading to the formation of a highly expansive secondary ettringite, formed after the hardening of concrete, can be mentioned as a source of deterioration. Contrary to the primary ettringite which is formed during the fresh state of concrete and with the possibility of absorbing, secondary ettringite is formed in hardened concrete. This process occurs when concrete is exposed to aggressive environments rich in SO₄²⁻ ions. The main conditions fostering such a deterioration are a high permeability of concrete and high C₃A content.
The concrete can also undergo deterioration through bacterial action, often related to the sulfur cycle, leading to concrete erosion and expansion and occurring mainly in sewage systems or in concrete structures in downtown areas due to sulfur emissions from car exhausts.

The alternatives for preventing these problems are basically related to an appropriate selection of materials, cement and aggregates, and good concrete preparation (curing, adequate rebar cover thickness, lowest possible w/c ratio). The use of blended cement is also a very good alternative to minimize these potential deterioration processes.

6.8 The Evolution of Concrete Technology

Humankind has experienced great advances in binder technology over the last 10 000 years. The use of plaster, lime, burnt clay, and natural pozzolans were extraordinary developments 5000 to 10 000 years ago. It is interesting to note that some of our ancestors were able to build durable structures and that some of their knowledge still remains as the basis for a number of present achievements.

The Romans are considered by many people as the discoverers of the technology of hydraulic binders because some of their works such as the Pantheon and the Coliseum in Rome, and Hadrian’s Wall in England [Adam in Aitcin 2001], are still operational or in relatively good shape. However, archeologists have found much evidence that before the Romans and the Greeks, the Phoenicians were using hydraulic binders in smaller quantities [Baronio in Aitcin 2001].

Joseph Aspdin patented an artificial hydraulic binder in 1824, but it took 25 years before a material resembling Portland cement was manufactured. Later on, concrete technology started to develop. For many years, concrete has basically consisted in Portland cement, its main hydraulic binder, aggregates, usually natural gravel or crushed granite, basalt or limestone, sand and water.
Today, concrete is increasingly made with blended cements that contain certain amounts of supplementary cementitious material and admixtures.

Conventional concrete is basically characterized by a high w/c ratio, usually between 0.6 and 0.7, with high porosity and an average strength around 20 MPa. A conventional concrete used in most construction projects has an average composition, similar to the one presented in Table 9 [Tuutti 1998]:

Table 9: AVERAGE COMPOSITION OF CONCRETE (W/C=0.67)

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (kg)</td>
<td>300</td>
</tr>
<tr>
<td>Aggregate (kg)</td>
<td>1 900</td>
</tr>
<tr>
<td>Water (kg)</td>
<td>200</td>
</tr>
<tr>
<td>Total (1m³)</td>
<td>2 400kg</td>
</tr>
</tbody>
</table>

For a long time, the concrete industry and designers have produced and specified such a universal concrete, to be used in any circumstances, whose compressive strength was usually comprised between 15 and 25 MPa. In some places, over the years, it has been possible to notice a slight increase in concrete compressive strength, so that presently, in some developed countries, the concrete used for structural purposes has a compressive strength comprised between 25 and 35 MPa [Altcin 2000].

Until the end of the 60s, a 30 MPa concrete was produced using a cement content around 400 to 500 kg/m³. During the 70s and 80s, with the advent of new organic admixtures and
mineral additives, it was possible to produce better concrete, having lower w/b ratio, with a much better performance, improved workability and higher strength [Aitcin 2000].

In the 1970's, concrete having a higher strength (40 MPa to 50 MPa) started being specified to build slender columns in high-rise buildings, offering more architectural possibilities and more renting space [Blick et al. 1974]. With the years, the designation of these initial high strength concrete has been transformed into high performance concrete because it was realized that they offered more than simply high strength. High performance concrete started to be used outdoors and faced, in some cases, severe environments such as in the case of offshore platforms, bridges, roads, etc. [Aitcin 1998].

High Performance Concrete-HPC is a low w/c ratio concrete (usually under 0.40) that not only offers high strength, in the range of 50 to 120 MPa, but mainly excellent durability because of its very low permeability and good matrix characteristics. It is possible to make such a fluid concrete using less water by using superplasticizers. These admixtures provide an excellent dispersion of the cement particles and a convenient use of the lower amount of available water to produce a stable concrete having a much higher slump. HPC is virtually impervious, providing higher durability and also high resistance against abrasion [Kosmatka et al. 1995]. Usual concrete, when mature, shows a permeability corresponding to 1x10^{-10} cm/s, while HPC can have a permeability of 7.6x10^{-13} cm/s. By comparison, the most common rocks used as aggregate show a permeability ranging from 1.7x10^{-9} to 3.5x10^{-13} cm/s.

According to Tuutti [1998] the difference in ingredients between a conventional concrete with a compressive strength of 30 MPa and a HPC with a compressive strength of 80 MPa, is small. The typical difference in composition for HPC is approximately 5% less aggregate and 5% more cement expressed as a percentage of weight. A HPC can also contain 5 to 10 % silica fume and 1 to 2 % superplasticizer expressed as solid content as a percentage of cement.

The gains achieved in performance compensate for the additional costs in HPC production. One may mention the use of less formwork, less concrete to be placed and less reinforcing steel, slenderness of columns providing more space (extremely important in high density cities, where
real-state prices are a major concern), lower maintenance costs due to higher durability, lower visual pollution as a consequence of the lower porosity, and a much better recycled aggregate at the end of the structure’s life cycle.

In most urban areas, in developed as well as developing countries, tall office buildings will have to be built in order to compensate for the very expensive cost of real estate. These high-rise buildings will be built with high performance concrete. Most of the sky-scrappers built recently in Toronto and Montreal, for instance, have been built with high performance concrete, as well as the Petronas Towers (1997), built in Kuala Lumpur, Malaysia, which is at this moment, in 2002, the highest building in the world (450 m), as can be seen in Figure 23 [Aïtcin and Marciano Jr, 1999].

![Figure 23: Evolution of sky-scrappers' height](image)

In one particular case in Toronto, the use of an 80 MPa instead of a 40 MPa concrete in the columns of a 6-floor underground parking garage resulted in space for 2 more cars per row, a
decisive economic factor in the decision to switch to an 80 MPa concrete and to eliminate an initial steel design [Aïtcin and Marciano, 1999].

An interesting application of combined use of different classes of concrete is shown by Vaz de Campos [1999]. Vaz de Campos took part in a construction project for 3 residential buildings in Goiania/Brazil, the 3 buildings had the same characteristics, the same size and were built under the same management. One building was built using a standard 20 MPa concrete, the second was built using a 30 MPa concrete and finally the third one was built combining different strength concretes (25 MPa, 30 MPa, 40 MPa and 50 MPa) according to the requirements of each functional unit (slab, column, etc). The results showed that it was possible to achieve a cost reduction of between 12 to 17 percent for the structure by using concrete with different strengths.

Another type of concrete that is getting success on the market is the self-consolidating concrete (SCC). It is a highly flow concrete that requires less or none vibration to fill the formwork.

Some applications of SCC in Canada include the repair of severely damaged beams in external parking garages, the construction of a strong reaction wall for structural testing of large structures and the repair of a small wall in Montreal. Recently, SCC was used in the Toronto airport pumped to fill up steel tubes from their base. The steel tube plays the role of a form and confines concrete. Perspectives for the development and use of SCC in the short term will be cost driven and it will be especially useful for the construction of horizontal elements and for casting of concrete in areas of difficult access necessitating placement with minimum or no vibration. SCC should gain wider acceptance for the construction of vertical members and prefabricated elements as well as casting of highly reinforced sections to reduce the duration of construction and enhance performance [Khayat 1999].

Roller compacted concrete (RCC) is another concrete alternative, that uses much less cement, but more aggregates and that demands a strong external compaction. It is a dry, no slump concrete, obtained by adding a relatively small proportion of cement paste to a well graded mix of coarse and fine aggregates.
Since the 1980s, RCC has been accepted worldwide as the most rapid and economical method for the construction of medium-height dams [Metha 1998]. In such a case, typical compressive strength ranges from 10 to 25 MPa. According to Dunstan [in Metha 1998], until the end of 1992, ninety-six RCC dams were built in seventeen different countries of which 82 contained pozzolan in the mixture, mainly fly ash.

The first use of cement in road base construction dates back to 1935 when relatively low percentages of cement in compacted soil-cement mixtures were used. RCC is an evolution of this technique. RCCP for pavement, is made with smaller size aggregates and contain a high quality cement paste having a relatively low water/binder ratio. RCCP strength ranges between 40 and 60 MPa with a modulus of rupture between 5 and 8 MPa, which is twice the modulus of rupture of a traditional concrete having the same compressive strength. RCCP technology has rapidly developed in the last 15 years. [Gagné 1998].

Lightweight concrete is another technological option. Lightweight concrete can be made in different ways, it can be made by autoclaving a mixture of cement, fine sand and an expanding agent (usually aluminum powder) that releases hydrogen in the fresh mixture when aluminum powder reacts with the lime produced when C₃S is hydrating. This hydrogen remains trapped in the fresh paste so that it generates a kind of artificial pumice. The formation of tobermorite (crystallized C-S-H), a key element in such a concrete, is a function of autoclaving conditions and the CaO/SiO₂ ratio of the C-S-H. lightweight concrete can also be obtained by introducing air bubbles in a conventional mortar through the use of a foam or eventually by using light aggregate a more complicated and not always easily available alternative.

The advantage of these lightweight concrete is their low density, requiring less foundation, and also their good thermal and acoustic properties representing an excellent alternative for low-cost housing in temperate countries [Marciano & Esper 2000].

Reactive powder concrete (RPC) is probably the most spectacular product from a technological point of view because it shows what can be achieved in concrete technology.
Although still of limited use, due to its high cost, RPC shows a great potential for the pre-cast industry, with some practical applications in France and in Canada with the Sherbrooke footbridge (Figure 24). In the literature, a compressive strength a bit above 800 MPa was reported in a laboratory for an RPC containing steel powder as aggregate [Richard & Cheyrezy 1994].

RPC is a concrete having a very low water/cement ratio, comprised between 0.15 and 0.20, made with fine aggregates, with a maximum diameter lower than 300 μm in order to provide a dense structure and a minimum of voids. Its usual strength is around 200 MPa. Its ductility can be improved by confining it in steel tubes or through the use of fibers.

![Image of Sherbrooke footbridge](figure24.jpg)

Courtesy P.C. Aitcin

**Figure 24**: Sherbrooke footbridge

### 6.9 Conclusion

Recently, concrete technology has experienced great development and provided alternatives for various applications, from low-cost houses to skyscrapers, from paving to bridges. However, it is important to be assured that these new types of concrete are conveniently used. It is not acceptable to waste concrete, mainly in developing countries, due to bad use or bad management.
or even due to lack of convenient information. It is also regrettable to face a much lower structure lifespan than expected, requiring maintenance in a very short time frame, when concrete are badly placed and cured. Concrete must be a durable material and should last much longer than it presently does.

High performance concrete is a suitable alternative for buildings and bridges, while roller compacted concrete seems a very attractive alternative for dams and paving constructions. Self-consolidating concrete will play a very important role in a near future in specific construction applications. For low-cost housing, lightweight concrete currently seems the most promising alternative.

The use of admixtures is essential to produce these concrete. The convenient use of admixtures will play a major role in enhancing the sustainable use of concrete as well as the use of increasing quantities of by-products in blended cements or directly in concrete.

Increasing durability, lowering natural raw material consumption, improving the compatibility of their constituents with the environment, all these actions together with cost reduction, improvement of technological versatility, reduction of the environmental impact, and the increase in the social added-value will certainly contribute to increasing the sustainable use of concrete.

Presently 20 MPa concrete is still largely used, since it is a cheap product suited to the reality of limited budgets. This type of concrete satisfies numerous applications for which designers do not need a high compressive strength such as footings, basements, etc. However, from the sustainability point of view, concrete with higher strengths with wide application will the best option for achieving optimal durability/cost ratio and market needs.
7. IMPROVING THE SUSTAINABILITY OF CEMENT PRODUCTION

7.1 Introduction

The target of a cement plant is not only to produce a good and environmentally clean product, but also to reduce energy consumption, save raw material, promote the valorization of by-products and waste materials which is a significant contribution to increase profit margin and for sustainability as well.

The cement industry has experienced many changes and achieved great progress in the last 30 years. The cement industry has been mitigating its own emissions, saving raw material and non renewable fuel sources. From raw material quarrying to the dispatch of cement technological improvements and concern about process, optimization has been impressive. However, despite the progress achieved, physical limits in process technology for further energy savings have almost been reached and any technological improvement is becoming excessively expensive. Also, the change from older to modern cement plants is not always advantageous, depending on several parameters such as foreseen cement demand, investment capability, etc. For all cement plants, and specially for older ones, the search for a sustainable production must be carried out with the assumption that production must be optimized according to available technological conditions.

Therefore, many general measures can be implemented such as improving raw meal burnability, replacement of natural raw materials by by-products, efficient control of the manufacturing process such as kiln ovality, avoiding air infiltration in the kiln, ensuring a good and stable coating formation in the kiln a good mixing of fuel and air in the burning process, etc. In modern cement kilns, the automatic process control substantially reduces these risks, but in old cement plants these minimal controls can provide significant energy savings.

Moreover, several cement plants worldwide are already producing a so-called low energy clinker by using fluxing agents such as F or by manufacturing high belite clinker, having a much lower proportion of C₃S/C₂S than a conventional clinker. These measures result in a significant
mitigation of gas emissions and a saving in fuel consumption. This represents a further sustainable alternative in cement production.

The worldwide cement industry has a great environmental contribution. The increased use of industrial by-products such as blast furnace slag and fly ash is one of its main contributions. Worldwide, the annual generation of coal ash from power stations is estimated at 650 million tonnes, while slag generation is around 100 million tonnes, with presently nearly 90 percent of both by-products ending in low value applications such as landfills and road bases or just simply disposed of or stockpiled with resulting environmental impact. The cement industry has been using these by-products for more than 50 years and is promoting their economic and technological valorization. As the most significant increase in cement demand is expected to occur in countries that generate high quantities of these by-products, they can be used to prevent a further production of clinker, with the corresponding CO₂ emissions mitigation, and fuel consumption and raw materials savings.

Cement plants are presently being used to safely eliminate great amounts of various industrial waste that otherwise would have to be disposed of in landfills. The amount of fossil fuel replacement by alternative fuels is about 8 percent, but in some countries, the cement industry is reaching a replacement level of nearly 40%. The burning of waste in cement kilns helps to alleviate the environmental burden since there is no need to use incinerators without energy recovery and with ash generation that must be disposed of.

The cement industry is playing a major role in environmental issues and this contribution must continue, simultaneously with improvements in process control.

7.2 Quarrying

Until a few decades ago, raw material extraction sites were organized as a standard mining operation. Today, it is necessary to operate the mine with a previously prepared landscaping plan for the subsequent reclaiming of the area or its reconstruction for rare or unique flora and fauna. The cement industry has often been at the forefront of developing and applying quarry restoration
methods to return depleted quarries to productive, scenic or recreational uses. Successful examples of the rehabilitation of a cement quarry are Butchard Gardens on Vancouver Island (Figure 25), British Columbia and the Centre de la Nature de Laval, Quebec (Fig 26), both in Canada.

Figure 25: Butchard Gardens on Vancouver Island (British Columbia, Canada)

Figure 26: Centre de la Nature de Laval (Quebec, Canada)
Undoubtedly, these two cases are highly successful examples of landscaping restoration, showing that it is possible to achieve a sustainable program at the end of a quarry’s life cycle.

Moreover, in many cases the quarries had been established relatively close to urban areas; new residential areas have reached them and grown around them. In many cases, urban development has greatly influenced extraction and production technologies. More complex explosives techniques, mobile crushers, direct mining, i.e. extraction without explosives by ripping or surface mining, have been and probably will increasingly be the answer to more stringent exploitation conditions, if raw material reserves are to be exhaustively used.

7.3 Raw Meal Burnability Improvement

In order to achieve a sustainable cement production, it is necessary, first of all, to optimize the use of available resources and equipment from raw material to machinery. To reach this goal, it is necessary to conveniently adjust basic operations according to available resources. This single step contributes to alleviate the burden on the environment and also to increase the competitiveness and profit margin of cement producers.

Raw meal burnability is a very important step in this optimization process. Raw meal burnability means how easy it is for a raw meal to be burnt, providing the manufacturer an idea of the energy input required by the clinker manufacturing process. Raw meal burnability always has a great impact on cement production. Energy consumption, the stability of the kiln’s operation and the quality of the final product depend on several parameters related to the raw meal. Among these parameters, the following can be mentioned:

- Values of the chemical moduli;
- Fineness of the raw meal;
- Homogeneity of the raw meal;
- Type and quantity of minor elements;
- Use of by-products as raw meals.
The adjustment or optimization of these parameters can result in significant energy savings without any further investment in equipment. Therefore, it is the first step to achieve a sustainable production.

In the manufacturing process of Portland cement clinker, limestone decomposition, related to the Lime Saturation Factor (LSF) value, contributes most to energy consumption, CO₂ and NOx emissions. An increase of the LSF adversely affects raw meal burnability, resulting in a higher thermal specific energy consumption.

An LSF equal to 88 corresponds to a clinker having the same quantities of alite and belite. For Gouda [1977], the ideal LSF is about 94 in order to optimize the thermal consumption and the final composition of a clinker. However, it must be pointed out that the LSF also depends on the type of fuel used. If the cement manufacturer uses gas or oil, that do not contain or contain negligible amounts of ashes, the LSF will remain the same. On the contrary, if the cement producer uses coal, the amount of ash present in the coal will require an increase in the LSF of the raw meal in order to compensate for the siliceous nature of the ashes. The higher the ash content in the coal, the higher the LSF and the thermal energy consumption and CO₂ emissions, unless that the ash partially replaces the clay components.

An increase in the Silica Ratio (SR) will also affect the energy consumption making the mix harder to burn. An increase in the SR will cause a further problem since it will be more difficult to develop a protective coating for the refractory lining, and therefore, the heat loss through the kiln wall will increase. The clinker also will have a higher dust content which will adversely impact clinker grindability.

Another important parameter affecting raw meal burnability is the fineness of quartz/feldspar and limestone grains. The quantity of free silica grains coarser than 45µm and limestone grains coarser than 125µm must be kept below 2 percent and 6 percent, respectively, otherwise the raw meal will be harder to burn and will consume more thermal energy than expected. The resulting clinker will have the expected Bogue potential composition, but belite
crystals will be distributed in nests, resulting in a harder clinker to grind, with lower strength development compared to well-distributed belite crystals.

Many authors have discussed the impact of the fineness of the raw meal on its burnability. Heilmann [in Centurione 1997] suggests to reduce the LSF in the case of a coarse raw meal in order to compensate for the presence of coarse grains, he argues that an increase of kiln temperature from 1400 to 1500°C will lead to an increase of 4 to 5% in energy consumption.

Even when the chemical composition and the fineness of the raw meal is well controlled, some energy can be wasted if the homogenization of the raw mix is not properly carried out. This problem is quite rare presently due to the progress achieved in homogenization systems, but for older dry systems, bad homogenization can sometimes occur.

Minor elements found in the raw materials can affect either the final product performance or the operation of the kiln. The main minor elements that can reduce the viscosity of the liquid phase, which is very important for the burning process, are MgO at a content of up to 2 percent, K₂O, Na₂O, SO₃, and mainly F⁻.

The alkalis and SO₃ contents must be carefully controlled in order to keep their ratio (SO₃/Na₂O + 0.5K₂O) around one, otherwise buildups and accelerated wear of the refractory lining can occur leading to a kiln shutdown.

In order to promote the reactions and facilitate the operation of the kiln, the quantity of the liquid (LP) phase must be carefully adjusted. The LP usually varies between 23 to 28 percent, depending on the composition of the raw meal. Higher amounts may “washout” the coating, increasing heat loss through the kiln wall and also infiltrating into the refractory causing premature wear and a kiln shutdown. A low quantity of liquid phase will impair the development of clinker reactions and of the coating, resulting in higher thermal energy consumption and lower quality clinker.
A further very important role to be played by the raw meal is its ability to develop a stable coating in the burning zone in order to protect the refractory lining. The basic refractory bricks used in this zone are more sensitive to abrasion than those from other parts of the kiln, therefore they must be more abrasion resistant. Too high a rate of abrasion can result in a premature kiln shutdown. In order to evaluate the coating development ability (AW) of a raw meal the following formulas, are used, according to the alumina ratio (AR):

\[
\begin{align*}
\text{AR} \geq 0.64 & \quad AW = C_3A + C_4AF + 0.2C_2S + 2F \\
\text{AR} < 0.64 & \quad AW' = C_2F + C_4AF + 0.2C_2S + 2F
\end{align*}
\]

If AW < 20, the coating ability is too low; if AW > 35, there is an excess of coating. These formulas are very useful because they provide an idea of the behavior of the raw meal regarding this important parameter of kiln operation.

From a sustainable perspective, there is also a clear trend towards increased use of substitute materials. Foundry sands, iron cinder, brick split, slags and fly ashes may be used as alternative raw materials. These materials can influence the burnability of the raw meal [Bittner 2000]. The use of by-products as alternative raw materials is a sustainable possibility that can bring the following advantages:

- Increasing the life cycle of the quarry;
- Saving non renewable raw materials;
- Mitigating emissions;
- Increasing production;
- Saving energy consumption;
- Reducing cost production.

Other by-products that can be used are [Chatterjee 1981]:

- Sludge from the paper, sugar and fertilizers industries
- Pyrite cinders from the chemical industry
- Lime-silicates, wollastonite rocks, metallurgical slags, nepheline waste from the aluminum industry.

Carbonate sludges have the disadvantage of having a high LOI; on the other hand, they have a high CaO content (46 to 53 percent), but they can have up to 2.5 percent of P₂O₅ and up to 1.2 percent of F. Nepheline waste is also a good alternative, keeping in view that it has a high CaO content (52 to 55 percent), an insignificant LOI, but a non-negligible alkali content.

At the Aalborg cement plant, in Denmark, it is necessary to use a wet process due to the high moisture content of the raw materials. In order to reduce the high energy consumption that arose after the 1973 energy crisis, the use of fly ash was initiated as a partial replacement of the clay used in clinker production. In order to reduce its water content, fly ash was injected in a dry state into the burning zone through a pipe parallel to the burner, resulting in a reduction of the specific energy consumption from 6 300 kJ/kg clinker to 5 400 kJ/kg clinker. The quantity of fly ash which could be used with this method was limited to 10 percent of the weight of clinker. The quantity of fly ash decreased after 1993, because its composition had changed as a result of a change in the coal used at the power station [Damtoft, 1998]. Nearly the entire quantity of alumina, iron oxide and silica needed in this plant is still presently derived from recycled waste or homogeneous by-products.

Many cement plants are already using fly ash to replace sand, a common operation in Japan, for instance, with the advantage that it also provides other elements such as iron, aluminum and even small amounts of decarbonated CaO, which is valuable.

Slag was already used as raw material in Brazil in the preparation of the raw meal during the eighties, by a plant that had difficult access to another source of Al₂O₃. The aim was to improve the formation of a protective coating in the kiln. According to some American plant personal information, the use of up to 13 percent of slag as raw material can provide an energy saving of 5 percent and a 10 percent production increase. Presently, two U.S. patents cover the process of feeding a kiln with either Steel Electric Arc Furnace Slag or Air Cooled Blast Furnace
Slag in spite of the fact that it is a very old technology. Slag is introduced at the feed end of the kiln. The benefits observed in plants using this technology are [Personal communication]:

- Increase in clinker production up to 10 percent without any modification of the kiln system except the feeding system;
- 2.5 percent decrease in thermal energy consumption for a plant equipped with a pre-heater system and 12% in a wet process plant;
- Reduction of CO₂ emissions as a function of slag amount feed to raw meal;
- Reduction of burning zone temperature of about 40-90 °C;
- 25 percent reduction in NOₓ emissions using a preheater/calciner system and 48 percent using a wet system.

### 7.4 Kiln Operation Optimization

A good kiln operation must take into account some simple but frequently forgotten or omitted verifications, especially in older plants not equipped with an intelligent system to monitor the majority of the operation phases. Some factors disturbing the kiln system are:

- infiltrated air;
- dust in the direction of the gas due to inefficient dust collection by the cyclone;
- short circuit flows of hot gases through the cyclone.

The following items are the most important for follow-up:

- False air entrance prevention in the kiln system due to open inspection doors left open or bad sealing conditions in the kiln;
- Kiln ovality control;
- Good fuel oil atomization or coal fineness adjustments;
- Ensure adequate air-fuel mixing;
- Wear of the burner may lead to a bad configuration of the flame and wasted energy;
- Optimization of the quantity and temperature of secondary air from the cooler.
A varying amount of air infiltrates into the pre-heaters depending on the construction and state of the kiln inlet seal. This, for instance, is a simple problem to solve- which causes significant energy loss. The heat losses from the cooler can be reduced by improving the heat exchange between hot clinker and air.

According to Krefl (1989), the thermal losses in order of importance are:

- 22 percent heat loss in waste gases;
- 14 percent heat loss from coolers;
- 10 percent heat loss through radiation and convection.

When cement sales are stagnating, there will be a preference for less expensive measures, which does save some energy but rapidly pays off. The best alternatives for energy savings, aiming heat loss prevention and increase in the secondary air temperature are [Krefl 1989]:

- Reduction of waste-gas heat losses by reorganizing the pre-heaters and incorporating dip pipes and flap valves as well as eventually installing additional cyclone stages;
- Improving the clinker cooler in order to improve the recovery of heat and increase the heat of secondary air;
- Reducing heat losses along the walls of the combustion system.

As a result, the following savings can be obtained [Krefl 1989):

- going from 4 to 5 cyclones results in 4 percent savings;
- going from 5 to 6 cyclones results in 2 percent savings;
- using dip pipes and flap valves in the cyclones results in 3 percent savings;
- improving cooler efficiency from 62 to 70 percent and using a 6 stage cyclone set up results in up to 10 percent savings.

