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Global Warming Impact on the Cement and Aggregates Industries

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Summary

CO_2 related energy taxes are focusing essentially on fuel consumption, not on actual CO_2 emission measured at the chimneys. Ordinary Portland cement, used in the aggregates industries, results from the calcination of limestone (calcium carbonate) and silica according to the reaction:

$$5CaCO_3 + 2SiO_2 \Rightarrow (3CaO,SiO_2)(2CaO,SiO_2) + 5CO_2$$

The production of 1 tonne of cement directly generates 0.55 tonnes of chemical-CO_2 and requires the combustion of carbon-fuel to yield an additional 0.40 tonnes of CO_2. To simplify: *1 T of cement = 1 T of CO_2.* The 1987 1 billion metric tonnes world production of cement accounted for 1 billion metric tonnes of CO_2, i.e. 5% of the 1987 world CO_2 emission. A world-wide freeze of CO_2 emission at the 1990 level as recommended by international institutions, is incompatible with the extremely high cement development needs of less industrialized