The kiln must also be operated under oxidizing conditions, using an excess of air that varies according to the fuel used, otherwise reducing atmosphere will result in problems for the quality
of the cement (mainly strength and setting time), in an accelerated wear of the refractory lining and will significantly increase the thermal energy consumption.

7.5 Low Energy Clinker Production

The main Portland clinker phases are C₃S, C₂S, C₃A and C₄AF. The proportions of these phases define the main properties of the cement such as short and long term strengths, setting time, heat of hydration, sulfate resistance, alkali-aggregate reactivity, etc., as well as the thermal consumption during the burning and the electrical consumption for grinding.

The search for energy savings therefore focuses not only on technological developments but also on the study of raw materials.

7.5.1 Mineralized clinker

Among the possibilities for saving thermal energy, a very promising alternative seems to be the production of the so-called mineralized clinker, produced at lower temperature, by means of using fluxing agents.

In the mid-1970's, Blue Circle Cement found that a certain combination of sulfate (from gypsum) and fluoride (from fluorspar) in the kiln feed could lower the temperature in the burning zone and improve cement strength. After performing some production tests, the company successfully applied this technology and filed three patents, but for various reasons, mainly frequent blocking in the pre-heater, it was decided not to pursue this experiment [Borgholm 1996].

In the late 1980s, Aalborg Portland worked on the new concept for more than two years, carrying out numerous experiments to overcome cyclone blocking. Today, most cements sold in Denmark are made from mineralized clinker. [Borgholm 1996].
The clinker should contain close to 0.25 percent F while the SO\textsubscript{3} level depends on the alkali level in the clinker and is typically 2.5 percent. Since the burning temperature must be kept low to prevent the destruction of CaSO\textsubscript{4}, no excessive sulfur circulation is generated. Consequently, cheaper high sulfur pet coke or any high sulfur fuel can be used. The evaporation of chloride is lower and NO\textsubscript{x} emissions are reduced to less than half, typically to around 40 percent of the usual amount.

The formation of alite from the reaction of belite and lime in mineralized clinker takes place theoretically at around 1 170°C when an equilibrium is reached. In practice, however, the temperature has to be close to 1 350°C due to inhomogeneities. The alite crystal’s structure is expanded by replacing SiO\textsubscript{2} with up to 1.5 percent Al\textsubscript{2}O\textsubscript{3} and 0.5 percent SO\textsubscript{3}. This makes the crystalline structure more vulnerable to chemical reaction with water. The SiO\textsubscript{2} liberated in turn reacts with more lime to form belite or alite. F is also, to some extent, trapped into the structure. Microscopic and XRD examinations show that there is 10 percent more alite or belite in mineralized clinker than originally calculated [Borgholm 1996].

If the alkali content in the clinker exceeds 0.8 percent Na\textsubscript{2}O equivalent and the SO\textsubscript{3} level is adjusted accordingly, the control of the setting of mortar and concrete will probably not require that gypsum or anhydrite be added during cement grinding. Effective control of the setting is ensured by calcium langbeinite (2CaSO\textsubscript{4}, K\textsubscript{2}SO\textsubscript{4}) formed by alkali sulfate, lime and the surplus of SO\textsubscript{3} in the clinker that is not entering in the silicate phases.

The use of mineralizers allows a temperature reduction for the same LSF of around 100°C and results in an energy saving of 2 to 3 percent. A reduction in the sintering temperature of 200°C and of 50°C in decarbonation would result in a saving of 6 percent [Ludwig et all 1993].

In his Ph.D. thesis based on laboratory tests and industrial trials, Centurione [1999] shows the following trends due to the mineralization of clinker by F and SO\textsubscript{3}:

- Decrease of 5 to 6 percent in thermal energy consumption;
- Possibility of using lower grade fuels with higher S content. It is possible to use up to 100 percent pet coke, an alternative fuel that can contain up to 6 percent S;
- Increasing refractory life cycle in the kiln due to the lower temperature. The duration of the lining may increase twofold;
- 30 percent lower grinding energy consumption due to the fact that mineralized cement is more reactive and may be ground coarser
- Possibility of increasing the amount of supplementary cementitious materials due to the higher alite content and higher reactivity of the alite, 15 percent more slag could be used in industrial applications without impairing the strength performance of cement;
- Compressive strength increase of 50 percent at 1 day, 30 percent at 7 days and 20 percent at 28 days;
- Potential beneficial advantages may vary from plant to plant, but in some cases they may not be economically or technically feasible;

The increased reactivity may be due to the polymorphic transformation or increased content of alite crystals. Usually, the formation of rhomboedric alite was noticed with F contents over 1 percent which results in a decreasing of the C₃A content, probably due to the incorporation of Al₂O₃ in the alite structure. Over 1.5 percent F⁻ could be found in C₃A, probably associated with the formation of C₁₁A₇. CaF₂. The main challenge of the mineralization process is to increase the Al₂O₃ content in the alite by using F⁻ since these combined components promote a change in the polymorphism of alite with the formation of the rhomboedric phase. The role played by SO₃ is essential since by reacting with the alkalis, the alkalis are not trapped in the alite structure, which otherwise would have favored the formation of the less reactive monoclinic and triclinic forms of alite.

### 7.5.2 High belite clinker

In usual Portland cement clinker, alite is the most important component, contributing to strength development basically during the first 7 days. Usually, alite represents about 50 to 70 percent of the clinker. Belite can usually be found in the range of 10 to 30%. Belite contributes
slightly to early strength but has a greater importance for strength after 7 days, providing uniform strength development for the cement.

Belite clinkers are those that show a reverse proportion of C₃S and C₅S, without impairing early strength. This can be achieved by increasing the reactivity of belite.

For a belite clinker, the LSF is in the range of 0.78 - 0.83, making possible the formation of a certain amount of alite (approximately 10 to 20 percent). Below 0.78, no significant energy and quality advantage can be achieved [Chatterjee 1996]. The average coal consumption per tonnage of a high belite clinker is reduced by 15 to 20 percent when compared with that of ordinary Portland cement clinker. The emission of CO₂ caused by coal combustion and limestone decomposition is decreased by 15 to 20 percent and 5 to 10 percent, respectively. A higher specific output of clinker, around 20 percent, and a lower amount of limestone (about 5 to 10 percent) are achieved when producing such a clinker [Sui et al. 1998]

In some countries, the basic reason for the use of belitic cements was to preserve raw material in order to allow low grade limestone to be used in cement manufacturing. Nowadays, the concept is changing, focusing more on durability of the concrete when using such a type of cement, since the concrete matrix of a belite cement provides a more durable structure than an alite-rich cement [Chatterjee 1996]. Belite cement generates less heat of hydration and less Ca(OH)₂. The lower Ca(OH)₂ provides, among others effects, less risk of carbonation and better interface between aggregate and mortar.

As previously mentioned, in a very simplified way, the hydration reactions of C₃S and C₂S may be represented as follows:

\[ 2C₃S + 7H → C₃S₂H₆ + 3 CH \quad ΔH = 114kJ/mol \]
\[ 2C₂S + 5H → C₃S₂H₄ + CH \quad ΔH = 43kJ/mol \]

The hydration of C₂S is basically characterized by the same hydration products, but with much less hydration heat and a lower amount of released Ca(OH)₂. Theoretical calculation
indicates that 100 g of C₃S generates 79 g of C-S-H gel and 49 g of CH, while the same quantity of C₂S results in 105g of gel and 21.5g of CH, indicating the higher durability of the matrix provided by belitic cement [Chatterjee 1996]. Belitic cements have a low heat of hydration and meet the requirements for mass concrete for huge structures such as dams.

Belite stabilization can be achieved by a technology based on the use of natural raw material, chemical stabilization and fast cooling techniques. The target of stabilization is to develop a more reactive polymorph phase by incorporating minor components in its structure and a fast cooling to maintain the targeted reactivity. Concerning chemical stabilization, the best components are K₂O, Na₂O, SO₃, and secondarily, B₂O₃, Fe₂O₃, Cr₂O₃ and BaO. In the case of alkalis, it has been noticed that in the absence of SO₃, a great part of the alkalis are incorporated in the belite phase. By increasing the quantity of alkalis in belite, the more reactive forms α and α' are developed. In the absence of alkalis, with increasing SO₃ contents, the amount of alite formed decreases, resulting in a lower initial strength but considerably increasing the longer term strengths (28 and 90 days), a remarkable effect when a fast cooling is provided. In the absence of alkalis, SO₃ results in the formation of CaSO₄ and no further increase of α or α' content. It is stated that the optimal SO₃ content in the clinker lies in the range 0.6 to 0.8 percent.

The low initial strength, which is the great disadvantage of belitic cements, can be overcome by making the concrete workable even at low water/cement ratios through improvement of belite’s hydration property of, adjustment of particle size distribution of the cement and use of organic admixtures [Uschikawa 1998]. However, the production of belitic cements causes a main problem regarding electrical energy consumption: belite has a higher elasticity modulus than alite, and therefore requires higher energy inputs to achieve a good grindability and fineness. An attractive issue for disseminating its use can be the possibility of trading CO₂ emissions or by pressure of environmental agencies or governments.

7.6 Use of Supplementary Cementitious Materials

Keeping in view the 1.5 billion tonnes of cement presently produced and used in the world and perspectives for increasing demand, fuel and raw material consumption will reach very high
levels in the medium and long terms. The cement industry is responsible for approximately 6 percent of CO₂ emissions worldwide, which highly impacts the environment due to the role played by this gas in the greenhouse effect. Therefore, any action toward the mitigation of these impacts must be taken into account. The use of blended cements containing industrial by-products or natural products represent the best, easiest and fastest alternative for significantly reducing the cement industry’s level of emissions.

Supplementary cementitious materials are industrial or natural materials that can develop cementitious property when blended with Portland cement clinker. Blending materials can be divided, according to their origin, into two main groups: industrial by-products and natural materials [Yamamoto et al 1997].

The main by-products are:

- fly ashes from power plants and steam generation plants;
- blast furnace slags;
- silica fume;
- active clays from the burning of oil shales;
- rice husk ash.

From technological point of view, silica fume is an excellent pozzolan and could be used to fulfill this function, besides improving early strength. Some plants that have used up to 8% silica fume in blended cement together with 35% slag [personal experience]. Silica fume is a replacement material, but silica fume is NOT a feasible replacement material from economic point of view since its extremely expensive compared to the other by-products.

The other group is made up of natural pozzolans from mineral deposits. Calcined clays, mainly metakaolin, are usually classified in this group. Some of these pozzolanic materials are:

- metakaolin;
- analcimites;
- tuffs;
- diatomaceous earth;
- opaline shale.

The main advantages to using supplementary cementitious materials in partial replacement of Portland cement are:

- Environmental: reducing the consumption of non renewable raw material and fossil fuels, mitigating emissions levels (CO₂, NOₓ and SOₓ), and reducing the generation of CKD (Cement Kiln Dust);
- Strategic: promoting the increase of the life cycle of limestone quarries and avoiding their accelerated exhaustion;
- Economic: improving the competitiveness of the final product, reducing production costs, depending on the impact of freight costs. Freight costs are decisive in the selection of the best alternative in a sustainable context. However, if conveniently used, supplementary cementitious materials can be an interesting option to increase production without further significant investments or the building of new facilities;
- Technological: improving the performance of the cement in aggressive environments, mainly sulfate and chloride-rich environments, minimizing the problem of alkali aggregate reaction, reducing the heat of hydration, a property of great importance for mass concrete.

The use of supplementary cementitious materials cannot be generalized but should be carefully evaluated on a plant by plant basis, in order to maximize its use from an economic, technological and environmental point of view, as well as in the search of new niche markets and market requirements. It must be regulated by standards that are both pragmatic and flexible that could be used as a regulation tool for customers. International standards vary significant but show a trend, among a majority of countries, for following European standards. As a general rule, standards permit contents of up to 70 % of slags and 50 % of pozzolans (fly ashes, calcined clay, volcanic rocks, etc), and up to 35 % limestone filler.
Metha [1998] mentions that relatively huge amounts of disposable coal ash and blast furnace slag are available in countries, mainly China and India, which would require additional large amounts of cement. Such huge amounts can be used to increase the production of blended cements without increasing the production of clinker. It is a pity that nearly 90% of the coal ashes and metallurgical slags produced nowadays end up either in low-value applications such as landfills and road bases, or are simply disposed of or stockpiled Metha [1998].

7.6.1 Fly Ash

According to Metha [1998], the current annual generation of coal ashes worldwide is estimated to be about 650 million tonnes, of which at least 70% or 450 million tonnes are generally suitable to be used as a pozzolan. The worldwide yearly rate of consumption of fly ash today by the cement and concrete industry is reportedly about 30 million tonnes (4.6%) which is very low. China and India together produce about 200 million tonnes/year. European countries, mainly Russia, Poland, the former Czechoslovakia, Romania, Germany, Spain and the United Kingdom generate 250 million tonnes per year.

In Table 10, data from production and use of fly ashes are presented [Komatsu 2000]

**Table 10: PRODUCTION AND USE OF FLY ASH**

<table>
<thead>
<tr>
<th>Country</th>
<th>Production (10^6 tonnes)</th>
<th>Used (%)</th>
<th>Cement &amp; Concrete (10^6 tonnes)</th>
<th>Landfill &amp; Roads (10^6 tonnes)</th>
<th>Back fill in Underground Mines (10^6 tonnes)</th>
<th>Other uses (10^6 tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan</td>
<td>4.0</td>
<td>52.1</td>
<td>1.5</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>USA</td>
<td>60.0</td>
<td>30.3</td>
<td>7.2</td>
<td>4.9</td>
<td>0.1</td>
<td>6.0</td>
</tr>
<tr>
<td>Britain</td>
<td>16.0</td>
<td>35.3</td>
<td>2.9</td>
<td>1.3</td>
<td>ND</td>
<td>1.2</td>
</tr>
<tr>
<td>Germany</td>
<td>20.0</td>
<td>99.0</td>
<td>3.8</td>
<td>3.0</td>
<td>12.1</td>
<td>0.9</td>
</tr>
<tr>
<td>France</td>
<td>2.0</td>
<td>95.0</td>
<td>1.0</td>
<td>0.5</td>
<td>ND</td>
<td>Nd</td>
</tr>
<tr>
<td>USSR (?)</td>
<td>62.0</td>
<td>34.0</td>
<td>8.4</td>
<td>11.9</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>China</td>
<td>91.0</td>
<td>37.4</td>
<td>13.8</td>
<td>10.5</td>
<td>8.0</td>
<td>1.8</td>
</tr>
</tbody>
</table>
ND: Not Discriminated (?)

For each 100 tonnes of fly ash, 25 tonnes of bottom ash and slag are generated.

The majority of available fly ashes that can be used in concrete are low calcium ashes (ASTM C 618 Class F) which are basically the by-products of anthracite or bituminous coal burning. Class F fly ashes have a little or no hydraulicity, but in the presence of Ca(OH)₂ they react at room temperature to form hydrates having binding properties. Recently fly ashes having a higher calcium content (ASTM C 618 Class C) from the burning of lignite and sub-bituminous coal have been used. They have better binding properties and a stronger pozzolanic activity (reaction with Ca(OH)₂ and hydraulic binder formation).

The pozzolanic properties of a fly ash (Figure 27) depend on a number of factors such as the type of coal (lignite, pit coal), the deposit from which it is mined, preparation and firing conditions (coal grinding, firing temperature, boiler rating).

![Microphotograph of fly ash](image)

*Figure 27: Microphotograph of fly ash*

The main characteristics affecting the reactivity of a fly ash are:

- chemical composition including loss on ignition (L.O.I.);
- carbon content;
- glass content;
- specific surface;
The carbon content is evaluated by the loss on ignition. It depends on the burning conditions of the coal. The higher the carbon content the more difficult it is to entrain air in concrete. A high carbon content also means poor water retention resulting in higher bleeding. It is interesting to point out however that the bleeding of pozzolanic cements is lower than ordinary cement when the carbon content is low.

The main technological issues related to the use of blended cement, using fly ashes with composition close to ASTM class F, are:

- Low heat of hydration;
- Low initial strength and higher long term strengths;
- High resistance against sulfate and chloride;
- Prevention of alkali-aggregate reaction;
- Low permeability;
- Better workability and lower trend to bleeding;
- Higher elastic modulus due to a lower hydration rate compared to ordinary Portland cement, reducing the risk of cracking due to shrinkage or expansion.

The cost of disposing of fly ashes can play an important role in promoting their use. In Japan, coal ash disposal costs can be as high as $100 US per tonne, this is the reason why Japan prefers to buy low ash coal (from Indonesia, for instance) to save disposal costs or use as a raw material [Komatsu 2000].

7.6.2 Blast Furnace Slag
Blastfurnace slag is another by-product which is useful for the cement industry. Although the world production of slag is about 100 million tonnes/year, with at least 50 million tonnes produced in China, India and Europe. Slag must be essentially vitreous (Figure 28). In many countries, the utilization rate as a cement substitute is still low because only a small portion of the slag is quenched into the granulated or cementious form. With the possibility of CO₂ taxation, the use of slag may substantially increase even under adverse freight costs.

![Image of vitreous slag](Courtesy of S. Centurione)

**Figure 28:** Microphotograph of a vitreous slag

According to Battagin [1988], the first reference to the use of blast furnace slags date back to 1774, when Loriot discussed the cementitious properties of slag when mixed with lime. In 1818, Vicat noticed the similarity between slag composition and clinker and forecast its use in the cement industry prior to Joseph Aspdin’s Portland cement patent in 1824. The great driving force behind the use of slag in the cement industry can be attributed to Langen, who in 1862 in Germany developed the slag granulation process.

The first commercial cement containing slag was developed in 1882 by Prüssing in Germany. The clinker and the slag were ground together. In 1909, the German government recognized the use of up to 30% of slag in cement. Later, in 1917, a cement containing up to 70% of slag was standardized.
Usually slags are more difficult to grind than clinker and therefore cement having high slag contents demand higher electrical energy. This extra energy requirement can be minimized by the use of grinding aids and by the use of high efficiency separators. Some Canadian slags that are partially water cooled and then air cooled are easier to grind than clinker.

A limiting factor for a greater dissemination of the use of slag may be the freight costs. Frequently, transportation of slag may result in a high cost impact since the source of slag is often far from a cement plant, making the cost of slag greater than the production cost of clinker. In such a case, the use of slag is possible if special products are required by the market (sulfate resisting cement, low hydration heat, etc.).

The energy consumption required to produce Portland cement amounts to 4050 MJ/tonne whereas slag cement needs only 3 080 MJ/tonne [Reinhardt 1998], representing a great advantage.

The main criteria for the evaluation of the quality of a slag are:

- chemical composition and;
- glass content.

The chemical composition indicates the basic or acid character of the slag. The higher the basic nature of the slag, the higher its reactivity. There are many chemical formulas to evaluate the reactivity of a slag but, as a general rule, it can be stated that slags with the following ratio offer good reactivity:

\[
\frac{(\text{CaO} + \text{MgO} + \text{Al}_2\text{O}_3)}{\text{SiO}_2} > 1
\]

Some standards, such as those in North America, consider that \(\text{Al}_2\text{O}_3\) shows an amphoteric character and in this ways suggest:

\[
\frac{(\text{CaO} + \text{MgO} + 1/3 \text{Al}_2\text{O}_3)}{(\text{SiO}_2 + 2/3 \text{Al}_2\text{O}_3)} > 1
\]

Keeping in view that slags react more slowly than clinker, they can be activated by either grinding or by a chemical process. The main chemical activators are \(\text{Na(OH)}\), \(\text{Ca(OH)}_2\), \(\text{SO}_4^{2-}\) and
water glass (Na₂SiO₃). Under an alkaline pH, Al₂O₃, SiO₂ and CaO are solubilized and generate hydration products. The type of calcium sulfate, as well as the C₃S content of the clinker, are important factors for blended cement containing high amounts of slag since they are catalysts for the slag.

The main technical benefits provided by the use of a blended cement containing slag are:

- permeability reduction;
- increased resistance against sulfate and chloride attack;
- lower hydration heat;
- reduction of AAR;

7.6.3 Other supplementary cementitious materials

Some clays, when conveniently activated by calcination, present a structural disorder that provides them with some pozzolanic characteristics; they can develop hydraulic compounds and cementious properties in the presence of Ca(OH)₂. The activation of a clay depends on four main parameters:

- The type of clay mineral;
- The clay mineral content;
- The burning temperature;
- The color of the clay.

The best clay mineral for obtaining a good pozzolan is kaolinite. Montmorillonite also shows some activity when burnt, but much less than kaolinite [Zampieri 1993].

When a particular clay contains above 20 to 30 percent of kaolinite, its pozzolanic activity starts to be satisfactory, but in order to obtain a good quality pozzolan, it is recommended to burn a clay containing at least 50 percent of kaolinite (Personal experience). The quality of the calcined clay will increase with increasing content of kaolinite.
The burning must be performed in the range of 700 to 900°C, usually 800°C, in order to promote the complete kaolinite deshydroxilation that results in the structural disorganization (metakaolin generation) that will ensure its reactivity. If the temperature is above 900°C, the resulting metakaolin starts to recrystalize and forms mulite, causing it to lose its reactivity.

The color of the clay is basically a market criteria since clays with a high iron content will develop the final red color often unacceptable to customers, as noticed with calcined clays in Brazil from a local cement plant in 1974. However, depending on the country, on local tradition or on the application, there could be no problem in the use of colored calcined clays.

**Table 11** shows the benefits of using calcined clays as pozzolan instead of clinker from a thermal and an environmental point of view [Zampieri, 1993].
Table 11: ENERGY AND ENVIRONMENTAL COMPARISON BETWEEN CLINKER AND CALCINED CLAY PRODUCTION

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1 tonne of Clinker</th>
<th>1 tonne Calcined Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Oil</td>
<td>Wet Kiln</td>
<td>Dry Kiln</td>
</tr>
<tr>
<td>Fuel Consumption (kg)</td>
<td>159</td>
<td>85</td>
</tr>
<tr>
<td>Emitted CO₂ (kg)</td>
<td>1063</td>
<td>824</td>
</tr>
</tbody>
</table>

The corresponding fuel consumption and CO₂ emissions values for calcined clay are advantageous from an environmental point of view compared to clinker manufacturing. CO₂ emissions represent only 22 percent of dry kiln emissions and 17 percent of wet process emissions, while the fuel consumption corresponds to only 67 percent and 36 percent, respectively.

It would be extremely valuable if calcined clay could be produced by burning alternative fuel, what could add an even higher environmental value to the final product. The lower temperature required for calcined clay production could be a risk, however, due to the insufficient temperature to destroy some organic compounds. An interesting sustainable possibility is to produce pozzolans from calcined clays using contaminated soils.

Calcined clay is a very important alternative when there is not enough available fly ash in the vicinity of a construction site where low heat cement is required, for instance. In 1973, Brazil and Paraguay signed the Itaipu Treaty on the hydroelectric resources of the Parana river, which belongs to both countries. The construction of what was going to become the largest hydroelectric power station in the world (Figure 29) began in 1975.
Before the construction of the dam, studies on local aggregates showed that they were potentially reactive to alkalis. As it was impossible to find sufficient amount of low alkali cement that could solve the problem, it was decided to use fly ash as a supplementary cementitious material. The fly ashes available in southern of Brazil were not sufficiently abundant and were very expensive due to high transportation costs. Keeping in view that huge deposits of kaolinite were available in the area, a calcined clay plant was built near by the site of the future dam. The use of calcined clay as pozzolan considerably reduced the hydration heat of such a huge structure.

Another very common supplementary cementitious material is limestone filler. It is a very easy material to grind, easier than clinker for instance, and easily available in the quarry of a plant.

Limestone filler has a physical effect which is beneficial for the grain size distribution of cement. It is sometimes stated that it has reactive properties by means of surface reaction. The quantity of limestone filler used is generally around 5 percent to 10 percent in ordinary Portland cement. Higher contents, such as in masonry cement, will adversely affect strength properties and will also cause the coating of balls and lining in the grinding mill, impairing grindability.

Aside from the previously mentioned supplementary cementitious materials, the use of silica fume must be mentioned. Silica fume is an extremely fine residue of Si, Fe-Si or zirconium manufacturing. Silica fume is commonly used in high performance concrete and in the manufacturing of special blended cements (5 to 8 percent silica fume) with high initial strength. Another possible blended cement combination consists of the same silica fume content with
around 20 to 30 percent blast furnace slag or fly ash addition. Such cement will present high initial strength and a good resistance to sulfate attack.

Silica fume provides technological advantages, improving cement reactivity and workability besides being pozzolanic. The price of silica fume varies, however, from $150 US to $1 000 US per tonne, depending on local market conditions, while clinker costs about $50 US, making the use of silica fume less attractive from an economical point of view.

The global husk rice production in 1994 was 535 million tonnes. As the ash corresponds to 4% by weight of husk rice, it resulted in an ash generation of approximately 21 million tonnes [Gava et al 1999]. Rice husk ashes are also excellent pozzolans made up of extremely fine particles of vitreous SiO₂. Rice husk ashes are highly reactive, but due to their shape and carbon content, their use can present problems with rheology and color.

Certain volcanic rocks can be also used as pozzolans after being finely ground. In his thesis research, Zampieri [1993] mentions the the ancient Greeks and Romans already knew that certain volcanic materials, when ground and mixed with lime and sand, could provide more durable mortars. The Romans were quarrying some of these rocks in the city of Puteoli near Mt. Vesuvius. The modern name of Puteoli is Pouzzoli, from which the word pozzolan is derived.

### 7.7 Alternative Fuel Burning

Energy and environmental policies in most countries have experienced great changes, especially in the last decade, and it is one of the main consequences of globalization.

Not only is the availability of fossil fuels limited but uncertainty regarding fuel supply in the future from a geopolitical point of view must also be considered. As the cost of energy in cement production may vary from 30 to 40 percent of the cost of production, any variation in fuel price will greatly affect the competitiveness and final price of cement.
The search for alternative fuels, which reduces this instability as well as providing a mitigation of CO₂ emissions, can be achieved by burning waste-derived fuels and waste co-firing. A further advantage of these two alternatives is that they reduce cement manufacturing costs, as well as mitigating the environmental burden.

The clinker firing unit is a useful incinerator for the disposal of hazardous materials due to a number of characteristics which make them ideal installations in which alternative fuels can be valorized and burnt in a safe manner, such as [Cembureau 1997]:

- High temperatures;
- Long residence time;
- Oxidizing atmosphere;
- High thermal inertia;
- Alkaline environment;
- Ash retention in clinker;
- Continuous fuel supply.

Normal operation of cement kilns provides combustion conditions which are more than adequate for the destruction of even the most difficult-to-destroy organic substances. This is primarily due to the very high temperatures of the kiln gases (2 000°C for the combustion gas from the main burner and 1 100°C for the gas in the precalciner).

The gas residence time at high temperature in the rotary kiln is of the order of 5–10 seconds and of more than 3 seconds in a precalciner. The complete combustion of an organic compound composed only of carbon and hydrogen produces CO₂ and water. Additionally, if the organic compound (conventional fuel or alternative fuel) contains chlorine or sulfur, then acid gases such as HCl and H₂SO₄ are also produced. These gases are absorbed and neutralized by the freshly formed lime and other alkaline materials within the kiln.
The first successful experiments to evaluate the efficiency of the destruction of chlorinates were performed in the 1970's, in a wet kiln in Canada, at the St. Lawrence Cement plant [Moore 1995].

Co-firing in the cement kiln is a combined operation of burning wastes while producing clinker using these wastes as an alternative source of energy or as raw meal replacement, without impairing the final product quality and the kiln operation [Kihara 1999]. The co-firing industry started in the U.S. in the 1970's. If the current legislation had existed at that time, co-firing would not have started due to the current stringent environmental requirements. This is a reason why developing countries should start co-firing step by step, according to their local situation, instead of trying to copy the North American model [Moore 1995].

The wastes that could be co-fired should meet the following criteria:

- They must not cause further environmental impact;
- They must not impair the manufacturing process;
- They must not adversely alter cement quality;
- They must not cause health problems.

The following materials can be co-fired with restrictions:

- Highly corrosive materials (pH < 3 or pH > 12);
- Reactive products;
- High Hg and Tl content materials (due to the high volatility of these elements);
- Reactive chemical products such as isocyanates and some amine compounds;
- Highly controversial chemical substances such as dioxines and BPCs (Biphenyl Polychlorides) that can generate dioxins and furan, two highly toxic gases.

In 1995, about 10 percent of the thermal energy consumption used in European cement plants originated from alternative fuels, representing a saving of 2.5 million tonnes of coal every year [Cembureau 1997]. The German cement industry has been using selected wastes for many
years. In 1999, wastes accounted for 15 percent of the total energy required. In order to ensure the competitiveness of local cement production, this percentage should reach 30 percent in the following 5 years [VDZ, 1999].

In the U.S. about 7.5 percent of the required energy is provided by waste-derived fuels, as can be seen in Figure 30. The use of alternative fuels is definitely an excellent environmental alternative. Replacing just 10 percent of fossil fuels by waste-derived fuel would correspond to the total annual energy demand of 21,000 houses in Canada or the corresponding energy provided by 142 million liters of gasoline [Conseil Canadien du Ciment 1994].

The importance of alternative fuel use in six developed countries is shown in Figure 30. As it can be seen, the rate of substitution can be as high as 35% of Switzerland’s fuel energy [Bittner 2000].

![Figure 30: Substitution rate of alternative fuels in different countries](image)

The use of wastes as alternative fuels has the following environmental benefits [Cembureau 1997]:

- Reduces the use of non-renewable fossil fuels such as coal as well as the environmental impacts associated with coal mining;
- Contributes to a global decrease of greenhouse gases by replacing the use of fossil fuels by the burning of materials that would otherwise have to be incinerated, with corresponding emissions and final residues;
- Eliminates the landfilling or destruction of these wastes in dedicated incinerators;
- Maximizes the recovery of energy from wastes.

If substitute fuels are listed according to energy content, the following groups are obtained [Gaebel et al. 2000]:

- The high-grade group, with calorific values of 30 to 46 MJ/kg, includes plastics, tar, scrap rubber, used oil and used tires;
- The medium-grade group, with calorific values 16 to 20 MJ/kg, includes biogas, acid resins, electrode coke, paint residues, biological waste such as coconut shells, olive stones, fuller’s earth, sawdust, rice chaff and bracts;
- The low-grade group, with calorific values of up to 15 MJ/kg, includes scrap vehicles, household waste, paper, sewage sludge, oil shale and contaminated soil.

Some typical alternative fuels with their calorific values are presented in Table 12 (Kilb et al. 2000).
Table 12: CALORIFIC VALUES FOR ALTERNATIVE FUELS, COAL AND GAS

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Calorific value (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste light oil</td>
<td>42</td>
</tr>
<tr>
<td>Waste heavy oil</td>
<td>40</td>
</tr>
<tr>
<td>Pure polystyrene</td>
<td>40</td>
</tr>
<tr>
<td>Pure rubber</td>
<td>36</td>
</tr>
<tr>
<td>Waste tires</td>
<td>33</td>
</tr>
<tr>
<td>Bituminous coal</td>
<td>29</td>
</tr>
<tr>
<td>Acid tar sludge</td>
<td>16 - 22</td>
</tr>
<tr>
<td>Palm nut shells</td>
<td>19</td>
</tr>
<tr>
<td>Pressed olive cake</td>
<td>18</td>
</tr>
<tr>
<td>Rice husks</td>
<td>16</td>
</tr>
<tr>
<td>Shredder wastes</td>
<td>15</td>
</tr>
<tr>
<td>Cardboard, paper</td>
<td>15</td>
</tr>
<tr>
<td>Dried sewage sludge</td>
<td>7.5</td>
</tr>
<tr>
<td><strong>Coal</strong></td>
<td><strong>18 - 35</strong></td>
</tr>
<tr>
<td><strong>Natural gas</strong></td>
<td><strong>40 - 42</strong></td>
</tr>
</tbody>
</table>

Depending on the characteristics of the alternative fuel, they may lead to an accelerated refractory wear and kiln shutdown due to salt formation. A 10 day loss of production corresponds to the breakeven point or critical point where losses equal gains [Grosse-Daldrup et al, 1996].

Of all combustible waste used, tire-derived fuel, TDF, is the most often used as secondary fuel in the cement industry throughout the world [Terry, 1999].

The use of TDF dates as far back as 1973 in Europe and is common in the U.S. since the mid-to-late eighties. In Germany, for instance, about two-thirds of the existing amount of 350,000 tonnes of used tires are used for energy production and the remainder for reconditioning and reuse. In the U.S., the generation of tires corresponds to 1 tire/head/year, an immense quantity. The use of scrap tires in rotary cement kilns began with the oil embargo of 1973. The increase in the
cost of fuel had a very serious impact on the cement industry. The first cement company to
experiment with the use of scrap tires as a supplementary fuel was Dyckerhoff Cement in the
mid-1970s, followed by Heidelberg cement, who in 1978, started testing this new fuel. Through
their experiments, they determined that the maximum fuel replacement that could be reached was
25% [Blumenthal 2001].

A cement plant usually cannot use more than 25 percent TDF because of zinc content. The
zinc oxide may ultimately retard the setting time and the maximum zinc content in the clinker is
usually limited to 4 000 parts per million (ppm) [Blumenthal 2001].

The second largest substitute energy alternative is used oil. In Germany, 1.2 million tonnes
of oil per year are used as lubricants. Out of this, 690 000 tonnes are collected in the form of used
oil and 170 000 tonnes are used as an alternative fuel in the cement industry. Used oil consists of
various kinds of oil: 64 percent motor and gear oil, 10 percent machine and turbine oil, 7 percent
hydraulic oil, etc.

An important group of waste fuel materials is plastics. Industrial plastics are mainly based
on polystyrene and polyethylene. The calorific value of these materials is 40 to 46 MJ/kg. Plastics
are therefore high-grade energy carriers. The disadvantage of these substitute fuels is their
chemical composition, especially their high chlorine content.

7.8 Conclusion

The development of wet kilns to modern dry kilns with preheater and precalciner systems
were the main advancements in cement manufacturing technology during the seventies. It was
possible to substantially reduce thermal energy consumption, by about 50 percent, and CO₂
emissions by 20 to 30 percent. However, the fact that there are still many old cement plants that
are not expected to change to more modern manufacturing facilities must be taken into
consideration.
Therefore, in order to assure a sustainable cement production, older plants should ensure
the optimization of production according to available resources, improving raw meal burnability,
mainly fineness and dosing, substituting natural raw material by industrial by-products, as well as
developing a good machinery maintenance program and good operation conditions. A thermal
energy saving of up to 10 percent could be obtained with these single measures.

The production of mineralized clinker or belite clinker can be a suitable alternative for
reducing CO₂ emissions and providing energy savings. By proceeding with the mineralization
with F and S, 5 percent of the thermal energy can be saved, aside from reducing NOx emissions
and improving clinker grindability. By producing a belite clinker, a 15 to 20 percent reduction in
coal consumption can be achieved, with a CO₂ reduction corresponding to 10-15 percent,
however clinker grindability is highly impaired.

The most sustainable alternative for any plant would be the burning of alternative fuels and
the use of supplementary cementitious materials. Based on foreign experiences, a replacement of
fossil fuel by alternative fuel of at least 10 percent could be achieved, though an optimal
replacement of 30 percent should be targeted. A mean CO₂ reduction of around 10 percent could
be reached, besides reducing the need for dumping corresponding wastes and saving non
renewable fossil fuels.

The use of by-products as supplementary cementitious materials represents a great
environmental, technological and economic advantage. Of primary importance is the valorization
of by-products that would otherwise have to be disposed of. The contribution of these by-
products to improve the performance of blended cements is remarkable providing lower
hydration heat, higher resistance to AAR, higher resistance to sulfate attack, etc. The occurrence
of these by-products (mainly fly ash and blast furnace slag) is frequently high in countries where
cement demand will probably experience the highest increases. For each 2 percent of slag used, a
corresponding increase in clinker production and an approximately mitigation of 1 percent CO₂
emission will result. A further reduction in NOx emissions, raw material and fossil fuel
consumption will also occur. In many countries where these by-products are not available, large
quantities of kaolin can be found that, when convenient burned, produce metakaoloin, a good
supplementary cementitious material that contributes to a 20 percent reduction in CO₂ emissions and an energy saving corresponding to 40 to 65 percent compared to clinker production.

The use of separate SCM, in concrete, is not the best option compared to the use of blended cement, although still being an option. The cement industry is much more able to provide a more uniform, more adequate (compatibility clinker-SCM) and better performance product. The developments in cement grinding are great, with high efficiency separators, new hybrid systems of grinding, allowing to achieve a final hydraulic binder (cement + SCM) with more convenient grain size distribution, fineness adjustment, convenient heat of hydration (independent of the clinker composition) and gypsum optimization. Blended cement prevents the generation or at least minimizes a lot (more than 80%) the generation of CKD that must be discharged, landfilled, causing significant problems for the environment and leading to waste of energy and loss of production. Moreover the use of the limestone quarry could be optimized, saving non renewable raw material.
8. SUSTAINABLE USE OF CONCRETE

8.1 Introduction

Social debts, such as the lack of housing and infrastructure, as well as the further pressure of a potentially increasing rate of urbanization in many developing countries, point to the key role to be played by concrete in providing sustainable solutions for many of these problems.

At the beginning of the 20th century, only approximately 10 percent of the world’s population lived in cities, while in 2001, around 50 percent lived in or around cities. China and India, which represent nearly the half of the world population, still have a low rate of urbanization, suggesting the possibility of an even worst scenario. According to the United Nations [Metha 2002], the planet hosts 19 megacities, each with 10 million or more in population, 22 cities with 5 to 10 million inhabitants, 370 cities with 1 to 5 million inhabitants and 430 cities with one half to 1 million in population. Each person living in a city consumes much more concrete than a person living in the country.

In the years to come, repair and rehabilitation of concrete structures will be subjected to strict requirements with regards to environmental impact and economical constraints. Shrinking budgets for governmental agencies and municipalities will be one of the critical factors in the renewal of infrastructures. At the same time, the high costs of maintenance, repair and rehabilitation of concrete structures will cause delays and postponement of required actions, further increasing problems of deterioration and damage.

The environmental issue is becoming an essential part in the chain of production. The deterioration of the environment may cause an impact on social costs derived from a greater incidence of diseases, and a loss of working hours and productivity affecting business and company competitiveness.
In this scenario, the use of concrete must be optimized in order to maximize its social benefits and reduce its impact on the environment and the economy. A few important points should therefore be the focus of a deeper reflection:

- The need to reduce the consumption of non-renewable materials without penalizing social demand;
- Promote research for alternative materials;
- Improve material recycling from a technological and economic point of view;
- Establish strategies concerning the use of materials that meet environmental, industrial and economic policies in a synergetic process;
- Select better, environmentally friendly materials;
- Increase the durability of concrete;
- Review and adjust standards;
- Improve the level of comfort of the population without further burdening the environment.

Regarding the optimization of concrete use, a few points require further consideration, among them: improvement of the durability and life span of structures, reduction of on-site wasting, training of the labor force, enhanced site management, increasing use of recycled concrete waste, proper selection of concrete as an alternative in some less traditional applications, and continuous dissemination of information about available concrete technologies.

8.2 Improving Durability

Concrete is a durable material. Reinforced-concrete structures, for instance, can last anywhere from several decades to more than a century, but some reinforced concrete structures are presently demolished and removed much earlier. During the last two decades, deterioration of concrete structures has emerged as one of the most severe problem and, at the same time, one of the most difficult challenges facing the construction industry worldwide. Public agencies are already spending a significant portion of their annual construction budget on repair and rehabilitation [Horrigmo 1998]. The following data emphasizes this issue:
In Japan, it is estimated that maintenance and renovation costs for infrastructure will exceed 70% of total public investments in 2010, assuming that the growth rate of construction and improvements costs remain at 0% [Shimada et al. 1998];

In the U.S. alone, it has been estimated that the cost of repairing corroded bridges stands at $24 billion US, with an annual increase of $500 million US [Gjørv 1998];

According to the American Society of Civil Construction, about $1.3 trillion US is required to address infrastructure problems [Metha 2002].

One contractor [Ronstam 1999] has ventured rough estimate of what the true relative costs would be to ensure the required life cycle of a concrete. Based on his yearlong experience, the “Law of Fives” was introduced, which states that:

“One dollar spent in Phase A equals five dollars in Phase B equals twenty-five dollars in Phase C equals one-hundred-and twenty-five dollars in Phase D”, where each phase corresponds to:

**Phase A**: Design, construction and curing period;

**Phase B**: Initiation processes under way, no propagation of damage has begun yet;

**Phase C**: Propagating deterioration has just begun;

**Phase D**: Advanced state of propagation with extended damage occurring.

This simple example illustrates the importance of good engineering practices, a synergetic integration between participants, the selection of suitable materials and a follow-up of the work, in order to prevent further extra costs for maintenance, repair or rehabilitation of concrete structures in order for them to reach their expected service life.

For most construction materials, it is generally accepted that regular preventive maintenance is needed. Several steel bridges, for instance, are still in good condition after more than 100 years of service. The difference between steel and concrete structures, from a performance point of view, is that concrete structures should require much less preventive
maintenance, and the more durable the concrete structure, the less preventive maintenance should be needed [Gjov 1998].

It is interesting to note that one of concrete’s best properties can frequently turn against it. Since it is so easy to work with, anyone can make concrete of good or bad quality, but bad concrete has a much higher impact on public judgement than good quality concrete. The poor durability of some concrete structures, that present a life span often much shorter than expected, contributes to concrete’s bad image as well as the estimated 1 billion tonnes per year of demolition and construction concrete waste generated worldwide.

Despite all the developments that have occurred recently in concrete technology and the excellent properties of the concrete presently available, an initially good product may sometimes result in poor or less-than-expected quality. It is not enough just to have up-to-date material technology in order to make good concrete, it is also necessary to know how, where and when to use such a product, the required care and good management it demands, and the follow-up to be implemented on the work site. Among the factors that may lead to lower performance, bad curing and poor workmanship, combined with a lack of proper quality control on the construction site, can be emphasized. Such a combination of bad practices also often results in concrete problems and low durability, and in these cases the vulnerability of concrete structures facing aggressive environments will increase.

The best options to improve concrete durability, and therefore contribute to sustainability, can be summarized as follows:

- Selection of suitable aggregates, avoiding reactive aggregates that may lead to the deterioration of concrete by AAR, avoiding flat or friable aggregates that can contribute to reducing the final strength of concrete, besides impairing its workability;
- Selection of the adequate type of cement according to the final application, for example, the use of blended cements reduce hydration heat in mass concrete, aside from preventing deterioration by AAR and by chemical attack by SO$_4^{2-}$ and Cl$^-$ ions;
• More frequent use of concrete admixtures in order to improve the properties of concrete such as workability, fluidity, transport control, strength, lower permeability with lower risk of external aggressive deterioration;
• Use of a suitable thickness of concrete cover over steel bars;
• Use of lower w/c ratios in conventional concrete, avoiding the use of unnecessary water that will only generate high porosity, impairing concrete strength and durability against external factors and aggressive agents.

The problem of materials wastage due to debris, layer over thickness (excessive thickness of mortar), open cement bags, etc on sites must also be urgently addressed, mainly in developing countries, keeping in view its environmental, economic and social impact. A survey carried out in Brazil [Universidade de São Paulo 1999] shows that materials waste on construction sites approaches 20%. According to Bitar [1999] the wasting of materials in construction may reach up to 30% in Brazil on some work sites. This high percentage of wasting is not due to the quality of materials, but rather to their bad use.

Until very recently, environmental issues did not figure prominently in discussions in the construction sector. For many years, the balance was restricted to the binomial cost-quality. With the advent of quality demands, translated by society's expectation and partly represented by the emergence of the ISO – 9000 standards, this scenario began to change so that wasting is no longer acceptable, neither from an economic nor from an environment point of view.

The process of accreditation has slowly but voluntarily grown in several segments of the construction industry. When companies in the construction sector obtain their certification, they can improve their products and services, with potentially increase in business results due to improved management. An encouraging step, no doubt, to mitigate existing problems.

The alternative for small fragmented concrete or construction companies to really improve quality without impacting their costs can be based on progressive accreditation, step by step along the process, or by means of a co-operative association between small companies. The contribution of technical services of cement companies and cement associations toward a better
use of cement and concrete can also contribute to mitigate wasting. It is a paradox that high levels of wasting occur mainly in developing countries where the budgets are much lower, the social debts are higher and the urbanization rate is often low, suggesting a future increase in construction demand. Advances in quality must be continuously sought as well as the good use of concrete.

Therefore, from an environmental point of view, what is more important than simply searching for improvements in the quality of products that have already reached a high level of quality, is the development of a broad program for labor training, construction management, improvement of building techniques and the setting of mechanisms that make the contractor or financing organization responsible for wastes and for the lower than expected durability of the structure built.

The selection of the most suitable material according to the targeted life cycle of structures and its correlated advantages should also be a priority, since it would be possible to save materials and reduce frequently neglected indirect impacts (such as traffic jam caused by the repair of a bridge, for instance).

It must be considered that 20 MPa concrete is still largely used, since it is a cheap product, convenient to the reality of limited budgets, 20 MPa concrete satisfies numerous applications for which the designers do not need a higher compressive strength such as for the construction of footings, basements, etc. Based on commercial information provided by a traditional concrete supplier it was possible to get Figures 31 and 32 that show cost trends per m$^3$ and per MPa for different concrete strengths. From a sustainability point of view, concrete with a strength range of 30 to 35 MPa can be the best option for achieving optimal durability/cost ratio satisfying many market needs. The remaining use of higher strength concrete must be discussed on a case by case basis.
From a durability point of view, and mainly for larger structures, the use of concrete admixtures is also essential to produce good and durable concrete. In Figure 33, the costs of different components of concrete in a precast plant in Belgium can be seen. The important role of concrete admixtures in modern concrete production can be observed as the required strength increases. It is necessary to evaluate the required properties and expected lifespan of the structure to find the best cost-quality product. The cost of admixtures, however, does not exceed 5 percent of concrete cost for concrete strengths up to 60 Mpa, which satisfies the majority of HPC applications [Aitchin 2002, personal communication].
Figure 33: Impact of component costs in different concrete  
[Aitcin 2002, Personal Communication]

The concept of eco-efficiency will surely guide future policies in environmental issues. Eco-efficiency is basically a technical and management concept related to the maximization of the energy and material inputs, in order to reduce resource consumption, pollution, and waste generation.

8.3 Concrete Recycling

The construction industry is a major consumer of materials and also a major consumer of energy used in the production and transport of building materials, site assembling, and in the post construction phase, use and operation, maintenance and decommissioning.

According to Metha [2002], ordinary concrete contains about 12 percent cement, 8 percent mixing water, and 80 percent aggregate by weight. This means that, in addition to the 1.5 billion tonnes of cement used worldwide, the concrete industry consumes 10 billion tonnes of sand and rock, and 1 billion tonnes of mixing water annually. The concrete industry, which uses 11.5 billion tonnes of raw material, is the largest consumer of natural resources in the world.
The mean consumption of natural aggregates corresponds to 5 to 10 tonnes/year/head in developed countries [Bitar 1999]. In Ontario, Canada, during the eighties, an unusual economic growth boosted the consumption to 15 tonnes/head. In Europe, the consumption per head has been over 7 tonnes for many years already [Valverde 1999].

In France, 80 percent of the extracted aggregate is used in public works: 35 percent for building construction and 45 percent for new roads and streets and for the maintenance of existing ones; the remaining 20 percent goes to other construction types. Half of the aggregate production is for concrete and the other half for asphalt or used without any addition to build embankments, etc [Valverde 1999]. In England and Wales, around 33 percent of the total production of aggregates ends up in concrete [Valverde 1999].

In Ontario, Canada, 50 percent of all aggregates ends up in construction and repairing and maintenance of roads, 30 percent for other uses such as airports, harbors, the sanitation network, 17 percent for non residential buildings and 3 percent for residential buildings [Valverde 1999].

The magnitude of accelerated exhaustion of natural resources is therefore a serious issue and concrete production represents a great part of consumption share. Besides materials consumption, ever-growing urbanization levels must be also considered. Quarries for aggregate exploitation are often becoming closer to urban areas, affecting the local population, and are subjected to tighter environmental regulations. New quarries, situated further away from consumer markets, will produce aggregates at higher price due to the longer hauling distance and to environmental requirements.

In contrast to this situation, a global construction and demolition waste generation of 2 billion tonnes per year represents another environmental problem that has been mainly affecting urban areas. These quantities mostly consist of concrete demolition waste or other rubble such as masonry, gypsum and wood. Around 1 billion tonnes of concrete waste is generated worldwide every year. Presently, the majority of concrete demolition waste is dumped, but significant parts of it could be used to replace natural aggregates. The trend toward the use of recycled concrete
seems irreversible from a sustainability point of view, providing a solution for two environmental problems at once: raw material savings and landfilling mitigation.

The first significant process of debris recycling was experienced after the Second World War when many cities where completely destroyed. Their debris were recycled as artificial aggregates used for reconstruction. With so much construction to be done and faced with the difficulties of cleaning up the cities from debris, the option for recycling was compulsory.

Despite the good potential for concrete recycling, this process is still in its first steps of implementation and has not reached a high percentage. The level of generation and recycling attained by some European countries regarding construction and demolition waste (CDW), are shown in Table 13 [Vázquez et al. 2000]. The main reasons for the differences in the percentage of reuse and recycling of CDW are related to natural resources availability, hauling distances, geographical characteristics of the country, mainly its size, specific environmental legislation, and state-of-the-art recycling technology [Dorsthorst et al. 2000].

In order to reach the goals of concrete demolition waste management, it is necessary that all barriers and obstacles be detected and considered. A long-term action plan has to be drawn-up, combined with adequate development and research. Implementation of the necessary economic, technical and administrative tools require that initiatives involving legislation and regulations be taken. Kawano’s work [1998] lists the main barriers against reuse:

- Lack of suitable laws;
- Lack of codes, specifications, standards and guidelines;
- Cost;
- Poor image;
- Lack of experience ;
- Poor quality;
- Variations in quality;
- Inefficient supply system;
- Shortage of proper information.
Table 13: LEVELS OF GENERATION AND RECYCLING OF CDW IN SOME EUROPEAN COUNTRIES [Vásquez et al, 2000]

<table>
<thead>
<tr>
<th>Country</th>
<th>Core CDW (million tonnes)</th>
<th>Re-use or Recycle (in %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>5</td>
<td>41</td>
</tr>
<tr>
<td>Belgium</td>
<td>7</td>
<td>87</td>
</tr>
<tr>
<td>Denmark</td>
<td>3</td>
<td>81</td>
</tr>
<tr>
<td>France</td>
<td>24</td>
<td>50</td>
</tr>
<tr>
<td>Germany</td>
<td>59</td>
<td>17</td>
</tr>
<tr>
<td>Greece</td>
<td>2</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Italy</td>
<td>20</td>
<td>9</td>
</tr>
<tr>
<td>Netherlands</td>
<td>11</td>
<td>90</td>
</tr>
<tr>
<td>Portugal</td>
<td>3</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Spain</td>
<td>13</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Sweden</td>
<td>2</td>
<td>21</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>EU-15</td>
<td>181</td>
<td>28</td>
</tr>
</tbody>
</table>

The use of recycled materials in construction is, however, expected to increase due to the following reasons:

- A greater sensitivity in public opinion regarding environmental issues, leading to a political pressure toward minimizing the generation and transport of waste and the implementation of regulations for waste disposal, making the recycling option more competitive;
- The rapid depletion of the remaining natural aggregate resources (primarily sand/gravel), that will lead to a lack of such materials in many regions and consequently to higher prices and more stringent regulations. Moreover, new production sites will be located further and further away from urban areas;
• The technical development of the production and use of recycled materials will lead to more cost efficient demolition methods and recycling plants, a better control of quality, and more knowledge on application technology.

The improvement of concrete’s quality will result in better recycled aggregates. Any action that promotes such philosophy should be politically and economically stimulated by official mechanisms. Recycling in civil construction is good, prevention it is even better.

8.4 Sustainable Use of Concrete in Construction

The housing deficit that affects humankind is a serious issue in sustainability, but the existence of many housing units lacking infrastructure (water, sewage, energy, garbage collection) and of housing units precariously built or excessively populated is also of major concern. This problem must be urgently solved in developing countries.

People living under viaducts, Figure 34, are a common scenario in cities in developing countries. The sub-human conditions of many people living in precarious buildings (Figures 35 and 36) must be faced and solved. Aside from the social shock caused by such a situation, it must be emphasized that there are also further economic impacts and arguments to fight such a situation. These marginal communities, frequently spread out in megacities, are much more susceptible to diseases and therefore require more health care, besides developing informal activities that are not subject to tax (Figure 37), and living in fragile wood and paper buildings, often with illegal and precarious energy networks posing enormous fire hazard (Figure 38). Fire in these constructions will affect the structure of viaducts, leading to their closure to traffic. Just the cost of repairing the structure and the intrinsic costs from traffic congestion will be high enough to justify a preventive transfer of these people to better building facilities.
Figure 34: Common scenario in megacities: people living under viaducts and highly exposed to diseases.

Figure 35: Sub-human living conditions
Figure 36: Low quality standard of living

Figure 37: Developed informal activities.
A serious and pragmatic housing program target, according to the country's particular national housing policy, must be achieved. The Brazilian program, for instance, has the following targets, which are essentially described below and can serve as a reference [Marciano and Esper 2000]:

- To universalize access to housing;
- To enlarge the housing offer and improve existing housing;
- To regularize irregular settlements and promote access to urban land;
- To modernize the housing sector by improving the legislation and agents' capacitating.

There are many ongoing projects aimed at solving this dramatic social situation. Popular buildings are, however, often synonymous to low quality materials use, low durability and high materials wasting, regrettable typology and no landscape concerns. In Figures 39, 40 and 41, a population transfer project from a shantytown to buildings where the situation of lack of quality and no landscape concern is improved are shown. Though they undoubtedly represent a remarkable improvement, authorities should be concerned with finding better and more definitive alternatives.
The use of better materials, concrete performance included, will result in lower maintenance and less waste, resulting in optimized budget expenses.

A good typology of the building, providing a better use of natural resources like sun light, ventilation, better construction distribution, more convenient distances between buildings, etc., can help improve health. **Figure 42** shows an example of a bad arrangement of buildings. With a good landscape project, in harmony with the concrete structure, and better typology, users will be
proud of their environment leading to enhanced concern about maintenance and contributing to reduce the stress and potential violence that usually occurs among dwellers in such buildings.

Figure 42 Bad typology of buildings, with lost potential natural advantages for users.

The importance of developing a good integrated project is described by Hawken [1999] as “Green Development” and takes into account resource efficiency, environmental sensitivity, attention to human well-being and financial success. The ING bank in Holland developed a project called “Organic Building”. With art, sunlight, green plants, energy conservation and noise concern, and have decreased absenteeism by 15 percent and gained an estimated labor productivity of around 10 percent [Hawken 1999]. The EPA estimates that building-related illnesses in the U.S. account for 60 billion $ US in annual productivity loss [Hawken 1999]. This concern for human welfare should be extended to every building and would contribute to attaining a more sustainable society. It is not enough to simply transfer people to better conditions if a deeper intervention in quality and landscape is not carried out, and there is the risk of building a “vertical shantytown” (Figure 43).
The use of Cellular Concrete (CC) in a Brazilian popular housing program can be mentioned as one form of alternative construction systems in accordance to sustainable development. This alternative is fast, cheap and generates almost no waste in low cost construction.

Such a light concrete is obtained by introducing air bubbles in conventional mortar. It uses a moulding process in the housing site with all the framework components and electric and hydraulic fittings built in, allowing to make 1 unit a day per framework.

Cellular Concrete is used to fill the moulds as well as the welded wire netting wall reinforcement, allowing the use of slabs for either the floor or the roof. It is important to observe that this is a highly competitive alternative, having a 2 men.hour/m² productivity, at a cost of $90 US /m² with a scale of 1 house/group of mould/day.

Some preliminary pictures of the initial steps of a local ongoing housing program being carried out with success in Brazil can be seen in Figures 44, 45 and 46.
This type of project has a very important concept, since it introduces a high level of integrated partnering between different industrial segments involved in these construction (concrete, hydraulic, electrical, windows, etc.), which is not usual in such social projects. The quality of the products used is very good and served as the basis for further improvements and there are some attempts to improve landscape although still not enough. Also the typology of the houses could be improved.

The issue of sustainability is, however, not only linked to low cost constructions, but rather extended to overall construction. From a sustainability point of view, harmony must exist between the various factors involved in the constructive chain, among others its socio-economic...
and environmental impact. The main items to be considered must take into account comfort and maximization of space, swiftness in execution, safety, durability, low maintenance cost, preservation of non-renewable natural resources and mitigation of pollution, besides accessible final prices. Bonanni et al. [2000] proposed the following objectives for construction and building under a sustainable perspective:

- Reduction of the length of time of construction;
- Reduction of production costs;
- Reduction of waste and environmental pollution;
- Reduction of construction and work;
- Reduction of construction and work-related operation;
- Increased project productivity
- Reduction of operation and maintenance costs;
- Reduction of energy consumption during operation;
- Increased comfort for users.

A further very important alternative for sustainability in civil construction is the use of precast elements in buildings. The use of precast elements greatly reduces waste during building construction. Nowadays, precast concrete stairs, windows and many other alternatives for low-cost housing can be found as well.

8.5 Advantages of Concrete Use in Paving

The road sector represents an excellent market opportunity for the cement and concrete industries and also an important area for contribution toward sustainability. In all countries, road transportation is a key factor of economic activity and industrial competitiveness, and some data concerning the road scenario are shown in Table 14 [Restrepo, 1997]. Moreover, with accelerated urban development, the need for infrastructure has been growing, intensive maintenance and rehabilitation is required, especially in developing countries where the highest population growth and urbanization rates can be found.
Table 14: ROAD PAVEMENT SCENARIO IN SOME COUNTRIES

<table>
<thead>
<tr>
<th>Country</th>
<th>Population $10^6$ inhabitant</th>
<th>Road Extension $10^3$ km</th>
<th>Paved (%)</th>
<th>Road density m/inhabitant</th>
</tr>
</thead>
<tbody>
<tr>
<td>U. Kingdom</td>
<td>56</td>
<td>387</td>
<td>100</td>
<td>6.9</td>
</tr>
<tr>
<td>Italy</td>
<td>57</td>
<td>304</td>
<td>100</td>
<td>5.3</td>
</tr>
<tr>
<td>Germany</td>
<td>81</td>
<td>636</td>
<td>99</td>
<td>7.8</td>
</tr>
<tr>
<td>France</td>
<td>57</td>
<td>811</td>
<td>92</td>
<td>14.3</td>
</tr>
<tr>
<td>Sweden</td>
<td>9</td>
<td>135</td>
<td>72</td>
<td>15.8</td>
</tr>
<tr>
<td>USA</td>
<td>250</td>
<td>6280</td>
<td>89</td>
<td>25.3</td>
</tr>
<tr>
<td>Mexico</td>
<td>81</td>
<td>244</td>
<td>35</td>
<td>3.0</td>
</tr>
<tr>
<td>Brazil</td>
<td>150</td>
<td>1.504</td>
<td>10</td>
<td>10.3</td>
</tr>
<tr>
<td>Chile</td>
<td>13</td>
<td>80</td>
<td>14</td>
<td>6.0</td>
</tr>
<tr>
<td>Japan</td>
<td>124</td>
<td>1.113</td>
<td>71</td>
<td>9.0</td>
</tr>
<tr>
<td>India</td>
<td>850</td>
<td>2037</td>
<td>49</td>
<td>2.4</td>
</tr>
<tr>
<td>Egypt</td>
<td>48</td>
<td>47</td>
<td>73</td>
<td>1.0</td>
</tr>
<tr>
<td>South Africa</td>
<td>31</td>
<td>182</td>
<td>30</td>
<td>5.9</td>
</tr>
</tbody>
</table>

Urban paving should be more judiciously considered, and not only in terms of materials selection, such as rigid or flexible pavement, but also in terms of strategy and criteria for selecting them, in which case each one could provide the best cost/benefit performance, including: maintenance impact on local traffic, cost and budget availability, traffic volume and characteristics, available technology, durability, local pollution levels, improved safety for users (pedestrians and drivers), extension and localization of the work, etc. It is not acceptable that the traffic be impaired too frequently by successive pavement maintenance work, causing further problems. Concrete pavement can contribute to reduce such problems. Nevertheless, if the use of concrete in urban paving is not well planned, as well as the choice of available current technological developments, a great part of potential advantages may be offset.

The more vulnerable situations where concrete pavements could perform better than asphalt pavements in urban areas are listed below [Marciano 1999]:

8-21
- Bus corridors and terminals;
- Bus stops;
- Stretches under viaducts;
- Main arteries of the road network (avenues with high flows of cars or trucks);
- Intersections of avenues with high traffic volume, as already done in New York city;
- Central area streets with high vehicle density and where traffic deviation is difficult;
- Access or exit to highways or main arteries;
- Darker areas with high incidences of casualties.

The use of concrete pavement in these cases would undoubtedly bring many advantages for cities. A better traffic flow could be achieved, as well as a decrease in the emissions of gases in critical areas (there is an increase of 20 percent in emissions during traffic congestion), less human stress and less lost hours and money. A truck stopped in a traffic jam, for instance, means a $1 US/min loss [O Empreiteiro 1996]. With a more uniform pavement with less corrugation and holes, the risk of accidents and car breakdowns would drop. Braking on concrete pavement is also safer and could ensure less accidents and injuries.

From the material point of view, concrete shows greater technological and environmental advantages than asphalt [Pitta et al, 1999], being much more durable and less polluting than asphalt. From the point of view of initial costs, a key market issue, it is becoming more and more competitive, since in the longer term (more than 7 years) it shows better and easier to prove competitiveness due to higher durability, less required maintenance, among other reason already mentioned. Unfortunately, there is often the option for short term lower costs as main paving alternatives at the expense of the longer durability criterion.

Concrete pavement has some technological and environmental advantages over asphalt pavement:

- The life cycle of a rigid pavement varies between 25 to 40 years and may exceed it, even under heavy traffic volume conditions, while the maintenance of a good flexible pavement will usually start during the 5th year of operation;
- Durability 3 to 6 times higher than asphalt [L’Industrie du Ciment et du Béton du Québec 1994];
- Each 4% of maintenance of a rigid pavement network corresponds to 14% of flexible pavement maintenance [L’ Industrie du Ciment et du Béton du Québec 1994];
- Higher resistance of concrete pavement against degradation due to oil or gasoline spills, with asphalt pavement being much more sensitive to this problem;
- Rigid pavements show less deformation and therefore promote a better performance for heavy vehicles with a fuel savings amounting to 20% [Zaniewski 1997];
- Electrical energy savings of 30% due to better reflection of light on a lighter concrete surface [L’ Industrie du Ciment et du Béton du Québec 1994];
- Rigid pavement allows to reduce the thickness of the foundation, therefore saving natural aggregates;
- Roads with paving problems may increase the operational cost of vehicles by as much as 38% and impact transport costs by about 18%.

The lighter surface of concrete pavement compared to asphalt pavement significantly contributes to reduce the temperature by 3 to 4 °C in the surrounding area, especially when combined with a good landscaping program [Hawken, 1999]. The use of concrete pavements therefore is especially recommended in hot climate areas.

Whitetopping, the use of a layer of high strength concrete over an asphalt pavement, is an alternative to improve pavement efficiency and should be considered in several cases, especially in large cities where the volume to be paved is high and the inconvenience for users should be minimized.

In the field of high performance roller-compactd concrete, researches must continue and due to its characteristics can be a more suitable alternative from an economical point of view. High performance roller-compactd concrete seems to be one of the most promising alternatives because it can be adapted more easily to the existing local culture and asphalt paving machinery.
Finally, the use of recycled concrete should be seriously considered in urban paving as a base or sub-base material, keeping in view the great volume generated, especially in the megacities. It is a pity to dispose of concrete waste in landfills considering its good intrinsic properties and the extra cost for its transportation, without bringing any benefit. Frequently, the waste material generated comes from demolition work due to the spreading of their own road infrastructure network to satisfy growing traffic needs. It seems that a good part of this material could be used on site after a convenient treatment.

8.6 Further Sustainable Uses of Concrete

In order to provide some applications of concrete that may contribute to sustainability, it would be interesting to discuss some important issues and provide practical examples.

Precast elements can also be used in sky-scraper facades; replacing some ornamental stones such as granite; as can be seen in Figure 47. The replacement of ornamental stones by concrete presents environmental advantages since it provides a very good appearance without further use of rarer natural rocks, and making the whole structure lighter. The main problem, at least in developing countries, is the cost of the equipment to lift big precast units. There are also a lot of potential uses of light precast elements for replacing ornamental stones, such as blocks and paving blocks because they have the same esthetic characteristics, more flexibility and can be a good alternative to contribute to architectural improvement, the restoration of old sites, re-urbanization, etc. An application of architectural precast panels can be seen in Figure 48.
Figure 47: Concrete ornamental facade

Figure 48: Concrete blocks used to replace natural stones

Another important issue to be considered in sustainable uses of concrete, which is often neglected, is related to the construction of sidewalks. It contributes to preventing injuries, improves the esthetics of the city, reducing visual pollution, and therefore, stress. It is not
acceptable to make sidewalks with low quality concrete that will resist only one or two years or even less (Figure 49). A good sidewalk network also contributes to increasing the mobility of handicapped people, inserting them in society as well as that of consumers. Sidewalk must be built with a convenient declivity slope in order to allow handicapped people in wheel chairs to use it (Figure 50). Skid materials should be avoided and durability must be ensured in order to achieve 30-years life span. Instead of using natural stones, concrete blocks can be used, providing high durability at affordable prices and contributing to a more pleasant scenario in the city (Figures 51 and 52).

Figure 49 : Low durability sidewalk

Figure 50 : Sidewalk with convenient slope

Figure 51 : Ornamental interlocked concrete blocks used in a sidewalk contributing to a more pleasant environment.
Figure 52: Use of concrete blocks to improve the urban environment.

The great workability of concrete also allows to make interesting artistic wall designs to provide a more pleasant environment, as can be seen in Figure 53.

Figure 53: Interesting design of a concrete wall

Equally important is the circulation on bridges and viaducts. An increased durability for these structures must be provided in order not to impair the traffic flow with frequent
maintenance works. When a lane has to be closed for maintenance, the work must be carried out as quickly as possible in order to minimize the risks of accidents and prejudice to users.

The use of HPC, with its intrinsic low permeability and higher initial and final strengths, is very convenient for bridges and viaducts, reducing even the aesthetic pollution caused by vehicle emissions. As HPC having low porosity, the impregnation in the concrete by the released high amount of vehicle particle emissions in urban areas will be correspondingly lower. The concrete will keep a lighter color during the life span of the structure, when compared to the same structure using concrete with lower performance. The appearance of a “dirty structure” will be not so remarkable as usually seen in urban areas.

The American road network has many structures built with conventional concrete that experienced accelerated wear due to steel bar corrosion and resulted in additional costs and lower life cycles for these structures [Ozyildirim 1993]. In Canada and the U.S., the number of bridges built with HPC has been increasing, providing cost savings; and are being recommended for durable infrastructure works [Bickley 1996].

Concrete is also often used in the cattle-raising industry (Figure 54), in different ways. The use of HPC should, however, be more judiciously evaluated considering the advantages it provides. Due to its much lower intrinsic porosity, compared to conventional concrete, the presence of bacteria in pores is reduced, and an easier and more efficient cleaning of the facility is achieved, consequently the incidence of animal diseases is significantly reduced. Moreover, due to HPC's higher strength, floor durability is enhanced reducing the risk of animal injury, which frequently occurs when using conventional concrete.
At the Manchester airport, the use of aerated panels made of concrete reduced radar distortion from the terminal building [Clarke and Sommerville, 1992]. It could also be a good alternative to reduce noise in subway tunnels in order to improve the comfort of users. Concrete acoustic barriers can also be useful in reducing high noise levels (Figure 55), such as airport areas or road vicinity. The use of recycled concrete could be especially useful in making sound barriers, since these barriers don’t require major structural loads, they consume high amounts of waste and they add a social contribution to a waste use by a practical application in reducing noise.
The use of RPC for interim storage of nuclear waste is a further non conventional attractive possibility, due to its excellent microstructural properties, including a very low porosity which diminishes mass transfers. These characteristics are of great interest in the design of High Integrity Containers (HIC). These containers should be designed for long durability (300 to 500 years) and for a drop-resistance limitation of about 5 meters. Matte et al. [1998] mention the preliminary performance in the use of RPC for type B wastes (low and medium activity wastes containing long half-life radionuclides) superior to any other cementitious material.

8.7 Conclusion

Concrete is undoubtedly an essential material to satisfy the high demand for infrastructure for a long time. The technological progress in concrete technology have been remarkable, there is a large spectrum of concrete types available, but sometimes such technological achievements are lost due to a bad use of concrete or due to the low quality of the labor force.

From a sustainability point of view, it is absolutely necessary to enhance concrete performance and use. It is necessary to save money, to have an impact on the environment that is as low as possible and urgently solve social needs. At the same time, life quality must be improved by reducing stress, visual pollution, unnecessary maintenance costs of houses and buildings, and even reducing violence, creating employment and a more pleasant atmosphere in the urban scenario or in the buildings. The use of concrete alone will not promote such improvements, but its optimized use can significantly contribute to reach these goals.

The first step in the sustainable use of concrete is to improve its durability. It can be reached by the suitable selection of materials (aggregates, cement) and mainly by lowering the w/c ratio. With lower w/c ratio concrete, porosity is reduced so that concrete has a much higher resistance to aggressive environments (Cl⁻ and SO₄²⁻ attack for instance, biological attack, corrosion, etc).
With a lower w/c ratio; it is also possible to improve concrete strength. Conventional concrete with strengths around 10 to 20 MPa have w/c ratios around 0.70 to 0.80, implying a waste of quality and performance.

The use of concrete admixtures also contributes to improve concrete properties and durability. Admixtures will be more and more used in the future. Superplasticizers, retarders, accelerators, and air-entraining agents are among the potential admixtures to be more widely used. Air-entraining agents contribute not only to minimizing freezing and thawing problems but also to improve concrete deterioration by hindering the propagation of cracks, a property it was not initially designed for.

For structures such as bridges and viaducts, High Performance Concrete is an excellent alternative to enhance their lifespan. HPC can also be also used for paving, for instance as whitetopping as a quick alternative, and Roller-Compacted Concrete is also a very promising option.

For buildings, the traditional use of 15 to 20 MPa strength concrete must change. The use of at least 30 MPa concrete is somehow easily achievable and would result in much less maintenance for users and better aggregates to be recycled at the end of their operation phase.

Combined use of different strength concretes in building construction, according to the functional performance (wall, foundation, slab, stage level, etc) must be targeted. It is easier to build with the same concrete, but although requiring better management and logistics, the combined use of different strength concretes can be better for owners and cheaper for entrepreneurs.

The increased use of precast elements in construction can provide a significant contribution in terms of waste reduction. The replacement of natural ornamental stones by concrete blocks can also contribute to save natural raw materials. We presently have the technology to make beautiful replacement materials for skyscrapers or for houses.
For low cost dwellings, it seems that Cellular Concrete represents a good alternative, providing almost no waste, good thermal and acoustic behavior, low cost and fast execution. A synergetic commitment within the chain involved in low cost construction can allow the use of better products without increasing prices. It must be kept in mind that low-cost housing cannot be synonymous to low quality materials. The apparent initial advantage will be completely offset by long term maintenance and repair costs, also leading to a short life span and even sometimes requiring the reconstruction of the dwelling. It is highly recommended to provide a good landscaping program for these buildings as well as a good typology in order to stimulate the conservation of the building and natural resources, a concern that is becoming more and more evident.

Improving the comfort and quality of mobility of drivers and pedestrians is also a further sustainable requirement. The use of concrete paving can carry an initial higher cost, but the advantages for users are remarkable since it demands much less maintenance, with less impact on traffic flow. Concrete paving is safer, clearer and therefore results in lower temperature in the surrounding area, a useful property, especially in hot areas. On the other hand, sidewalks must be built with concrete of higher strength, around 30 MPa, they must have an increased durability; promoting the mobility of pedestrians and handicapped people and creating a more pleasant visual impression in the urban scenario.

The waste of concrete must be reduced, placing and curing of concrete must be optimized as well as improving workmanship. The implementation of ISO 9000 accreditation in construction companies would be a suitable alternative for reducing this problem, especially due to the fragmented nature of the concrete industry.

The creation of site management programs can be very useful, as well as the implementation of a broad and intensive program for labor force qualification, especially in developing countries.
Finally, it is very important to promote concrete recycling in order to mitigate the use of natural aggregates as well as the need to dump concrete waste, simultaneously solving two environmental problems.
9 FINAL DISCUSSION

9.1 General Issues

Sustainable development is a transitory process, committed to promote an equilibrium between consumption, a fairer distribution of income and a lower environmental burden. Sustainable development should also lead to reducing the ever-growing social stresses worldwide and the danger for climate change. It is a time of changes, adjustments and opportunities toward social equity. When focusing exclusively on climate change, some important components regarding sustainability such as social, economic and industrial issues are frequently neglected or considered in a fragmented way. Indeed, it is necessary to know and understand the whole process that affects life quality in order to take the right measures to achieve pragmatic goals.

The health of the economy is experiencing a difficult period worldwide. The current unstable stock markets, due to scandals and abusive speculation, emphasizes the need to move from volatile to productive investments. At the same time, there is an urgent need for infrastructures, buildings or renovations to satisfy basic social requirements, for employment generation, to provide alternatives that ensure the survival of small and medium-sized companies, and to promote a better income distribution and more productive investments instead of only speculative investments. All these components must be achieved in harmony with our ecosystem. So far we have not been very successful in this process. Furthermore, history has proven that, in periods of recession, investment in civil construction is the best alternative to keep the economy moving. In such a context the cement and concrete industries have a key role to play for many years to come.

The concrete, and consequently, the cement industry fulfill several of the sustainable needs in our societies. The cement and concrete industries greatly contribute to productive investments and job generation, with large applications in general constructions, besides providing great contributions to alleviating the environmental burden caused by other industrial sectors. Nevertheless, many people have been focusing mainly on the polluting nature of cement production and the low technological added-value of concrete, inducing the public to develop a negative perception about both industries. This image is reinforced by the lack of good
communication provided by the industries themselves. The technological progress that has been achieved, the environmental contributions provided by the cement industry and the social role played by the concrete industry are too often ignored. These industries still have a significant environmental impact and some progress to achieve, but the great efforts already made and the progresses achieved should be recognized in order to deal with existing conditions to make the use of concrete even more sustainable than it is presently.

9.2 Proposal of a Schedule for Implementing Sustainable Alternatives

The production of green products should be perceived as a concept basically associated with good practices carried out with sensitivity and ethics, that will provide a profit for companies and society, in a win-win path. Contrary to what could be expected, being sustainable is not necessarily costly, but can be rather an opportunity to improve the profit margin and a contribution for the whole of society.

Indeed the meaning of green cement should be translated by good and profitable cement production while green concrete should represent high social and technological added value.

In the cement industry, current environmental issues have begun to be solved, although in an unconscious way, as a consequence of the efforts and the synergy developed between cement groups and machinery and equipment suppliers. Ever-growing stringent anti-pollution regulations have required a substantially increased investment from the industry, with dust collecting facilities, for instance, currently representing 10 to 15 percent of the construction cost of a plant. Energy savings, pollution mitigation and higher production output were almost compulsory alternatives to survive in a more and more competitive market.

The following goals were achieved over the last 20 years:

- conversion from wet to dry process;
- increase in the use of preheater and precalciner systems;
- improvements in burners and in more efficient cooling systems;
- use of expert systems;
- high automation;
- use of more efficient electrofilters and dust collectors;
- improvement of refractory lining;
- prehomogenization of raw meal and better performance homogenization silos;
- multichamber silos;
- closed circuit mills, vertical mills and hybrid systems with roller and ball mills;
- last-generation dynamic separators;
- valorization of industrial by-products from other industrial sectors;
- partial replacement of fossil fuel by waste-derived fuel or alternative fuels from several segments of the industry.

In order to enhance even further the sustainable production of cement, the following main steps are proposed, according to their complexity:

- **Short term goals (two years)**

  The first and fundamental step to reach a sustainable production it is the optimization of existing facilities. Such a process can be achieved by implementing preventive mechanical maintenance programs (control of kiln ovality, burner wear, and burner design, etc.), by improving energy consumption efficiency through a better control of simple parameters such as prevention of false air entrance due to improper kiln sealing or open inspection doors, adequate atomization of fuel oil or coal fineness, suitable adjustment of primary air (amount and speed), improvement of cooler efficiency to increase secondary air temperature, a good and stable flame, etc.

  The second step would be the improvement of the raw meal burnability without major investments. Adequate dosing of raw materials, preventing unnecessary high LSF or SM, and therefore a raw meal that is difficult to burn, as well as providing a good and stable protective coating in the burning zone of the kiln, are recommended practices. The replacement of coarse quartz grains from sand or clay, by finer fly ash, the use of mineralizers, such as small amounts of
fluorine when available, or the use of slag to replace limestone as a raw material are also useful alternatives. The use of a water reducer in the still existing wet process kilns may also represent some energy savings.

The maintenance and optimization of grinding units is a further key issue in order to save electrical energy, often expensive and scarce. Moreover, this alternative will contribute to manufacture a better cement with higher performance (by improving cement strength, reducing water demand, preventing false set and pack set, by adjusting and optimising SCM amount, and sometimes “correcting” the production of a bad clinker for instance), that will contribute positively to enhance the durability of structures made with concrete.

The implementation of quality control systems, such as ISO 9000, and the implementation of training programs are also helpful procedures.

These are general recommendations for any cement plant, but especially for old cement plants that have no expert systems available. By implementing these alternatives, it will be possible to save money that could be reinvested in the upgrading of the cement plant with more up-to-date technologies

- Medium term goals (up to 5 years)

There are many options to be implemented in such a time span. The first is a higher use of waste-derived fuels for replacing non renewable fossil fuels. This alternative is profitable for the cement producer and represents an enormous contribution to alleviating the environmental burden worldwide. Ideally, a 15 percent replacement of fossil fuels worldwide could be a feasible target, although the higher the substitution, the greater the contribution for the environment and the better the return on investments made by the cement producer (higher logistic requirement, stocking facilities, more sophisticated environmental equipment for control and follow-up, etc.).

As the magnitude of the impact of waste generation on the environment requires urgent solutions, the existing favorable conditions found in a cement kiln will certainly extend this
contribution of the cement industry to the global environment for many years. The potential contribution of cement kilns is remarkable, even autoclaved powder from “mad cows” have been burnt in France and Portugal with the support of the local government. Some dangerous and hazardous wastes (CFC for instance) have also been burnt in cement kilns, sometimes for short periods [Sutoh et al., 1996]. Although some experiments with urban wastes have been carried out, it seems difficult presently to burn them in cement kilns due to inherent difficulties such as: high humidity, heterogeneity and deleterious components. On the other hand, old tires, which constitute a great environmental problem, have been and are burnt in cement kilns, which represents a good solution to minimize the impact of their elimination. The major challenge has been the long delay to obtain an environmental permit for burning waste. Potential problems caused by the waste to the process must be taken into account, such as preheater blocking and accelerated wear of the refractory lining, among others.

The second option is the production of blended cement by using by-products largely generated by other industrial sectors and mainly disposed of. Among these by-products, the two most important are fly ash from power stations and blast furnace slag from the pig iron industry.

The use of these industrial by-products in the cement industry is already well known and highly developed in several countries. This alternative allows to save large amounts of fossil fuel and raw material, to mitigate great amounts of CO₂ emissions and to add technological benefits for the resulting cement and its further use in concrete (enhanced durability against sulfate and chloride, lower heat hydration, better resistance against alkali-aggregate reaction, etc). The main problem in several countries has been the difficult and slow pace of changing attitudes and the adjustment of standards to allow the use of these mineral components. A further limiting issue to be considered is the impact of freight costs from the generating source to the cement plant because freight costs can lead to prices higher than those of the clinker, offsetting economic benefits and adversely impacting the use of these materials.

In many countries, a good alternative to produce blended cement in a sustainable context would be the use of calcined clay as a pozzolanic material. A clay containing over 50 percent kaolinite can already be conveniently used, after burning, as pozzolan. The higher the amount of
kaolinite in the clay, the better its technological performance. High purity kaolinite clays can be used to obtain high technological and economical products. The amount of energy consumed, as well as the decrease in the CO$_2$ emitted, are advantageous when replacing some clinker in cement by calcined clay, due to the much lower temperature required (900°C for calcined clay compared to 1,500°C for clinker) and due to the absence of CaCO$_3$ to be decomposed in the calcined clay.

The use of limestone filler as a supplementary cementitious material contributes to save thermal and electrical energy and to mitigate emissions, but not to save raw materials. It is a simple and easy alternative for cement producers, besides contributing to improve concrete workability.

Further alternatives that contribute to a sustainable cement production are more costly but still reasonable. Implementation of expert systems, more efficient coolers, use of low NOx burners, modern homogenization silos, good conveyors for materials transport, lower-energy and lower-noise vertical mills for raw materials, better grinding units and high efficiency separators for final grinding, among others. They represent a step forward toward a sustainable production, reducing energy consumption, noise, dust generation, mitigating emissions, providing in some cases a better logistic in the plant and contributing to getting a final product with a better performance.

The production of low energy cement, either by using mineralizers or producing high belite clinker is a sustainable contribution. Indeed, the production of a clinker having a high belite content would be especially recommended for cement plants having problems regarding the life cycle of their limestone quarry, despite the higher electrical energy consumption required. Both alternatives could lead to a significant energy saving as well as emissions mitigation.

The previously mentioned possibilities will be almost compulsory for a sustainable cement production, since they are simple, effective and profitable.

- Long term goal (up to 10 years)
A long term goal is more complex and must take into account major economic investments, changes in logistics and overseas management which have an impact on each local economy. Payback is a main concern that must be considered.

To achieve a sustainable cement production it will be necessary to change from old technology cement kilns (shaft kiln, wet or long dry kilns) to modern preheater and precalciner kilns in order to save energy, mitigate emissions, and in some cases, produce a cement with a better performance. Some of the old kilns could be preserved for the production of high added-value cement (oil well cement, for instance) or for very low market demand. Under certain circumstances, such as high levels of waste burning, older kilns could also be preserved keeping in view such potential intrinsic environmental added value production.

In several countries, the incidence of up-to-date cement plants is already high, often responsible for over 95 percent of cement production. However, in other important cement producing countries, the incidence of old technology kilns is still significant, as is the impact on the environment. Among these countries, China and the U.S. are the most important and a change toward a more modern technology will lead to a significant contribution to the environment by the cement industry in global terms.

An alternative to optimize the cement production in these countries is to replace some old technology kilns by a modern cement plant with a network of grinding units, served by this plant, and conveniently distributed according to local demand and exportation potential.

It is important, however, to promote these technological changes according to a pragmatic and feasible schedule in order to carry out the necessary changes without causing significant impact on the local economy. This transition period will be necessary for the required adjustments.

To reduce the impact of their shutdown, some deactivated old kilns could be used for the production of pozzolans from burnt clays. The environmental benefits could be even higher if
pozzolans could be produced from contaminated soils, for instance. These old kilns could also be used to produce low energy cement, especially high belite cement.

*Table 15* shows some alternatives to save energy and mitigate the CO₂ emissions, based on the consulted literature, as well as further comments about each one, based on personal experience.
<table>
<thead>
<tr>
<th>Alternative</th>
<th>CO₂ reduction</th>
<th>Energy saving</th>
<th>Non renewable materials saving</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet kiln: 1% water reduction of the sludge</td>
<td>1%</td>
<td>1-2%</td>
<td>• Fossil fuel • Small amount of water</td>
<td>Restricted application due to the limited amount of wet kilns worldwide</td>
</tr>
<tr>
<td>Switch from wet to modern dry kiln</td>
<td>20-25%</td>
<td>40%</td>
<td>• Fossil fuel • Some amount of water</td>
<td>Highly effective but mainly for local application • Harder to implement due to high costs and dependence on the market situation • Increase of production output</td>
</tr>
<tr>
<td>Preheater: 4 to 5 cyclones</td>
<td>2%</td>
<td>4%</td>
<td>• Fossil fuel</td>
<td>Medium cost alternative</td>
</tr>
<tr>
<td>Preheater: 5 to 6 cyclones</td>
<td>1%</td>
<td>2%</td>
<td>• Fossil fuel</td>
<td>Medium cost alternative</td>
</tr>
<tr>
<td>New coolers</td>
<td>Up to 5%</td>
<td>Up to 10%</td>
<td>• Fossil fuel</td>
<td>Medium to low cost alternative</td>
</tr>
<tr>
<td>False air in the kiln system</td>
<td>1-2%</td>
<td>3%</td>
<td>• Fossil fuel</td>
<td>No or very low investment • Recommended in any circumstance being profitable for the plant • General application</td>
</tr>
<tr>
<td>Shaft kiln change to modern dry kiln</td>
<td>25%</td>
<td>40%</td>
<td>• Fossil fuel</td>
<td>Much higher production output • More uniform clinker production • Requires market demand</td>
</tr>
<tr>
<td>Expert system implementation</td>
<td>1-2%</td>
<td>3%</td>
<td>• Fossil fuel</td>
<td>Relatively low cost and profitable for the industry in the medium and long term • More uniform production and final product • Production increase of around 4% • Reduction in product variation • 15-30% less refractory wear</td>
</tr>
<tr>
<td>Optimization of raw material burnability</td>
<td>2-3%</td>
<td>4-5%</td>
<td>• Fossil fuel</td>
<td>General application in cement plants • Limited application by available facilities • Better performance of the final product • Easier grindability of the resulting clinker • Low to medium costs depending on cement facilities</td>
</tr>
<tr>
<td>Mineralized cement</td>
<td>2-3%</td>
<td>5-6%</td>
<td>• Fossil fuel</td>
<td>30% less grinding energy • Possibility of using higher amounts of by-products • More sensitive regarding compatibility with admixtures for HPC production</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>%</td>
<td></td>
<td></td>
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<tr>
<td>------------------------------------</td>
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<td>--------------------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| High belite cement                 | 15% | 15-20%        | Fossil fuel                    | • Depends on availability of a source of fluor near the plant but advantageous when using a waste as a source of fluor  
                                |     |               | Limestone (5-10% less)            | • Increased life cycle of the refractory lining                                        |
| Slag as raw material               | 0.5% for each 1% slag | 0.5% for each 1% slag | Fossil fuel                    | • 20% output increase  
                                |     |               | Limestone                       | • Higher electrical energy consumption  
                                |     |               | Bauxite or clay                  | • Lower initial strength  
                                |     |               |                                | • Higher durability for the resulting concrete  
                                |     |               |                                | • Limited possibility of using by-products  
                                |     |               |                                | • Increase in the life cycle of the high quality limestone portion of the quarry    |
| Fly ash (FA) as raw material       | 1% maximum | 1% | 1% sand for each 1% FA | • 1% production increase for each 1% slag  
                                |     |               |                                | • Can be used as a source of Al₂O₃ or even of SiO₂ contributing to better coating development |
| Blast Furnace Slag use for blended cement production (up to 80%) | 1% for each 1% slag | 1% for each 1% slag | Fossil fuel                    | • Higher electrical energy consumption  
                                |     |               | Limestone                       | • Lower initial strength  
                                |     |               | Sand or clay                     | • Higher concrete durability  
                                |     |               |                                | • General application, limited by local technical standards and also by the impact of cost and freight |
| Fly ash (FA) for blended cement production (up to 50%) | 1% for each 1% fly ash | 1% for each 1% FA | Fossil fuel                    | • Lower initial strength  
                                |     |               | Limestone                       | • Higher concrete durability  
                                |     |               | Sand or clay                     | • Enhanced concrete workability  
                                |     |               |                                | • General application, limited by local technical standards and also by the impact of cost and freight |
| Metakaolin production              | 80% | 50%           | Fossil fuel                    | • Depends on kaolin deposits availability  
                                |     |               | Limestone                       | • The purer the kaolin deposit the better the technological properties and the higher the amount of clinker that can be replaced |
| Limestone as additive in cement (usually up to 10%) | 1% for each 1% limestone | 1% for each 1% limestone | Fossil fuel                    | • Lower electrical energy consumption  
                                |     |               | Sand or clay                     | • Lower initial strength  
                                |     |               |                                | • Better concrete workability  
                                |     |               |                                | • Higher consumption of limestone    |
| Clinker composition optimization   | 1%  | 2%            | Fossil fuel                    | • Better final performance of cement  
                                |     |               | Limestone minor amounts          | • Improved clinker grindability, with lower electrical energy consumption |

9-10
| Use of waste-derived fuel | 1% for each 1% replaced | None | Fossil fuel | • General application but with restricted results depending on the plant and the raw material characteristics  
• Difficult to get environmental permit  
• Often the waste source is far from the cement plant  
• Waste transportation is a source of concern  
• Very high environmental added-value alternative |
| Gas use | 43% less than coal 48% less than pet coke | None | Fossil fuel | • Lower availability compared to other fossil fuels  
• May cause problems when raw materials have high alkali contents |
| Coal use | slightly increased compared to oil and gas | None | • Partial replacement of sand or clay | • Higher availability among the fossil fuels  
• Available source but often not spread out in many countries  
• Often low quality coal available |
| Pet coke use | slightly increased compared to oil and gas | None | • Fossil fuel | • As a by-product can be advantageous compared to fuel oil use  
• Often has high S content demanding better operational control. Can be used for the production of mineralized clinker |
| Good refractory thickness and stable coating | 1-2% 2-3% | None | Fossil fuel | • Not costly, and brings economical advantages for producer  
• Reduces kiln shutdown and enhances the competitiveness of the plant  
• Saving of refractory bricks |

The saving of electrical energy is also fundamental for sustainability considering the cost of electricity which is frequently very high in many countries. Depending on the source used to generate this energy (water or thermal power station) it can also contribute to mitigate CO₂ emissions and fight potential local scarcity of water. In Table 16 shows some possibilities to reach lower electrical energy consumption, based mainly in the consulted literature.
### Table 16: ALTERNATIVES FOR ELECTRICAL ENERGY SAVINGS

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Electrical Energy Saving Reduction in Percent</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final grinding: open to closed circuit</td>
<td>20</td>
<td>• Higher output</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Better performance of the final product</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Necessary to achieve higher cement fineness</td>
</tr>
<tr>
<td>Switching from ball mill to vertical mill for cement grinding</td>
<td>Up to 30</td>
<td>• Lower space required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Convenient for good plant logistics</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Lower noise</td>
</tr>
<tr>
<td>Switching from ball mill to high pressure grinding roll system</td>
<td>40</td>
<td>• No moist supplementary cementitious materials</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Lower noise</td>
</tr>
<tr>
<td>Vertical mills for raw material</td>
<td>20</td>
<td>• Less space required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Convenient for good plant logistics</td>
</tr>
<tr>
<td>Switching from old to modern kiln</td>
<td>15</td>
<td>• Costly, depending on major investments</td>
</tr>
<tr>
<td>Modern silos</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Mineralized cement</td>
<td>30</td>
<td>• Also lower thermal energy consumption</td>
</tr>
<tr>
<td>Grinding aids</td>
<td>10</td>
<td>• Highly recommended for open circuit mill</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Energy saving includes also energy used for the separators and the transportation of the cement powder</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Possibility of output increase</td>
</tr>
<tr>
<td>Grinding unit optimization</td>
<td>5</td>
<td>• No cost</td>
</tr>
<tr>
<td>High efficiency separator</td>
<td>15</td>
<td>• Great improvement of the final performance of cement</td>
</tr>
<tr>
<td>Clinker optimization</td>
<td>1- 5</td>
<td>• Demands raw material fineness adjustments and burning residence time reduction</td>
</tr>
<tr>
<td>Expert system</td>
<td>3-5</td>
<td>• More uniform production</td>
</tr>
</tbody>
</table>
Table 17 shows some common alternatives to reduce NOx emissions generated during cement production, according to the whole consulted literature.

Table 17: POSSIBILITIES FOR THE MITIGATION OF NOx EMISSIONS

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Percentage in Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineralized cement</td>
<td>40</td>
</tr>
<tr>
<td>Wet/long dry kiln to precalciner kiln conversion</td>
<td>50</td>
</tr>
<tr>
<td>Preheater to precalciner kiln</td>
<td>15-20</td>
</tr>
<tr>
<td>Low NOx burners</td>
<td>15-30</td>
</tr>
<tr>
<td>High belite cement</td>
<td>30</td>
</tr>
<tr>
<td>Operating parameters</td>
<td></td>
</tr>
<tr>
<td>(flame adjustments, cooler, etc)</td>
<td>15-30</td>
</tr>
<tr>
<td>Gas to coal conversion (function of the type of kiln)</td>
<td>20-50</td>
</tr>
<tr>
<td>Slag as raw material (1% replacement)</td>
<td>2-4</td>
</tr>
</tbody>
</table>

It will probably much less costly to reach a sustainable production of concrete than sustainable production of cement, but the required time to implement them, and mainly to notice their benefits, will be surely longer.

In order to enhance the sustainable production and use of concrete, the following steps are proposed:

- Short term goals (up to 10 years)

The main alternative will be the training and improvement of the labor force and management on job sites in order to reduce wastage (cement bags opened, too high w/c used, inadequate thickness of concrete layers, etc.) and rationalize cement and concrete use. It must be taken into account, however, that self-construction is often the main procedure in developing countries, and consequently, it is necessary to reach this particular public by compatible and
specific ways. Training can be provided by institutions, unions, district associations, NGOs, etc., through easy-to-understand publications, TV, radio, etc. Considering that the people who will benefit from these campaigns are essentially low income earners without enough money to build or even maintain their houses, this alternative will optimize materials consumption, which is advantageous for the environment and for users who can save their scarce money.

For any official home building program addressed to low income earners, a paradigm has to be broken. These buildings are usually made with no or low concern about quality, at the lowest initial cost possible targeting essentially short-term solutions. It is necessary to change this attitude, otherwise they will only promote the transfer of these people from precarious shantytown to precarious concrete buildings, or even worst, creating vertical shantytowns. A durable building policy needs to find definitive or at least long-term solutions. For those that argue constraint budgets for not complying with such policy, marginal costs must be considered, such as premature maintenance and demolition, unnecessary waste, disposal of construction and demolition waste, health costs, and consequently, pressure on welfare systems, higher violence levels and higher expenses for security, among others. A serious commitment toward sustainable construction in these programs must consider:

- Use of durable materials, cement and concrete among them;
- Use of precast elements to accelerate construction and reduce waste;
- Implementation of a sanitation services network;
- Good typology for the constructions in order to maximize the use of natural resources (sun light, wind, etc) and provide a more pleasant environment;
- Affordable and innovative landscape implementation, respecting the local cultural heritage;
- Use of colored concrete blocks to contribute to a more pleasant environment
- Use of interlocked concrete blocks for paving.

The recycling of concrete must and can be quickly promoted in the years to come. The volume of aggregates used in concrete is high, and their availability is becoming scarce in many urban areas and as a consequence their price is increasing due to more stringent mining
regulations, longer hauling distances, etc. Therefore, the replacement of aggregates by recycled concrete is a necessary environmental alternative, but one that must be more competitive from a cost point of view, as well as from a quality point of view. As concrete is an environmentally friendly material, the generated waste is mainly a problem due to the volume rather than the danger it represents. In many countries, concrete waste is far from being considered a serious ecological solution. Governmental action alone, by organizing a better control and logistic of the collection and disposal of these wastes, together with economic incentives, will help promote a higher level of recycling. In small countries, such as Japan and many European countries, the scarcity of aggregates and the ever-growing increasing costs for disposal were the driving force to reach higher levels of concrete recycling. It must be emphasized, however, that the development of recycling equipment and machinery and special mobile machinery, may contribute to reduce costs of recycling and making recycled concrete a more attractive alternative to replace natural aggregates.

The use of precast elements will play a significant role in a near future, since the dismantling of whole structures or great parts of them for use in other works is an effective and promising alternative. The concrete precast industry has reached a high level of quality, performance and production swiftness, but its use must still increase in order to help reduce the wasting of cement and concrete.

A movement toward quality accreditation for small and medium-sized companies can have a high positive impact on concrete production, especially if it is considered that these companies are responsible for a great part of concrete production or consumption and often less concerned about performance and wasting.

- Long term goals (over 10 years)

The alternatives to improve durability are probably the long term key points for sustainability in concrete use. It is no longer acceptable to rebuild the same structure several times because it has a lower than expected life span. It is time to build durable structures well,
even at a higher initial cost, because the environmental and economic gains will be extraordinary. Concrete must last much longer than it currently does.

It is easy to see that providing a concrete having a higher durability, able to at least double the life span of present concrete structures, will decrease the material consumption by half in the same period. Besides, the demolished concrete, generated from a high quality concrete, will be much more suitable for recycling and aggregate production, with further environmental benefits. From an economical point of view it is also evident that if just minimal maintenance is required and major replacement or construction is postponed, for 50 years for instance, it will be much easier to find the resources in scarce budgets to make further works of social nature. Financial resources should be allocated simply as a commitment to reach the highest performance for the infrastructure to be constructed.

The prevention of premature concrete deterioration is essential. The prevention of AAR, of sulfate attack and of steel bar corrosion, probably the main sources of accelerated concrete wear, can be easily avoided by convenient selection of the cement, adequate analysis of the aggregates, convenient thickness of steel bar cover and good concrete practice (dosing, curing, placing).

A further significant contribution for sustainability would be water saving. Global water scarcity is becoming a bottleneck to promote progress and one of the main concerns of our society in the near future. Any possible saving of water is essential. For countries where water scarcity is especially dramatic, the use of water reducers, higher use of roller-compacted concrete, the optimization of conventional concrete production by reducing the w/c ratio, the recycling of water from concrete production, truck and concrete mixer washing for instance, could help save precious water.

Concrete paving is an additional alternative that must be implemented in a sustainable scenario and more frequently used. The economic benefits are evident, such as four times lower required maintenance than asphalt, 20 percent less fuel consumption for heavy vehicles, much lower incidence of broken vehicles [Pitta et al, 1999]. It is safer for users and pedestrian, since it is easier to brake on a concrete surface, it surface is clearer and there is no corrugation that may
lead to accidents. In a majority of countries, cement is a local product that can be used as the material basis for paving, while petroleum is often an imported product, very costly for several countries. From an environmental point of view, materials savings will be achieved due to the extended life span of 30 years, in contrast to the maximum of 7 years for asphalt [Pitta et al., 1999]. Besides, concrete paving will help to reach a significant decrease in CO₂ emissions from vehicles, due to a better car flow and lower incidence of traffic congestion. The fuel savings from heavy vehicles also contribute to mitigate emissions. Considering the higher abrasion resistance of concrete compared to asphalt, less dust will be released from the pavement. The main problem of concrete paving is the noise originating from joints, especially at high speeds, and this issue should be solved. However, the main advantages for society are related to the lower number of lost hours for users, reduced stress and therefore higher productivity, which usually has an estimated impact on the economy as high as 1 to 2 percent of the GNP and any alternative to reduce it must be taken into account. Concrete paving can also contribute to reduce the vicinity temperature in hot climate areas, providing some energy savings and CO₂ mitigation associated with less air conditioning requirements. According to Hawken [1999], an urban forestry program combined with lighter colored paving and building surfaces in Los Angeles could provide a drop in temperature of 3 to 4 °C, reducing the city’s cooling load by 20 percent and the smog by 12 percent, which corresponds to a $500 million US saving/year.

In Table 18, some alternatives for a more sustainable concrete production are presented and proposed.
**Table 18:** POSSIBILITIES FOR ACHIEVING MORE SUSTAINABLE CONCRETE PRODUCTION AND USE

<table>
<thead>
<tr>
<th>Action</th>
<th>Benefits</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Environmental</td>
<td>Economic</td>
</tr>
</tbody>
</table>
| Reduction of wasting | essential | essential | • Better skilled management required  
|                      |           |           | • Better labor force required             |
| Durability increase  | essential | essential | • Project for medium and long term life cycle  
|                      |           |           | • Paradigm of initial low cost to be broken |
| Use of HPC           | high     | high     | • Gain of construction space in dense cities  
|                      |           |           | • Saving of aggregates                     |
|                      |           |           | • Lower visual pollution                   |
|                      |           |           | • Great application in paving               |
|                      |           |           | • Good potential for use in the cattle raising industry |
| Use of RCC           | high     | high     | • Lower cost                              |
|                      |           |           | • Possibility of using high amounts of fly ash |
|                      |           |           | • Great potential for paving               |
|                      |           |           | • Use on industrial yards and farms        |
|                      |           |           | • Horizontal silos                         |
| Use of SCC           | medium   | medium   | • Low noise allowing work at night          |
|                      |           |           | • Large potential for use in congested reinforced structures             |
|                      |           |           | • Large potential for use in hard to reach areas                           |
|                      |           |           | • Labor and time savings                  |
|                      |           |           | • Lower aggregate consumption               |
|                      |           |           | • Higher volume replacement of cement by fly ash, blast furnace slag, limestone filler or stone dust to improve fluidity and cohesiveness and reduce heat generation |
| Use of admixture | high | high | - Significant contribution for concrete durability  
| | | | - Cement saving  
| | | | - Water saving  
| | | | - Increased demand requested to allow price reduction  
| | | | - Quality assurance of existing products requested to prevent low performance products  
| Use of precast elements | high | high | - Reduction of waste generation  
| | | | - Higher durability  
| | | | - Faster application  
| Recycling | essential | essential | - Technological improvement required  
| | | | - Standards and specifications required  
| | | | - Must be economically promoted  
| Use of lightweight concrete | medium | high | - Good thermal and acoustic properties  
| | | | - Less foundation required  
| | | | - Suitable alternative for low income housing programs  
| Concrete paving | high | very high | - Much lower maintenance required  
| | | | - Better traffic flow reducing lost hours due to low maintenance required  
| | | | - Lower heavy vehicle energy consumption  
| | | | - Lower incidence of vehicle breakdowns due to lower incidence of holes and corrugation in pavement  
| | | | - Higher safety for users  

*Table 19* presents some data based on calculations and evaluations performed by the author, showing the magnitude of the impact of the main bad practices on the environment.
Table 19: SOME ESTIMATED QUANTITATIVE DATA FOR CONCRETE COMPONENT LOSSES

<table>
<thead>
<tr>
<th>Problem</th>
<th>Losses per year (million tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cement</td>
</tr>
<tr>
<td>Construction debris</td>
<td>120</td>
</tr>
<tr>
<td>Construction wasting</td>
<td>70</td>
</tr>
<tr>
<td>Low Durability</td>
<td>130</td>
</tr>
<tr>
<td>Total</td>
<td>320</td>
</tr>
</tbody>
</table>

The previous table emphasizes how badly concrete has been and is still used, leading to low added value for each ton of CO₂ emitted in cement production. For sustainability purposes, what these materials provide in social terms and how their use could be improved and optimized is important, rather than the absolute value of the amount of materials used or of the CO₂ emitted.

In order to provide an idea of the potential material savings provided by certain special concrete, compared to a conventional concrete, the different mean consumption per cubic meter of materials for each type of concrete has been evaluated. It was assumed also a durability three times longer for these specially-designed concretes than that of a conventional concrete. The results are shown in Table 20.

Table 20: POTENTIAL RAW MATERIAL SAVINGS FOR DIFFERENT CONCRETES

<table>
<thead>
<tr>
<th>Concrete Type</th>
<th>Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cement</td>
</tr>
<tr>
<td>HPC</td>
<td>45%</td>
</tr>
<tr>
<td>RCC</td>
<td>90%</td>
</tr>
<tr>
<td>SCC</td>
<td>55%</td>
</tr>
</tbody>
</table>
The contribution of concrete to sustainability is fundamental, but it must be used to its full potential, since the technology for satisfying the necessary requirements is available. Concrete technology nowadays offers high architectural and esthetic flexibility, high performance technology, low cost alternatives, environmental opportunities through the use of by-products, alternatives to reduce water consumption, thermal and noise insulation, swiftness when required, among many other possibilities. The main issue is to know which are the available technologies, how to deal with them, avoiding to loose their best properties due to marginal reasons such as bad curing.

9.3 General Trends and Proposals

The pressure for a cleaner production and for a serious environmental management and commitment is increasing dramatically. From a sustainability point of view, however, it is essential to find a reasonable effective solution to mitigate not only the greenhouse effect, but also to reduce the social distance separating poor and rich people. The solution must be global, but the best options will have to be dealt locally and by sector. In such a scenario, the contribution of the cement and concrete industries can be remarkable.

The cement and concrete industries have no choice, they must add this development trend to all their other constraints. Undoubtedly, the cement and concrete industries will succeed in making this change in policy. They will become greener industries.

It must be pointed out that the cement industry didn't really face any great imbalance in the world market in terms of offer and demand until recently, and this scenario can change. The following environmental possibilities may impact future production:

- increased risk of the creation of environmental barriers in the case of higher imbalance offer to counteract the aggressive export policies of some foreign cement companies;
- growing quantities of waste co-firing which of course represents an enormous social advantage, but could also be adversely used by the competition in a hard competitive scenario;
- use of environmental marketing as a tool that will be conveniently appraised by the cement industry;
- environmental certification required for public tender;
- environmental accident risks with high penalties and negative impact for the image of the companies;
- differentiated insurance costs for companies with or without environmental policy and accreditation.

The possibility of compulsory government regulations targeting an even greater mitigation of emissions, as well as possible taxation on energy consumption, must be considered. Like any other human activity, cement production has an environmental impact, from the exploitation of the raw materials up to the emission of greenhouse gases, but this environmental impact has been systematically reduced, forced not only for environmental reasons but also as a consequence of competitiveness and survival. All these efforts and scenarios are yielding to the implementation of a coherent policy on energy and environment in the day-to-day operation of cement plants, which became a reality with the ISO-14000 standards. The majority of multinational cement groups have environmental management policies, but only a few of them have already obtained their environmental certification as opposed to what can be observed, for instance, in the pulp and paper and cellulose industries which have a longer tradition on exports.

Too stringent environmental requirements are the main blocking issue limiting the use of larger amounts of wastes. The ever-growing difficulties in getting permits to start new projects that may impact the environment (new plants, plant upgrading, waste burning, etc.), and also the increasing number of ecologically-protected areas is affecting general investment policies. Besides, with the intensive urbanization process developed in the last 20 years, many cement plants became virtually surrounded by invading suburbs, implying a drastic change in attitude related to communication with the vicinity and extra costs due to the necessity to develop a better environmental control according to more stringent standards. In extreme cases, this situation led and can still lead to the shutdown of some cement plants.
The turning point for the cement industry lies in the possibility of trading CO₂ emissions in the near future, since companies able to carry out this process rapidly and with sensitivity will improve their profit and competitiveness worldwide, while companies that do not perceive the importance and economical possibilities of this alternative or that postpone their initiatives will face great problems in the world cement market. The possibility of CO₂ trading has led a growing number of companies, the majority of them large transnational and leading companies, to begin monitoring and verifying emissions, as well as announcing goals for reducing them [Dunn et al., 2002]. The cement industry as a whole must focus on this issue.

The concrete industry, on the other hand, may have to adjust its activities, since concrete is a key element to promote the sustainable development of a nation. The concrete of tomorrow will be more durable and will be developed to satisfy socio-economic needs at the lowest environmental impact [Aitcin & Marciano 1998]. Constructors and owners have to realize that what is important for them is not the cost of 1 m³ of concrete but rather the cost of 1 MPa or one year of life cycle [Aitcin & Marciano 1998]. The cost of a project in the future will have to incorporate not only the present economic costs that we are used to calculating now, but also social and environmental costs, from the extraction of the raw materials to their use and disposal at the end of the life cycle of concrete structures.

The concrete producer of tomorrow will have to know how to work with all the different types of binders and admixtures to provide contractors with concrete that will be more high-tech and more economical, not in terms of the cost of 1 m³ but in terms of global performance [Aitcin & Marciano 1998]. At the same time, however, the concrete industry of tomorrow will have to produce a better commodity product in order to satisfy the requirements of society.

Concrete is just a material, a good one, but it must be correctly used, not only from a technological point of view but also taking into account direct and indirect environmental, economic and social benefits, otherwise some potential advantages are offset.

Concrete paving for instance may represent a great alternative for sustainability. Aside from the previously discussed advantages, it contributes to building a better road network, an
enhanced competitiveness issue for the economy of a country, since road transportation frequently represents 80 to 90 percent of the movement of goods.

Investments in sanitation are another contribution toward sustainability. Disease prevention is a key alternative for sustainability and expenses related to sanitation or properly treated sewage collected is a major contribution to prevent diseases and further more costly health care services later. The estimated cost of care, expressed by specialists in the press, is almost three times more expensive than the cost of prevention. From social and economical points of view, the option of investing in sanitation will be much more affordable. Collected sewage must be properly treated and durable concrete pipelines must be installed.

One important point in the sustainable approach is reducing social violence. Undoubtedly, a more pleasant environment contributes to reduce stress and violence. The great spectrum of available concrete technology allows to build good and innovative architectural elements to make the environment more pleasant for people. Moreover, developments in colored concrete blocks, advantageously replacing ornamental stones, the use of HPC in infrastructure contributing to reduce the visual pollution due to vehicle emissions, the concern about sidewalk durability, maintenance and appearance, all these durable alternatives can contribute to making the urban atmosphere more attractive, leading to reduced violence and developing a feeling of pride among people. The integration of landscaping programs to concrete structures is essential to reach such a target, both for low-income housing projects and for the cities as a whole.

The production of concrete, however, cannot increase indefinitely without penalizing the environment independently of the progress achieved. There are other parameters that can lead to an increasing unsustainable demand for concrete use.

A high birth rate must be considered as a driving force against sustainability. Population growth occurs mainly in developing countries, without the necessary concern about the welfare of the children and the population as a whole. In these countries, it is essential to build schools, hospitals and sanitation infrastructures in order to provide the population the required care and insert them into society as productive citizens and not in sub-human conditions. However, for
several reasons, such as lack of democracy, limited budgets, lack of ethics, no political vision and many others, this commitment of providing good conditions for children is postponed or just carried on at all. This perverse scenario is accentuated if one consider that, while in rich countries, families have usually 2 children for which they have to provide necessary care, in developing countries families can have often up to 10 children for which they cannot give the required education and health care, creating a marginal group. It is even worst when we consider that the growth of this population will always increase at a much higher pace than in developed countries, and therefore will create an ever-growing abyss between societies and an ever-growing demand for construction materials. In order to rectify such a situation, government’s economical policy often look for creating job for poorly qualified people, usually in civil construction, as well as the creation of low-cost housing programs without much concern for quality and durability, only putting even more pressure on the social situation and on the environment. Frequently, these low-skilled people are employed in civil construction. As a consequence, there will be significant materials wasting, including cement and concrete, low durability structures, and therefore short term demolition material to be disposed of, resulting in impacts on costs and on the environment.

Without a serious commitment to control the birth rate there is the risk of facing, in the next few decades, the same or even a worst scenario, with bad use of materials and specially cement and concrete, without achieving any social progress. If simultaneous action is not taken regarding this problem there will not be a sustainable consumption of concrete. Meanwhile, to minimize the problem great efforts should be made on improving the labor force and gradually turning to more up-to-date technologies.

As general developments, the following issues will probably emerge as trends in cement and concrete production:

- shutdown, modernization and upgrading of plants;
- increasing competitiveness rooted in technological development in the manufacturing process, greater automation levels, downsizing, contracting out, reengineering, just-in-time policy, benchmarking philosophy;
- change in the profile of energetic inputs, burning of alternative fuels and waste co-firing;
- more environmentally friendly-orientated manufacturing process.
- increased use of by-products in cement;
- dissemination of ISO 9000 and increasing ISO 14000 implementation;
- development of a more consistent environmental policy;
- expanding participation of cement groups in concrete ready-mix businesses and concrete products;
- durability becoming a key requirement rather than strength when selecting the concrete to build a structure or an infrastructure;
- search for diversification by conglomerates (petrochemical, steel, food, paper and cellulose, mining, and new construction materials).

**Figure 56** [Hackett, 1998] summarizes the basic requirements for achieving sustainability and the importance of harmoniously integrating the main issues that will allow to achieve a more just and pragmatic society.

![Three Pillars of Sustainability](image)

**Figure 56**: The three pillars of sustainability

Evaluating these requirements, it can be noticed that the cement and concrete industries contribute for economic vitality, promoting employment generation and creating conditions for improved competitiveness through the built infrastructure. From ecological point of view there is still a long way to achieve effective integrity. Greenhouse mitigation, better concrete durability, wasting mitigation, recycling are some the challenges to be faced. However, the environmental contribution of the cement industry has been experiencing great progresses and they represent a
meaningful contribution to alleviate general environmental burden. Finally, the political issue is still a serious problem, mainly in emerging countries. The power of conglomerates and big companies, close to the public administration, is very high, the ability of lobbies to influence politicians is remarkable, corruption is often disseminated, lack of ethics in detriment to the welfare of the population is a common scenario in these countries and changing this mentality or impregnated culture will be the hardest challenge to be overcome.

9.4 Mechanisms to Implement a Sustainable Policy

The main challenge to achieving a sustainable use of cement and concrete is how to implement the proposed alternatives. The large number of participants in civil construction, from the development phase to the demolition phase, through the operation phase of each component of the built environment, is a serious issue. The meaning and magnitude of the impact of civil construction on the environment is still not mature among entrepreneurs, politicians and clients, and the demand for sustainable construction is still weak. Initial price is still more important than maintenance and consumption of energy costs or the advantages of a longer life cycle.

The first alternative is the role of institutions, such as Cement and Concrete Associations.

They must prepare programs and courses for people involved in the construction chain, such as engineers, architects, designers, etc. They must be also in the forefront of the promotion of new products and their standardization, as well as in providing information about technological and environmental achievements for society, especially for politicians and decision makers and not only for the scientific community.
They should also improve the promotion and the great potential of concrete use, with emphasis on the importance of durability for new projects, to financing institutions and also environmental agencies, by means of a clear communication program that reaches this target public.

It is important also to promote synergetic partnerships with other associations that will benefit from the convenient use of concrete, such as vehicle insurance companies, road transportation associations (bus and trucks) and unions, in the case of concrete paving, keeping in view that concrete paving can contribute to reduce vehicle deterioration and accidents. They should also provide a closer contact with environmental agencies, by improving communications and avoiding mistrust. It is important to show that waste burning, for instance, is a good opportunity for the cement industry, that must be conveniently paid since cement plants undertake the risk of operational problems and invest in facilities. It is however an even better alternative to alleviate the environmental burden for society as a whole. In return, environmental agencies should accelerate, as much as possible, the process of emitting permits.

The cement industry should also pay even more attention to their market and to technical assistance services, in order to provide the access to good practices for small users of cement and concrete.

Professional associations (engineers, architects, etc) and unions related to civil construction must be involved in a broad program for improving the labor force, qualifying professionals through field training and courses. A better-skilled labor force would result in less wasting on the job site, an issue of major importance in developing countries. Foreign money from developed countries should be allocated to this process.

Universities can play a very important role in sustainability. Aside from carrying on research, mainly applied research, universities should be highly concerned with transferring their knowledge, by providing better training in concrete technology, introducing a broader humanist, environmental and holistic training to their students, allowing them to understand the complexity
of the issues involved in a sustainability approach. The introduction of courses on sustainability would also be a good alternative to complement the training of students.

Standardization associations must be more flexible and pragmatic, but mainly, must be quicker in making the necessary changes to the standards by creating transitory regulations and specifications. Standards must be a tool that will help users to clearly identify technical requirements and support the users of new technologies. They should also be based on performance, taking into consideration the environment the concrete will face.

Quality accreditation also represents a significant contribution for sustainability. The majority of large cement companies are already certified. It is time to extend this process to the concrete industry and especially to small and medium-sized companies dealing with civil construction. In order not to penalize these companies with extra costs due to accreditation, but also taking into account the need for enhancing their performance, a progressive accreditation process should be implemented, step by step and with fixed time frames to complete the whole process. It would be appropriate to create COOPS of these companies, allowing them to obtain their certification in a less costly way.

Financing agencies and banks should be concerned and should encourage the fulfillment of environmental needs, defining performance and life span criteria before financing buildings and infrastructures, taking into account not only the initial cost of a project but also considering the operational cost and the future costs of maintenance and disposal of the materials.

Owners and contractors should be held legally responsible for the lower-than-expected life span of their work, and in cases where they cannot be charged, the financing agency should be responsible, in order to force the financing agents to select better companies to carry out the work.

NGOs can provide good alternatives for the convenient selection of projects, materials and for follow-up of the work according to the social requirements of their community or in a more
comprehensive sense. They can play a major role in following and controlling bad private and government practices. They must be supported by good and continuous information.

Multinational companies can also contribute to quality improvement, the implementation of more environmentally friendly procedures, and in the organization of future trading of emissions, among other issues.

The creation of independent agencies focusing on implementing and promoting good practices in civil construction could be a helpful tool to promote a more consistent and pragmatic sustainable policy for the sector. These agencies must have credibility and flexibility to support the decisions taken. They should involve a large spectrum of representatives, with producers, users, researchers, unions and NGO representatives. Benchmarking can be a very useful tool for achieving sustainability.

The introduction of a green label or any other environmental indicator should be used for evaluating the overall performance of new buildings, residential or commercial, taking into account the materials to be used, operational performance, maintenance requirements and potential use. The construction of these ecological and more efficient buildings should be encouraged by lower municipal taxes, lower insurance premiums or any other mechanism to be proposed in the future. Individuals and companies must be convinced that good practices and durability result in any form of payback.

Finally, the idea of social responsibility is becoming an ever-growing requirement for companies. The existing SA-8000- Social Accountability 8000 standard is a clear evidence that this issue can contribute toward sustainability. This standard was conceived of by the CEPAA- Council on Economic Priorities Accreditation Agency with the support of CEPAB- Council on Economic Priorities Advisory Board [Explorer 2002]. The first U.S. company to be certified was Avon in 1998 [Explorer 2002]. The official requirement of environmental and social reports aside from the usual financial report, for larger companies, was introduced in France in May 2001, and incorporated by the Lafarge group. The concrete industry and related industries (raw material suppliers, mainly) will be affected by more stringent requirements of labor force skills, as well as
better income, mainly in developing countries, by reducing wasting, by better exploitation of raw materials, by adding social and environmental values to their products and this process will be strongly linked to the role of associations and big construction companies. This step is of major importance to promote the social commitment of companies. The main content of each report includes the following topics, among others:

Social Data Content

- Employees: stable, part-time, precarious;
- Plans for reduction and safeguarding of employment;
- Income policy and its evolution;
- Conditions for subcontracting activities;
- Foreign branch policy regarding its activity impact on the local population and regional development.

Environmental report:

- Consumption: water, raw materials, energy;
- Measures undertaken to improve energy efficiency;
- Use of renewable energy;
- Noise and odor;
- Use of soil;
- Emissions in air, soil and water;
- Waste.

The valorization of human capital will largely contribute to a more sustainable society and also to promote an improvement in the relationship between companies and society as a whole, and a greater commitment between companies and employees. The main points are:

- Human resources policy;
- Medium and long term valorization;
• Working conditions, dialog and benefits;
• Training policy;
• Integration of social plans;
• Productivity improvement of labor force;
• Relationship with the community and authorities.

Slowly, the concept of social responsibility can be extended to associations and medium-sized companies and with time, volunteer commitment will be expected once the shareholders and owners of these companies become conscious that profit is important but a contribution to society will not squeeze their profit to an unacceptable level, but rather will contribute to give a better company image and reduce stress and violence in our society.
10- SUSTAINABILITY AND THE CEMENT AND CONCRETE INDUSTRIES

10.1 General Considerations

The process of sustainability naturally involves efforts to mitigate CO₂ emissions on a worldwide basis. The selection of CO₂ mitigation as a main issue of sustainable development is not fortuitous. It is probably the only link that may affect rich as much as poor, developed as much as emerging countries, because the effect of this gas may cause severe climate change, whose global impact will affect us all. (Despite such circumstances, the present U.S. administration, for instance, does not want to adhere to the Kyoto Protocol, mainly because of the potential negative consequences on their local economy.)

In fact, sustainability must have a much broader focus. Sustainable development must undoubtedly include the mitigation of CO₂ emissions, but it must also take into account alternatives to alleviate the environmental burden further, reduce poverty and the wealth gap, and the implementation of pragmatic policies to help emerging countries while respecting their local cultural heritage and the availability of natural resources. On a worldwide basis, countries have a mandate to solve global problems, however, since solutions could result in a reduction in the profit margin of certain multinational corporations or adversely impact the economy of industrialized countries, this challenge will hardly be met unless sustainability is transformed into business opportunities.

The mitigation of CO₂ emissions is a key issue due to its global significance, but to be sustainable, mitigation alternatives must be pragmatic, and in particular, the mitigation must be carried out by adding social and economic value to the proposed options.

Before beginning any discussion, it must be taken into account that 3 billion people worldwide have an extremely low income and a huge need for all types of infrastructures. Among the remaining 3 billion, only 30 percent really have a high purchasing power. Consequently, priority orientations in achieving a sustainable world must be aimed at nearly 70 percent of the world population, which has limited economic resources to solve its serious problems. These people face death, extreme poverty, increasing violence, and are unknowingly harming the
environment. The majority of this population needs schools, houses, sanitation, and hospitals. On the other hand, around 15 to 20 percent of the world population consumes huge amounts of energy and generates great amounts of CO₂ to satisfy its high standard of living, but this population often also faces other challenges, such as scarcity of raw materials, lack of environmental solutions (such as landfill areas, for instance), and the perspective of the scarcity of fossil fuel.

Within the definition of sustainable development, concern for future generations is implicit. However, to reach this goal, it will be necessary to take care of the present generation first. There is no tomorrow without today. It is fundamental to protect the present generation, and even more important, to improve the standard of living of approximately 70 percent of the world population. Sustainable development must be an attempt to reduce the ever-growing social gaps caused by an increasing concentration of wealth. Up until now, and much too often, sustainable development models have been dictated by the interests of economically powerful countries, by conglomerates, and huge companies, and transferred from developed countries to emerging countries without much concern about their real needs. To implement a consistent sustainable policy, analysis must be specified for emerging countries and for developed countries, considering local driving forces and weaknesses. Often, sustainability themes have been discussed by authors from or living in a developed country, who are not sufficiently informed about local conditions in emerging countries. This misunderstanding has led to great efforts without proportional success in implementing valid and pragmatic worldwide solutions. The cost-benefit return has been low.

In the past years, we have been experiencing an “industrial feudalism” model, with governments being “surrounded” by big companies and conglomerates, as old Lords in their castles, influenced by their own interests and economic convenience. The economic policies of the 90s, which saw the implementation of management alternatives such as reengineering, subcontracting, etc., aimed at increasing competitiveness, resulted in the creation of small fragmented companies, a dilution process that fomented unemployment and caused ever-growing dependence of these small companies on large companies or conglomerates. In contradiction, the present driving force for social and economic development, mainly in emerging countries, is based on the strengthening of these small companies. Small and medium-sized companies cannot
invest in quality control, accreditation, new technological development, and environmental protection without impairing their already low profit margin. In emerging countries, the employment of a low-skilled labor force is a pseudo-alternative for reducing costs, in order to allow the survival of these companies in a competitive market. The concrete industry, for instance, has traditionally been an extremely fragmented industry, represented by small and medium-sized companies, and in such a scenario, this characteristic was only worsened. Lately, however, some concrete producers have been incorporated into cement groups as an alternative to protect and ensure their share of the cement market.

Despite the great technological progress achieved, the sustainability process has been not successful enough and the pace of changes too slow in proportion to the needs of society. This problem arises from the lack of pragmatic proposals and efficient alternatives to reach sustainable solutions, including the use of cement and concrete. Also, the problems affecting different countries demand different alternatives and should not be generalized.

Moreover, it must be considered that the birth rate is quite different in emerging and developed countries, and the pressure for higher cement/concrete demand will be much higher in the former countries.

A nation cannot be built without developing necessary infrastructure. The cement and concrete industries play an essential role in providing an alternative to build such infrastructures. If the economic added value of cement and concrete is low, its social added value is, however, meaningful. The challenge is to use these powerful construction materials to their maximum potential.
10.2 Global Scenario

A simulation of the world scenario in terms of cement production has been elaborated based on available data, projections, and evaluations. The proposals are based on the following main facts and premises:

- Present cement production is around 1.5 billion tonnes;

- CO$_2$ generation due to cement production is around 1 tonne CO$_2$/tonne of cement;

- World cement production was considered as two blocks, using as main criterion cement production characteristics (similar cement production with lower gaps in kiln technology, current use of by-products, use of waste-derived fuel). Block 1 comprises Europe and America and block 2 comprises Asia, Africa and Oceania;

- Cement production in block 1 corresponds to about 500 million tonnes of cement;

- Block 1 with a mean SCM content of 20 percent (estimation based on general literature);

- Block 1 with mean gypsum content of 5 percent (usual);

- **Therefore, block 1 clinker production corresponds to 375 million tonnes/year and an equivalent intrinsic amount of CO$_2$ generation**;

- Cement production in block 2 corresponds to about 1 billion tonnes, 930 million tonnes being produced in Asia (500 million tonnes in China);

- Block 2 with a mean SCM content of 10 percent (estimation based on general literature and personal information)

- Block 2 with a mean gypsum amount of 5 percent (usual);

- **Therefore, block 2 clinker production corresponds to 850 million tonnes/year with the inherent amount of CO$_2$ generation**;
Consequently, the current total CO₂ generation (from limestone decomposition and fuel burning) due to clinker production worldwide is 1,225 million tonnes;

Moreover, based on personal calculations and experience, the electrical energy used by the cement industry corresponds to 10-12 percent of all the CO₂ emitted by the cement industry. The variation depends on the nature of the source of electricity. A mean value of 10 percent of cement production will be considered, and therefore, around 125 million tonnes of CO₂ originate from electricity consumption;

Consequently, 1,225 million tonnes of CO₂ are related to thermal energy consumption and limestone decomposition and about 125 million tonnes are due to electricity, making a total of 1,350 million tonnes of CO₂ emission that will be considered as reference for emissions by the cement industry in the calculations performed.

The following evaluations have been carried out:

10.2.1 Thermal energy saving by changes in the manufacturing process

The implementation of a policy of changing old technology kilns to up-to-date kiln technology cannot be equally applied to every country, since many countries already benefit from a modern cement production technology. Most of the cement production in Europe, South America, and in some Asian countries (Korea, Japan, Thailand, Malaysia) have up-to-date technologies and do not have a big margin for improvement.

For the evaluation of the CO₂ that could be mitigated by this alternative, the following premises were considered:

- Block 1 clinker production: 375 million tonnes;
- Block 1 up-to-date production: 80 percent (300 million tonnes);
- Block 1 potential clinker production to be improved: about 75 million tonnes (375-300);
- Improvement in fuel consumption by using better technology: 30 percent;

- CO₂ generated from fuel consumption: 0.5 tonnes/ton of clinker;

- **Block 1 potential CO₂ mitigation:** \( 75 \times 0.3 \times 0.5 = 11 \text{ million tonnes to be achieved in 10 years} \) *(if all plants start at the same time, with immediate implementation)*;

- Block 2 clinker production: 850 million tonnes;

- Block 2 up-to-date production: 60 percent (510 million tonnes);

- Block 2 potential clinker production to be improved: around 340 million tonnes (850-510);

- Improvement in fuel consumption through use of better technology: 30 percent;

- CO₂ generated from fuel: 0.5 tonnes/ton of clinker;

- **Block 2 potential CO₂ mitigation:** \( 340 \times 0.3 \times 0.5 = 51 \text{ million tonnes to be achieved in 10 years} \) *(if all plants start at the same time, with immediate implementation)*.

Therefore, the potential CO₂ mitigation, regarding the 1,350 million tonnes generated worldwide by the cement industry, would be 0.8 percent for Block 1 and 0.38 percent/year for Block 2, corresponding to a total of 4.6 percent/year of CO₂ mitigation (71 million tonnes). It must be remembered that this alternative is very costly and not affordable for all countries and companies, and cannot be implemented at the same pace worldwide. Keeping in view that a new plant takes about 3 years to be in operation, a reasonable time span for implementing this change on a worldwide basis would be of 10 years.

It must be considered that in the first 3 years of building a plant, no CO₂ mitigation will be achieved. Moreover, it seems very unlikely that all plants can begin up-dating their technology at the same time and at the same pace. In order to evaluate the accumulated CO₂ mitigations over 10 years, the following scenario was considered: no mitigation in the first 3 years and a 40
percent rate of cement production technology update in this time span, a 70 percent rate of
achieved change by the 6th year, and the remaining 30 percent in the subsequent years. This
would lead to an accumulated CO₂ mitigation of about 318 million tonnes in 10 years, over
a total of 13,500 million tonnes of CO₂ theoretically generated in the same period by the
cement industry (at the current amount of 1,350 million tonnes/year). This mitigation
corresponds to 2.36 percent over the 10 year period.

10.2.2 Further alternatives for the cement industry

In order to satisfy the need for CO₂ mitigation and simultaneously promote further
contributions to world sustainability, the following steps can be implemented:

Plant Optimization

The optimization of plant operations is the first step in any process to mitigate CO₂
emissions and to achieve a sustainable production. Cement plants worldwide often have many
minor problems to solve (klin seals, improvement of cooler efficiency, fuel atomization or
fineness, etc). These problems alone can lead to a thermal waste of up to 9 percent, according to
references consulted. A conservative mean value of 3 percent was taken into account in this
evaluation.

Keeping in view that about 415 million tonnes (75 million tonnes from block 1 and 340
million tonnes from block 2, as presented in item 10.2.1) should, theoretically, experience a
modernization process by changing old technology into up-to-date technology, this amount of
clinker production will be not considered again, since it will not require a plant optimization.
Therefore, these alternatives should potentially be carried out on the remaining clinker production
(1,225 – 415 = 810 million tonnes).

The cement industry in Europe and some Asian countries, as well as that of Brazil in
South America and Mexico in North America also shows high levels of automation and
systematic control. Therefore, about 60 percent of this contingent (0.6 X 810 = 485 million
tones) would not need such improvements or would achieve low improvement levels. As a
result, the potential clinker production that could go through this process corresponds to 225
million tonnes (1,225- 415- 485 = 325 million tonnes).
- Plant optimization mean value: 3 percent fuel saving;
- CO₂ mitigation per each 1% fuel saving: 0.5 tonnes (only from fuel consumption);
- Potential clinker production improvement: 325 million tonnes;
- Total CO₂ mitigation: \( 325 \times 0.03 \times 0.5 = 4.9 \text{ million tonnes/year.} \)

The resulting CO₂ mitigation, over a 10 year period, would correspond to about 49 million tonnes, over a total of 13,500 million tonnes of CO₂ theoretically generated over the same period by the cement industry (at the current amount of 1,350 million tonnes/year). This mitigation corresponds to 0.36 percent over a 10 year period.

Replacement of fossil fuel by waste-derived fuel (WDF)

- Feasible increase in WDF use worldwide : 1 percent/year;
- Potential CO₂ mitigation through WDF use: 0.5 ton CO₂/ton clinker for each 1 percent fossil fuel replacement by WDF (only the CO₂ from combustion is considered);
- Feasible target in the next 10 years: 10 percent absolute increase in the rate of replacement;
- Potential CO₂ mitigation worldwide per year per each 1 percent replacement: \( 1,225 \times 0.5 \times 0.01 = 6.1 \text{ million tonnes CO}_2 \).

It can be seen that a 0.45 percent (6.1 million tonnes) CO₂ mitigation could be achieved in the first year through the replacement of fossil fuel by WDF. At an absolute increase rate of 1 percent per year, a rate of increase that has been achieved in Europe, accumulated CO₂ mitigations over 10 years would correspond to 264 million tonnes over a total of 13,500 million tonnes of CO₂ theoretically generated in the same period by the cement industry (at the current amount of 1,350 million tonnes/year). This mitigation corresponds to 1.96 percent over a 10 year period. It must be considered that this mitigation is indirect, because if these waste products had not been burned in cement kilns, they would have been incinerated,
generating further CO₂ emissions together with the CO₂ generated by the fossil fuel that was not replaced. Therefore, it must be considered as a source of CO₂ mitigation. Moreover, this alternative adds great environmental value by solving the serious problem of waste disposal

Use of by-products

- CO₂ potential mitigation through the use of by-products: 1 ton CO₂/ton clinker replaced (CO₂ from limestone decomposition and from combustion are considered);
- Feasible increase in the use of by-products: 1 percent increase/year over 10 years;
- Market share requiring major increase production: 900 million tonnes (Europe and some Asian countries excluded);
- Clinker savings: 0.01 x 900 = 9 million tonnes/year;

**CO₂ mitigation: 9 million tonnes/year/one percent.**

A 0.66 percent/year CO₂ mitigation worldwide could be achieved in the first year, which is especially recommended for some countries, such as the U.S., China, and India. The accumulated CO₂ mitigation, by increasing the amount of by-products at a substitution rate of 1 percent per year over a 10 year period, would correspond to 392 million tonnes. When referred to a total of 13,500 million tonnes of CO₂ theoretically generated in the same period by the cement industry (at the current amount of 1,350 million tonnes/year), this mitigation corresponds to 2.90 percent. This alternative provides a partial solution to the use of the huge amounts of by-products generated every year, especially fly ash from power plants, resulting in a major contribution to the environment. It can also add technological value to concrete production, since these by-products contribute to enhance concrete durability. However, this alternative cannot be applied worldwide, since the use of by-products depends on availability and is cost driven, and many countries, especially European ones, already use high amounts.

**Raw Meal Burnability**

It is difficult to estimate the potential benefit that could be achieved through this alternative, but it is in the interest of cement plants, in order to improve production and the profit
margin. Personal experience shows that almost every plant has a varying potential to improve raw meal burnability (raw meal fineness, composition, chemical module). Such an improvement can amount to up to 3 percent in certain plants, but a conservative mean value of 1 percent was considered. Usually, this problem will potentially affect mainly older cement plants (75 million tonnes from block 1 and 340 million tonnes from block 2), since new plants have usually previously carried out a raw material burnability optimization and consequently are less sensitive to such a problem. However, this amount should go through a modernization process and in such a case, it should not be considered. This alternative could be adopted by most of the remaining cement industry worldwide (1225 – 415 = 810 million tonnes), but its positive effect would be more remarkable in older or less efficient units. Considering that it could be implemented in 50 percent of the remaining 810 million tonnes, the potential improvement would affect 405 million tonnes.

- Mean potential raw meal burnability optimization: 1 percent in fuel saving;

- CO₂ mitigation per each 1 percent fuel saving: 0.5 tonnes/tonne of clinker;

- Potential clinker production improvement: 1225 - 415 million tonnes (already considered to implement new kiln technology, being 75 million tonnes for block 1 plus 340 million tonnes for block 2): 810 million tonnes;

- Percentage of the remaining production to be improved: 50 percent (405 million tonnes)

- Total CO₂ mitigation in raw meal burnability improvement: 405 × 0.01 × 0.5 = 2.0 million tonnes CO₂/year.

The total 20 million tonnes CO₂ mitigation over a 10 year period, referred to the total of 13,500 million tonnes of CO₂ theoretically generated during the same period by the cement industry (at the current amount of 1,350 million tonnes/year), corresponds to 0.15 percent over a 10 year period.

Replacing Raw Material Limestone by Slag
This possibility is highly promising, preventing not only the CO₂ mitigation due to limestone decomposition, but also promoting an improvement of raw material burnability, resulting in a raw meal that is easier to burn, with lower CO₂ emissions. Its use cannot be disseminated worldwide, since the cost of slag and of its transportation, as a raw material for clinker manufacturing, would be too high for many cement plants and therefore not attractive at all. The countries that could potentially use such an alternative are those that are producing higher amounts of slag. They are mainly located in Europe, South America, and some Asian countries, this represents a potential market of about 600 million tonnes of cement.

- Amount of slag replacing raw material limestone: 1 percent during 10 years;

- CO₂ mitigation per each 1% limestone replacement: 0.6 tonnes (0.4 from limestone decomposition and 0.2 from combustion improvement);

- Potential market share to substitute limestone by slag: 30 percent (500 million tonnes);

- **Total CO₂ mitigation by replacing 1 percent limestone by slag:** \(500 \times 0.01 \times 0.6 = 3.0\) million tonnes per year.

The total CO₂ mitigation achieved of 30 million tonnes over a 10 year period, referred to the total of 13,500 million tonnes of CO₂ theoretically generated in the same period by the cement industry (at the current amount of 1,350 million tonnes/year corresponds to 0.22 percent over a 10 year period. The attractiveness of using higher amounts of slag as raw material would depend on economic reasons (cost of slag, availability, possibility of CO₂ trading) in the near future.

**Electrical Energy Savings**

Electrical energy consumption represents between 9-12 percent of total CO₂ emission in clinker production, depending on the source of energy. Assuming a mean value of 10 percent, every year around 125 million tonnes of CO₂ are associated with the use of electricity by the cement industry. A reduction of 5 percent in electrical consumption, with a maximum target of 20 percent, could be a reasonable commitment. This optimization, however, could not be achieved
worldwide, keeping in view that the cement industry in many countries already exhibits high levels of electrical consumption optimization. Considering that about 415 million tonnes (75 million tonnes from Block 1 and 340 million tonnes from Block 2) of clinker are still produced using older technology, this 5 percent improvement should be mainly addressed to them. This means a 5 percent reduction of the 41.5 million tonnes of CO$_2$ generated every year using electrical consumption from this 415 million tonnes of clinker. A 5 percent saving could be progressively achieved every 2 years, up to a limit of 20 percent savings, resulting in a accumulative CO$_2$ mitigation of 40 million tonnes over a 10 year period. When referred to the total of 13,500 million tonnes of CO$_2$ theoretically generated over the same period by the cement industry (at the current amount of 1,350 million tonnes/year), this mitigation corresponds to 0.30 percent.

10.2.3 Waste mitigation in cement and concrete use

The problem of concrete waste mainly affects emerging countries, including China. This problem is not the main issue in Europe, North America and certain Asian countries, such as Japan, Taiwan, and Korea.

For the evaluation of the embodied “lost” CO$_2$, the following assumptions are considered:

- Cement produced by emerging countries: 850 million tonnes;
- Mean percentage used by small and medium-sized users (bags): 70 percent;
- Cement consumption by small and medium-sized users (self-construction): $850 \times 0.7 = 595$ million tonnes;
- Mean SMC content in cement: 10 percent;
- Mean gypsum content in cement: 5 percent;
- CO$_2$ emission: $595 \times 0.85 = 505$ million tonnes;
- Average waste in these countries by small and medium-sized users: 15 percent (using construction material waste data from Brazil as a reference);
- Wasted cement: $505 \times 0.15 = 76$ million tonnes;

- Feasible target for cement waste: 5 percent waste over a 10 year period;

- Feasible target for cement waste: $505 \times 0.05 = 25$ million tonnes;

- Resulting cement waste prevention: 51 million tonnes over a 10 year period;

- **Resulting CO$_2$ mitigation: 5.1 million tonnes per year.**

The 76 million tonnes of cement wasted worldwide represent about 5.2 percent of the total CO$_2$ generated yearly by the cement industry. The cost to improve this scenario is very low when compared with other alternatives, having further advantages, such as raw material savings and reducing economic impact (at $50$ US per tonne of cement, this results in a $3.8$ billion US loss). It would be hard to reduce this amount to zero percent. A feasible goal to be achieved over a 10 year period would be the reduction of waste from the current 15 percent (76 million tonnes) to a reasonable 5 percent level (25 million tonnes), resulting in a reduction of **51 million tonnes of CO$_2$ over 10 years.** When referred to the total of 13,500 million tonnes of CO$_2$ theoretically generated over the same period by the cement industry (at the current amount of 1,350 million tonnes/year), this mitigation corresponds to 0.38 percent.

### 10.2.4 Improved durability

Every year, approximately 1 billion tonnes of concrete waste is generated (based on the consulted literature) and must be disposed of or recycled. Each tonne of concrete contains an embodied emission of 0.12 tonnes of CO$_2$. This means that every year around 120 million tonnes of embodied CO$_2$ is lost due to the demolition of concrete structures. If durability (expressed as the increase in the expected life-cycle of a structure) could be improved in order to reduce this amount of concrete waste generation by half (60 million tonnes/year), within a reasonable time span of 10 years, an accumulated CO$_2$ mitigation of **115 million tonnes could be achieved over a 10 year period,** a 0.85 percent CO$_2$ mitigation referred to the total CO$_2$ emitted by the cement industry during that period (13,500 million tonnes).
In general terms, joint action between the cement industry and concrete producers and users, could provide significant and effective results. The proposed alternatives are feasible and realistic targets and can be implemented within a reasonable time span. It can be seen that the concept of CO₂ mitigation through the promotion of better concrete use has, by itself, a close relation to the measures proposed for the cement industry. Besides the environmental contribution, promoting better use of concrete will provide a better allocation of public and private funds and savings of raw materials (aggregate, water, etc).

The previously identified alternatives to CO₂ mitigation are summarized in Table 21.

**TABLE 21: ALTERNATIVES TO CO₂ MITIGATION OVER A 10 YEAR PERIOD**

<table>
<thead>
<tr>
<th>Alternative</th>
<th>CO₂ Mitigation over 10 year (in millions of tonnes)</th>
<th>CO₂ Mitigation (in %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Energy Saving by Process Change</td>
<td>318</td>
<td>2.36</td>
</tr>
<tr>
<td>Plant Optimization</td>
<td>49</td>
<td>0.36</td>
</tr>
<tr>
<td>Waste-Derived Fuel Use</td>
<td>264</td>
<td>1.96</td>
</tr>
<tr>
<td>Use of By-Products</td>
<td>392</td>
<td>2.90</td>
</tr>
<tr>
<td>Raw meal burnability optimization</td>
<td>20</td>
<td>0.15</td>
</tr>
<tr>
<td>Slag Replacing Raw Material Limestone</td>
<td>30</td>
<td>0.22</td>
</tr>
<tr>
<td>Electrical Energy Savings</td>
<td>40</td>
<td>0.30</td>
</tr>
<tr>
<td><strong>Total for the Cement Industry</strong></td>
<td><strong>1,113</strong></td>
<td><strong>8.25</strong></td>
</tr>
<tr>
<td><strong>CO₂ Theoretically Generated by the Cement Industry over 10 years</strong></td>
<td><strong>13,500</strong></td>
<td><strong>100</strong></td>
</tr>
<tr>
<td>Waste Mitigation in Cement and Concrete Use</td>
<td>51</td>
<td>0.38</td>
</tr>
<tr>
<td>Improved Durability of Concrete Structures</td>
<td>115</td>
<td>0.85</td>
</tr>
<tr>
<td><strong>Total for the Concrete Industry</strong></td>
<td><strong>166</strong></td>
<td><strong>1.23</strong></td>
</tr>
<tr>
<td><strong>Theoretical CO₂ Generated by the Cement Industry over 10 years</strong></td>
<td><strong>13,500</strong></td>
<td><strong>100</strong></td>
</tr>
<tr>
<td><strong>Total CO₂ mitigation over 10 years</strong></td>
<td><strong>1,279</strong></td>
<td><strong>9.48</strong></td>
</tr>
</tbody>
</table>
10.3. Proposed Scenarios in the Case of Emerging and Developed Countries

In order to implement effective and pragmatic sustainable policies, the following priorities should be implemented, always making a distinction between emerging and developed countries and respecting budgetary limitations, taking into account birth rate and consequently potential increase in cement demand, cultural heritage, raw material availability, current infrastructure, future social requirements, and the state-of-the-art of existing concrete technology, among many other parameters:

10.3.1 Emerging countries

To allow a better comprehension of local scenarios and the needs of emerging countries in achieving sustainability from the perspective of cement and concrete, the following issues must be considered:

- Very low income of the population (between $1,000 and 5,000 US/year/head and often less than $1,000 US/year/head);
- Population: 4.5 billion people;
- High birth rate: around 2 percent/year
- Approximate cement production: 950 million tonnes/year;
- Potential to increase this income, and therefore, cement consumption;
- Great need for the construction of infrastructure;
- Strong demand for cement and concrete;
- Significant potential increase in CO₂ emissions, however, social needs must be satisfied in order to promote a better standard of living;
- Limited budgets that cannot be spent on unnecessary maintenance, repair, and demolition;
- Cement consumption mainly in bags, and self-construction as a common practice;
- Low-skilled labor force, and therefore, higher risk of waste;

- These countries usually have a great availability of raw material, so that raw material savings is desirable, but not a priority.

These countries will play a key role in the implementation of a sustainable policy. They represent a major concern regarding environmental impact due to increasing CO₂ emissions, because their basic needs are so high, but these needs should be the main focus of discussion. The following priority steps are proposed:

1- Improving durability of concrete (at a rate of 5 percent per year). Better performance of ordinary concrete, since it is not acceptable to work with such low strengths (10-20 MPa) when higher performance (30Mpa, for instance) could be achieved without a major increase in cost. Reducing maintenance and repair costs are essential. It is important not to waste economic resources on repeated interventions. This alternative should be a priority for emerging countries, in particular for China and India, who still have a low level of urbanization, a high population, and, in the case of India, a high rate of birth all of which will strongly affect infrastructure demand.

**CO₂ mitigation: 0.55 percent (75 million tonnes) over 10 years**, based on the proportionality between emerging and developed countries in cement production, which stands at around 65 percent for the former;

2- Reduce concrete waste (at a rate of 1 percent reduction/year) by improving labor force skills and using better construction practices. It is not acceptable to lose 15 percent of material due to bad use or bad management at the work site.

**CO₂ mitigation: 0.38 percent (51 million tonnes) in 10 years**;

3- Increase the use of waste-derived fuel (at a rate of 1 percent/year) by the cement industry, in order to reduce fossil fuel consumption and reduce the general environmental burden in these countries.
CO₂ mitigation: 1.27 percent (172 million tonnes) over 10 years, considering the proportionality between emerging and developed countries in cement production, which stands at around 65 percent for the former.

By implementing these alternatives, a global CO₂ mitigation of around 298 million tonnes could be achieved over a 10 year period, corresponding to 2.2%. However, even more important is the low cost to implement these alternatives, the economic gains due to increased life-cycle of structure, and the optimized use of materials. These benefits will allow budget savings for these countries, that can be used in other social areas, instead of paying contractors to do systematic maintenance work. Also, a significant raw material saving can be achieved. Moreover, future concrete waste will be much more adequate for recycling. The main challenges will be the logistics of implementing labor skill improvement, overcoming short term policies adopted in emerging countries, the power of lobbies, and corruption. Results may not be measurable on a short term basis, but they will be much more effective.

On a local basis, further alternatives should be adopted in order to overcome local problems. The following options can be proposed:

- Upgrading of the Chinese cement industry (cement production of 500 million tonnes and clinker production of around 425 million tonnes) through better use of the present technology, with fuel savings of about 30 percent, while the CO₂ generated from fuel corresponds to 0.5 tonnes/tonne of clinker. If 30 percent of the local industry could undergo this process of modernization, over a 10 year period, about 130 million tonnes of clinker production could be improved, with environmental advantages.

CO₂ mitigation: 0.64 percent (86 million tonnes) over 10 years referred to a global cement CO₂ generation;

- Most Asian and African countries should, for instance, reduce their electrical energy consumption due to the limited availability of water sources to generate electrical energy. At least 50 percent of local cement production uses up-to-date technology and possibly possesses good and economical grinding facilities. Therefore, about 500 million tonnes of local cement production (about 35 percent of global production)
could potentially improve its electrical consumption and contribute to global CO₂ mitigation.

**CO₂ mitigation: 0.10 percent (14 million tonnes)** referred to a global cement CO₂ generation;

- On the other hand, some of these countries possess high amounts of fossil fuel, and although they worry about the judicious use of fossil fuel, this issue is sometimes not as much a source of concern as the lack of water, for instance;

- In countries such as India and Japan, the production of belitic cement remains a good alternative. In Japan, this is due to the lack of raw material resources and in India, it is due to the lack of high quality limestone and to the use of low quality coal;

- For countries having sources, natural or waste-based, of CaF₂ the production of mineralized cement is a good option.

**The proposed alternatives would allow CO₂ mitigation, on a worldwide basis, corresponding to 398 million tonnes, or 2.94 percent (referred to total CO₂ emissions by the cement industry over the period of 13,500 million tonnes), over a 10 year period.**

**10.3.2 Developed countries**

The main characteristics of these countries are:

- High income (over US$ 9,000/year/head), and no trend toward increased cement consumption;

- Population: 1.5 billion people;

- Low birth rate: around 1 percent/year

- Approximate cement production: 550 million tonnes/year;

- High standard of living with most of the infrastructure already available;

- Need to rebuild old existing infrastructure;
• High level of CO₂ emissions, but very low rate associated with cement production;

• Especially sensitive to pollution (acid rain, greenhouse effect) due to high population density;

• Often with geographic limitations, causing problems of raw material availability and space for waste disposal in landfills;

• Often highly dependent on foreign fossil fuel supply;

• High budgetary availability, but risk of collapse of welfare systems due to an aging population, lower working force, and good retirement conditions, consuming a great part of their budget;

• Higher perception of the importance of environmental issues in daily life and higher potential for consuming green products.

For these countries, the impact of cement CO₂ mitigation will be proportionally low. The main targets for these countries, which are much more important than focusing on the cement industry, would be to improve the operation of buildings (cooling and heating), as well as reducing the impact of vehicular individual transportation, mainly in the U.S. Savings in raw material is also a goal. From the perspective of the cement and concrete industries, the main proposed alternatives are:

1- Reduction in the generation of demolished concrete, through increased durability and increased use of recycled concrete, especially in small-sized European and Asian countries (around 300 million tonnes of concrete waste generated per year, based on the literature, with an embodied CO₂ of 36 million tonnes). The accumulated CO₂ over 10 years correspond to 36 million tonnes

**CO₂ mitigation: 0.27 percent (36 million tonnes)** referred to the global cement CO₂ generation;

2- Increasing use of Waste-Derived Fuel in order to mitigate the environmental burden caused by intensive industrialization and consequently waste generation, rather than
simply mitigating CO₂ emissions. Reduction in dependence on foreign imports of fossil fuels. Data extracted from Table 21 and proportionally evaluated according to the cement proportion of emerging and developed countries.

**CO₂ mitigation: 0.69 percent (92 million tonnes)** referred to the global cement CO₂ generation;

3- Use of Slag Replacing Raw Material Limestone to reduce CO₂ generation from raw material and improve raw meal burnability. Data extracted from Table 21

**CO₂ mitigation: 0.22 percent (30 million tonnes)** referred to the global cement CO₂ generation.

The implementation of these alternatives would result in a CO₂ mitigation corresponding to **1.18 percent (158 million tonnes)** over a 10 year period. Moreover, savings in raw material could be achieved, as well as fossil fuel preservation.

On a local basis, there are alternatives that could bring positive results.

- The perspective of allowing the use of up to 5 percent limestone filler in cement, currently being analyzed for the U.S. market, will be a major contribution for the local cement industry and for local society as whole. Hydraulic binder production will be increased without putting higher pressure on CO₂ emissions generation and without the need for building new plants. The result will be a CO₂ mitigation around 3 million tonnes (considering a 4 percent instead 5 percent cement substitution, in order to prevent the risk of exceeding the LOI standard requirement and a local cement production of 80 million tonnes).

**CO₂ mitigation: 0.22 percent (30 million tonnes)** referred to the global cement CO₂ generation;

- The US and the Canadian cement industries should stimulate the production of higher amounts of blended cement, using by-products as supplementary cementitious material (SCM) instead of using separate SCM in concrete. Blended cement production, rather than direct SCM addition to concrete, prevents the generation or at
least significantly reduces (more than 80%) the generation of CKD that must be discharged and landfilled, causing significant problems for the environment and leading to a waste of energy and loss of production. Moreover, the use of the limestone quarry could be optimized, saving non renewable raw material. The prevention of CKD generation in the U.S., for instance, could provide an increase in cement production, without further CO₂ generation or investments in new facilities, of around 1 million tonnes/year.

**CO₂ mitigation: 0.07 (10 million tonnes) percent** referred to the global cement CO₂ generation.

It must also be considered that the cement industry is much more capable of providing a more uniform, more adequate (compatibility clinker-SCM-gypsum) and better performing product. As mentioned in the previous chapter, developments in cement grinding are meaningful, with high efficiency separators and new hybrid systems of grinding, leading to the production of a hydraulic binder (cement + SCM) with more convenient grain size distribution, fineness adjustment, appropriate better heat of hydration, gypsum optimization, and strength development. Finally, the cement industry is much more qualified to control the quality of the SCM itself, of the final product, and more able to implement costly quality control than small concrete producers, most of whom cannot afford to have such controls. Stringent quality control is a main issue nowadays in the cement industry and the majority of plants (over 70 percent of production) in Europe and Brazil have had ISO-9000 accreditation for at least 10 years.

The proposed alternatives would allow CO₂ mitigation, on a worldwide basis, corresponding to 1.47 percent (198 million tonnes) over a 10 year period.

10.3.3 Global alternatives

Some alternatives can be implemented on a general basis, although its impact will be variable, according to specific problems for each plant. These alternatives are often less expensive than some of the previously proposed ones. The following results come from Table 21. To define the proportion for emerging and developed countries, a cement production of 800
million tonnes (950 less 150 million tonnes supposed to be updated within the Chinese industry) and 550 million tones, respectively, were considered:

- Raw Meal Burnability Optimization: CO₂ mitigation: 0.15 percent (20 million tonnes), being 0.09 percent (12 million tonnes) for emerging countries and 0.06 percent (8 million tonnes) for developed countries;

- Plant Optimization: CO₂ mitigation: 0.36 percent (49 million tonnes), being 0.22 percent (29 million tonnes) for emerging countries and 0.14 percent (20 million tonnes) for developed countries.

Finally, the use of by-products replacing clinker/cement is undoubtedly well known as the best alternative for CO₂ mitigation and also for enhanced durability of concrete However, it cannot be proposed as a “panacea”, because the key issue for its use is mainly related to cost and availability of these by-products on a local basis. Sometimes, local solutions can be more easily implemented, although without the same environmental benefits as substituting by-products to clinker.

In most Pacific rim nations, the availability of natural pozzolan in volcanic rocks is significant and these should be used to produce natural pozzolans in order to replace clinker. This would imply the consumption of raw materials, but further savings largely compensate for its use. In several other countries, from Africa to South America, the high availability of kaolinite clays could be a great source for calcined clay production. In highly industrialized countries, slag and fly ash will probably be the most suitable alternatives. In many countries, there exist several simultaneous alternatives and the best option will be cost driven. By increasing the amount of SCM (including volcanic rocks and calcined clay) at a rate of 1 percent per year in some countries, mainly in the U.S., China, and India, some CO₂ mitigation could be achieved, while improving the durability of concrete structures and providing fossil fuel savings. Considering the data obtained in Table 21, as well as the proportion between cement production in emerging countries (950 million tonnes) and developed countries (550 million tonnes), the following results are obtained
CO₂ mitigation: 2.90 percent (392 million tonnes) over a 10 year period. This corresponds to 1.83 percent (247 million tonnes) for emerging countries and 1.07 percent (145 million tonnes) for developed countries.

A further alternative to promote sustainability is the contribution of the growing use of concrete pavement, aimed at reducing CO₂ emissions. CO₂ generation due to transportation corresponds to 25-30 percent of CO₂ emissions worldwide and represents about 7 billion tonnes of CO₂, a huge amount. Any contribution to mitigate this enormous amount of CO₂ will have a significant impact. The main advantages of using concrete pavement could translate into a 20 percent fuel saving for heavy trucks and a reduction in time spent in traffic jams (which cause a 20 percent increase in vehicular emission), due to lower maintenance compared with asphalt. It is not easy to evaluate how much traffic could be improved, nor is it the objective of this work. This should be done by specialists in the field. However, for a simple evaluation and considering a conservative estimation of around 0.01% improvement in circulation through reduction in traffic jams caused by maintenance, as well as savings in fuel, a CO₂ mitigation of 700,000 tonnes/year could be achieved. This amount of CO₂ emission corresponds to the equivalent CO₂ resulting from the cement consumed in building about 185,000 homes for low income people every year (a 42 m² house, consuming 3.75 tonnes of cement, of which 1.25 tonnes is used in the foundation- (Personal communication of Esper from the Brazilian Portland Cement Association). Concrete pavement should be implemented mainly in emerging countries that are in the process of building their infrastructure, in order to achieve more durable solutions.

10.3.4 CO₂ generation due to population increase

To evaluate the CO₂ generation due to population increase, a birth rate of 2 percent for emerging countries and a 1 percent for developed countries was considered. The population of emerging countries was considered as 4.5 billion people, while for developed nations it was estimated at 1.5 billion people. The resulting accumulated population increase over 10 years corresponds to 984 million people for emerging countries and 157 million people for developed countries. The mean cement consumption for emerging countries were considered as 0.25 tonnes/inhabitant and 0.35 tonnes/inhabitant in developed countries. The resulting CO₂ amounts correspond to 245 million tonnes (1.81%) in emerging countries and 55 million
tonnes (0.40%) in developed countries, with the percentages being referred to the accumulated CO₂ generated by the cement industry over the period at the current 1,350 million tonnes per year.

### 10.4 Evaluation of the Proposed Alternatives

The possibilities for CO₂ mitigation must take into account different scenarios regarding developed and developing countries.

The proposed alternatives, according to their priority in emerging and developed countries, are summarized in **Table 22**.

The alternatives for CO₂ emissions mitigation presented are feasible and the proposed time span of 10 years is sufficient for achieving the proposed goals. They were defined not only according to the magnitude of CO₂ mitigation, but also considering the social and economic impact they will have in different regions.

It can be seen that the proposed possibilities will permit reaching a net CO₂ mitigation of 441 million tonnes (3.27 percent) for emerging countries and a net CO₂ mitigation of 316 million tonnes (2.34 percent) for developed countries, or a total of 757 million tonnes (5.61 percent) despite an increase in population and without putting major economic pressure on the industries. On the contrary, industries will benefit from the proposed alternatives, by increasing production, reducing energy consumption, increasing their profit margin, and providing better products, among other benefits. For public administrations, these proposals help alleviate budget restraints. The results are not spectacular, but they are realistic and can be effectively achieved with a very positive impact on society. Moreover, local alternatives can provide further advantages. Among these alternatives, the production of belitic cement in countries like Japan and India can be mentioned and the production of cement mineralized by CaF₂ and SO₄⁻⁻.
<table>
<thead>
<tr>
<th>Alternatives</th>
<th>CO₂ Mitigation (million tonnes/year)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Improving Durability of Concrete</td>
<td>75 (0.55%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduce Cement and Concrete Waste</td>
<td>51 (0.38%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increased Use of WDF</td>
<td>172 (1.27%)</td>
<td>92 (0.69%)</td>
<td></td>
</tr>
<tr>
<td>Upgrading Chinese Cement Industry</td>
<td>86 (0.64%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduction of Electrical Energy Consumption (Asia and Africa)</td>
<td>14 (0.10%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduction in Demolished Concrete Generation</td>
<td></td>
<td>36 (0.27%)</td>
<td></td>
</tr>
<tr>
<td>Slag Replacing Limestone as Raw Material</td>
<td></td>
<td>30 (0.22%)</td>
<td></td>
</tr>
<tr>
<td>Use of Limestone Filler in Cement (USA)</td>
<td></td>
<td>30 (0.22%)</td>
<td></td>
</tr>
<tr>
<td>CKD Mitigation in USA</td>
<td></td>
<td></td>
<td>10 (0.07%)</td>
</tr>
<tr>
<td><strong>Partial total</strong></td>
<td><strong>398 (2.94%)</strong></td>
<td><strong>198 (1.47%)</strong></td>
<td></td>
</tr>
<tr>
<td>Raw Meal Burnability Optimization</td>
<td>12 (0.09%)</td>
<td>8 (0.06%)</td>
<td></td>
</tr>
<tr>
<td>Plant Optimization</td>
<td>29 (0.22%)</td>
<td>20 (0.14%)</td>
<td></td>
</tr>
<tr>
<td>Use of SCM</td>
<td>247 (1.83%)</td>
<td>145 (1.07%)</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>686 (5.08%)</strong></td>
<td><strong>371 (2.74%)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Total emerging and developed countries</strong></td>
<td></td>
<td><strong>1057 (7.82%)</strong></td>
<td></td>
</tr>
<tr>
<td>CO₂ due to population increase</td>
<td>245 (1.81%)</td>
<td>55 (0.40%)</td>
<td></td>
</tr>
<tr>
<td><strong>Difference</strong></td>
<td><strong>441 (3.27%)</strong></td>
<td><strong>316 (2.34%)</strong></td>
<td></td>
</tr>
</tbody>
</table>

The dissemination of belitic cement production will probably be limited in the 10-year time span considered in this work, while the production of mineralized clinker could be more
easily disseminated, eventually reaching a market share of 200 million tonnes within the 10 year time span.

Finally, the main challenge for implementing these alternatives will not be of a scientific nature, since the recommended measures are somewhat simple and largely known in the cement and concrete community. The challenge is not of an economic nature, since their implementation will contribute to increasing the profit margin of companies, as previously mentioned. It is not linked to environmental issues, since there is a meaningful CO₂ mitigation and other environmental contributions. The main challenge will be of a human nature, because of such phenomena as lobbies, corruption, short term vision, and this point must be continuously emphasized.

10.5 Driving Issues for Sustainability in the Cement and Concrete Industries

Both the cement and the concrete industries play a key role in sustainable development. Both risk being penalized due, among other reasons, to the a lack of or inadequate communications with society, politicians, environmental agencies, and other institutions.

Based on the evaluations in this thesis, it has been seen that significant progress as can be achieved, often at low cost, but good logistics and political implication will be required.

The main issues for achieving sustainability in cement and concrete production and use, and for contributing to fairness in the world order, can be summarized as follows:

- Developed countries are responsible for a much higher generation of greenhouse emissions than developing countries and this situation will remain for a long time. While in emerging countries, CO₂ generation is mainly an attempt to solve serious social problems; the sources of greenhouse generation in developed countries are of a superfluous nature.
- The cement and concrete industry should not be the main focus of concern regarding the greenhouse effect from a global point of view, there are other priorities. Nevertheless, further efforts to reduce CO₂ emissions must be undertaken;

- Poor people from emerging countries have been often neglected, by providing them with inadequate technological solutions for housing and sanitation programs. Moreover, social, economic, and environmental policies have focused on short-term solutions, making them lose, for instance, many of the best advantages provided by concrete in the long term;

- Best solutions for the cement and concrete industries must consider all the issues involved in the sustainable concept in a realistic way, considering cost, benefit, feasibility, social contribution, and environmental burden alleviation;

- The sustainable use of cement and concrete is not a matter of technological knowledge, which is impressive nowadays, but rather a matter of lack of ethics, vision, and synergy, often leading to the offset of achieved technological progress. Current technological knowledge is more than enough to achieve much better performance of structures. Therefore, the key issue for sustainability is not technological;

- Concrete durability, even at higher initial costs, is much more important in emerging countries than in developed countries, as well as for poor people rather than rich people, because poor people cannot afford to pay for repeated maintenance and repair. Moreover, the economy of emerging countries, faced with budgetary constraints, cannot support rebuilding several times the same structure or carry out permanent avoidable maintenance;

- Short-term and low cost solutions have proved to be more expensive than opting for more durable, even if more expensive alternatives;

- Recycling concrete is just a palliative and transitory alternative, because prevention of concrete waste generation, due to enhanced durability, is the effective solution;
- Many of the problems in concrete or cement waste are due to the low-skilled labor force involved in the construction industry. This problem is a serious issue in emerging countries and has an impact on the environment, the economy, and social progress;

- The economic role of CO₂ emissions trading will certainly impact the search for promoting more intensive mitigation of greenhouse gases. The imbalance in cement production, with countries with decreasing cement demand and others grasping for higher consumption, will contribute to the trading process and multinational companies will be in the forefront of this process, through integrated economic and environmental policies;

- There will be many fewer cement plants and many more clinker grinding units worldwide, as well as a more intensive international trade of CO₂ emission due to integrated management and to possibly less stringent local environmental requirements;

- The global solution for mitigating CO₂ emissions should focus more on the concrete industry than on the cement industry. The lost embodied CO₂ in poor use of concrete is quite significant and much easier to solve than the costly equivalent CO₂ mitigation that could be achieved by the cement industry;

- Improving concrete durability, reducing concrete waste in emerging countries (through labor improvement and better work site management) are much more effective alternatives for CO₂ mitigation than just focusing on the cement industry. The prevention of excessive consumption of natural resources and unnecessary landfilling, are further advantages for society;

- Without an accreditation program for concrete producers, especially small and medium-sized ones, progress in concrete use will not be achieved. However, the issue for these small and fragmented companies is difficult to solve, given the restricted economic feasibility for these groups to invest in accreditation programs. The main
proposal to counteract this problem is their accreditation in increments and especially the implementation of cooperatives to minimize costs;

- The solution for global sustainability will be different according to the state of industrial development of each country.

Finally, it can be seen that it will be much more effective and less costly to reach sustainable production of concrete than to improve the production of cement, but the required time to implement the proposed alternatives, and mainly to notice their benefits, will surely be longer. The expectation of short-term results is so deeply impregnated in our world that it may lead to disappointment, thereby discouraging authorities and users. To counteract this tendency, perseverance will be required, as well as good communication between all participants in the construction chain.

There have been, however, some encouraging steps already taken toward sustainability. In Netherlands, for instance, the mean rate of clinker replacement by SCM is about 45 percent [Rik Van Loo, personal communication], the rate of fossil fuel replacement by WDF in Switzerland amounts to 40 percent [Personal communication]. The Holcim Cement Group, for instance, has a commitment to reduce its CO₂ emissions in the next 10 years by 20 percent compared to emission levels in 1990 [Anonymous, Concrete International, March 2003]. The perspective of a modernization of Chinese cement production is positive, the possibility of using up to 5 percent limestone filler in U.S. cement production, the ongoing broad programs to improve labor force skills in the Brazilian market, the upgrading of the cement industry in Eastern Europe as a consequence of successive mergers, are only some of the encouraging steps. The pace of implementing proactive alternatives in the cement industry regarding CO₂ mitigation and increasing environmental contributions is faster than that in the concrete industry. However, the greatest challenge, and the most important one, is to improve concrete durability.

Our society has spent the last 50 years causing severe damage to the environment without promoting a more just distribution of wealth. Consequently, it is not possible to carry out the necessary solutions in a short time frame. Prevention is still the best and least costly sustainable alternative and the increase of concrete durability is a key issue. Efficiency is to do well and efficacy is to do what is necessary. It is time to stop implementing palliative solutions and find
affordable and more durable solutions. Otherwise, the risk of being inefficient is too high and the whole of world will have to pay the “bill” of social and environmental disaster.
11. CONCLUSION

Sustainable development is an answer to exacerbated consumption and market speculation, due to less productive investments, generated by the present globalization process. It is a transition process necessary to adjust societal requirements. Sustainability is more than a challenge; it is a great opportunity for promoting a fairer and more equitable society, as well as for making more productive, socially responsible and profitable investments.

Sustainability has often been associated solely with the environment impact and climate change. The problem of the environment is undoubtedly a serious issue, but sustainability is a much more complex subject. Sustainability involves, among other parameters, economic issues in order to maintain a healthy economy, to meet social equity and human welfare needs as well as achieve technological development and pollution mitigation. Continuing urbanization reinforces the importance of creating a healthy and pleasant environment that is sustainable for future generations. The built environment constitutes one of the main supports for economic development and social welfare, and the provision of infrastructures, buildings and utilities are major resources that are a need for the development of nations, communities and business.

The ongoing contribution toward the sustainable development by the cement and concrete industries is remarkable, despite the community’s unfair perception regarding the performance of these two industrial sectors. The cement industry is frequently perceived and described as a polluting industry, an intensive energy consumer and a source of greenhouse gas (CO₂) emissions. This reveals a certain neglect on the part of the industry with regards to its image.

The progress achieved by the cement industry is meaningful. Dust emissions have been reduced by 90 percent in the last 30 years, the specific energy consumption by 50 percent over the same period, with a equivalent mitigation of CO₂ emissions. As environmental regulations became more stringent, further deleterious environmental emissions (NOx and SOx) and electrical energy savings have been drastically reduced.
Of course, the cement and concrete industries have an adverse impact on the environment, but their contribution to alleviating the environmental burden caused by other industries is not always recognized. The burning of industrial waste in cement kilns, that would otherwise have been incinerated or dumped, is a good example of the beneficial contribution of the cement industry to sustainable development. Industrial waste burning has reached a level of around 5 to 10 percent worldwide, but in some countries, the cement industry is already replacing 40 percent of its fuel consumption by the burning of waste. The valorization of industrial by-products (fly-ash, blast furnace slag, silica fume, etc) is another major environmental contribution, besides adding economic value to these by-products. Globally, an average of 10 to 15 percent replacement of clinker by these by-products has already been achieved in many countries. These two contributions of the cement industry are extremely important. However, the main challenge now is to make the cement and concrete industries greener and help them perform better from a sustainable development point of view.

CO₂ emissions generated by the cement industry represent only 6 percent overall of worldwide emissions, but it is just 3 percent in the European community due to more pragmatic cement standards and the transformation of most of the operational units into more modern facilities. It is not emphasized enough that the 6 percent CO₂ emissions overall is still much less than the CO₂ emitted by the transportation industry, which represents around 25 percent. It is also much less than the CO₂ emitted during the operation of a building, which corresponds to 40 percent of the CO₂ emitted by this building during its whole life cycle.

Keeping in mind that the cement industry is often pointed out as a great source of greenhouse gas, a pertinent consideration consists in looking at the social meaning of the one tonne of CO₂ emitted when building a house and one tonne of CO₂ emitted by a car driven by a single user. Certainly, the impact on climate change in both cases is the same, but from a social point of view, a house is usually a true necessity, while the private use of a means of transportation is the result of negligence in our “social” education or of public transportation agencies. An interesting new concept should be introduced, that of incorporating three classes of emissions: Necessary Greenhouse Emissions (NGE), addressed to satisfy minimum needs for a better standard of living, among these sanitation, houses, school, hospital, etc.; Transitory
Greenhouse Emissions (TGE), dealing with CO₂ emissions that can be reduced through technological development such as in the heating and cooling of buildings and in energy generation plants or by minimizing hazardous reasons such as forest fires; and finally, Superfluous Greenhouse Emissions (SGE), corresponding to the emissions produced by transportation systems, mainly by cars.

Concrete is a material necessary to build infrastructures, to help mitigate social problems and to create leisure areas, but unfortunately, it is still perceived as a low technological added-value product even though extraordinary progress has already been achieved. Concrete is a durable product that should last much longer than it usually does. Moreover, the impact of its production on the environment should be better evaluated.

According to Hawken et al., only 6 percent of the total global flow of materials, around 450 billions tonnes/year, actually ends up as consumer products whereas many of the virgin materials are being returned to the environment in the form of harmful solid, liquid and gaseous waste. In the case of the concrete industry, this percentage is over 90 percent, suggesting a significant level of incorporation of virgin materials in the final product. Even the reuse of concrete waste from demolition is environmentally friendly.

The question that arises is why have the cement and concrete industries often been pinpointed as a source of "major environmental problems". The answer is simple. For the cement industry, the following issues can be mentioned:

- Lack or inadequate communication with the community and politicians;
- Low lobbying ability;
- Unnecessarily defensive position regarding environmental themes, under the assumption that this information were strategic information;
- Poor image as a low technological added-value product in contrast with the public’s perception of a rich industry;
- Mistrust by cement users and environmental agencies.
For the concrete industry the main points that can explain this perception are:

- Fragmented profile of the sector, spread into many small companies;
- Difficulty in reaching higher standards of performance, sometimes due to higher production costs;
- Difficult to change technical standards;
- Lack of quality assurance often associated with the simplicity of making concrete or due to inherent costs;
- Low qualified labor force in the concrete industry resulting in bad use of a good product;
- Insufficient promotion of the progress achieved;
- Request from owners, builders and even financing from financing agencies, private or often governmental, for faster and lower construction costs instead of looking for higher durability and longer life span of concrete structures.

Assuredly, there are presently weaknesses in cement and concrete production processes in order to improve the performance of these industries from a sustainable point of view, so that research and development in this field must continue. However, it must be emphasized that the current technological level reached by the cement and concrete industries in some countries should be more than enough to give hope that a much more sustainable use of cement-derived products, providing much better performance, could be achieved overall by the cement and concrete industries worldwide.

In order to enhance the sustainable production of cement and concrete the followings essential recommendations can be made.

First of all, the cement industry will have to optimize its production independently of available facilities, while concrete users should be more conscious that better performance can be reached even for conventional concrete, by simply applying very fundamental and already well-known concepts in certain parts of the world. The implementation of ISO-9000 accreditation helps to reach the target of better environmental performance and quality production as well as achieving a more uniform product.
The burning of waste by the cement industry must increase and the process of getting the necessary permits must be accelerated. This can be done through a synergetic effort between environmental agencies and the industry or local associations. A worldwide average level of waste burning of at least 15 percent should be achieved and possible higher levels encouraged on a local basis. In Switzerland, a level of 40 percent has already been achieved. The burning of waste in wet kilns, an old technology characterized by a high energy consumption, should be compulsory.

It will be extremely important to support and facilitate access by the Chinese and Indian cement markets, which are still very much closed markets, to up-to-date technologies when replacing old manufacturing technologies (shaft kilns, wet and long dry kilns). These countries presently play a key role in worldwide cement consumption. This trend will continue for many years to come, since the urbanization rates of China and India are still very low compared to other developed countries.

The U.S., which is also a major consumer in the cement market, still has a significant share of its production based on old technology, so that some U.S. cement companies will have to undergo technological changes to more modern and better-controlled production units, even though recent progress has been achieved in this field after foreign companies increased their share of the U.S. market. The forecast use of limestone filler will contribute toward sustainability, by increasing local production without increasing CO₂ emissions.

The use of by-products in cement and concrete production is probably the second easiest way to reduce the CO₂ emissions associated with cement and concrete manufacturing. This practice should be strongly encouraged. It is necessary, however, to make the required changes in technical standards, which are often not adapted for this type of binder. The problem is that it is always a slow process. More pragmatic and updated standards are required to achieve such a change. The scientific community and the industrial sectors involved must make an effective contribution, not only by transferring their knowledge but also by helping accelerate the necessary changes. Changes, or at least adjustments, in standards must occur in order to focus on
the durability of concrete and the performance of cement-related products. Fair specifications for new products have to be developed, providing the necessary feedback and support for potential users of these technologies.

Reaching a sustainable use of concrete presents a special challenge. In developing countries it will be essential to reduce the sometimes very high level of waste on construction sites. Part of the solution resides in the use of precast elements, but the main problem lies in the very poor quality of the labor force used in civil construction in developing countries. An intensive and broad labor force training program must be developed as well as better job site management techniques for engineers. Even a good concrete, when badly used still represents an environmental problem, therefore, the training of skilled professionals is essential, mainly in developing countries.

The inadequately low expected life span of infrastructures must be urgently corrected. With more durable infrastructures such as roads, bridges, dams, etc., and therefore less required maintenance, more budgets can be allocated for necessary social improvements such as sanitation and schools, hospitals and houses for low-income earners. Investment in sanitation is a key element for health. The cost of hospital cares is almost three times higher than the corresponding investment in sanitation.

With just these alternatives – waste burning, higher by-products use, better labor force and the use of more durable concrete, a great advance toward sustainability could be achieved very rapidly. Further recommendations can be evaluated, case by case, and then implemented to obtain a significant proactive global impact for the environment.

For example, the increasing use of concrete admixtures can constitute a further contribution to the durability of concrete and to materials savings, including water, especially in developing countries. The main barrier to implementing such use is their impact on the initial cost of concrete, as well as a lack of tradition in their use. Quality and compatibility of admixtures must be ensured in order to prevent the introduction of poor products on the market simply to comply
with low price requirements. An increase in the demand for admixtures should promote a more competitive price, and the gains achieved in durability largely compensate for their use.

The larger use of concrete as a paving alternative can provide a major contribution to mitigating environmental problems and budgetary constraints, since the economic, environmental and social costs of travel represent at least 5 percent of the GDP. The initial higher cost of concrete highways is largely compensated by the much higher durability of concrete pavements when compared to flexible pavements, due to their lower maintenance and the much smaller impact on traffic flow. Another main advantage of concrete pavements of an indirect nature is that it reduces the amount of lost hours and stress for users, thereby mitigating deleterious environmental emissions during traffic jams. It results also in a lower risk of accidents and injuries for drivers and pedestrians and less vehicle maintenance. Concrete paving can also contribute to reducing surrounding temperatures in urban areas of hot geographical locations, providing some energy savings and CO₂ mitigation associated with less cooling requirements. Moreover, cement is a product often manufactured in local markets, while petroleum used in asphalt production is often an expensive imported product for many countries, consequently the partial use of concrete as a paving material could provide a further benefit for the local economy.

Good projects for low income social housing are essential. Materials selection, construction technique and a good typology and landscape program are essential to reduce waste to be disposed during construction and maintenance requirements, contributing to the saving of raw materials as well as improving the use of natural resources such as sun light, wind ventilation, etc. Moreover, with the current available concrete technologies (interlocking blocks, lightweight concrete, colored blocks, etc), the aesthetics of such buildings and their vicinity can be improved, providing a greater sense of pride for dwellers and more respect for their living environment, thereby contributing to less social violence.

It is also important to improve pedestrian mobility by building sidewalks of higher durability that could last at least 30 years. In many developing countries, one of the big sources of concrete demolition are bad sidewalks showing very premature wear, sometimes within a few months. A good sidewalk network can also help integrate the physically-challenged in the
consumer market, providing them with more dignity, and contributing as well to a more pleasant atmosphere, particularly in megacities.

The increase in concrete recycling can be a further significant contribution to sustainability. Higher levels of better-recycled aggregates have to be achieved. The recycling process should be fomented by more competitive prices, lower taxes, better technologies and good promotion as well as pragmatic standards implementation. Japan and many European countries are at the forefront of construction and demolition waste (CDW) recycling due to the scarcity of raw materials and of space for landfill.

To implement many of the proposed alternatives for a more sustainable production and use of cement and concrete, great efforts will be required. Conservative lobbies will have to be confronted, old habits will have to be changed, paradigms will have to be broken and authorities will have to change their administration philosophies moving away from selection on the basis of low initial cost to longer durability constructions. These are some of the main obstacles to be faced, among other difficulties. However, of all the issues affecting sustainability, one is emphasized more and more often: ethics. The available technology exists, there is enough knowledge, technological progress has been remarkable and limited budgetary constraints can be optimized, but if there is no ethics from authorities, companies and individuals, all these accomplishments will simply be offset.

The main agents that presently contribute to achieve a more ethical society are: Non Governmental Organizations (NGOs), governmental agencies that provide funding, environmental agencies, non profit research centers, and the media by denouncing unacceptable behavior and encouraging good practices. The roots of sustainability are education and health care, allowing a better-skilled professional with deeper environmental and social concerns access into the market. Universities will have to enhance their students’ training on environmental and social matters in order to provide, in the future, new professionals with a holistic vision of their professional activities.
In order to promote sustainability it is urgently needed to evaluate the success and progresses achieved by some countries in their environmental and social policies and promote these achievements. The concern about future generations start by improving the conditions of present generation, otherwise it will be not surprising that we will be discussing an even worst scenario in the next decades.
REFERENCES


Coulombe, L.G., Ouellet, C.- (1994)“The Montée St-Rémi overpass crossing Autoroute 50 in Mirabel. the savings achieved by Using HPC”. Concrete Canada Newsletter, Vol.2, No.1


Kihara, Y.- (1999) “Co-processamento de resíduos em fornos de cimento: tendências”, Proceedings of II Seminário Desenvolvimento Sustentável e a Reciclagem na Construção Civil,
Organised by Comitê Técnico do IBRACON CT-206-Meio Ambiente, São Paulo, Brazil, pp. 35-43.


**Lefebvre, G.-** (2001) "Maintenance is a Business", World Cement, Vol. 32, No.8, pp. 48-49


The Economist.- (2002) “How to save 1m children a year”, July 26\textsuperscript{th} -12\textsuperscript{th}.


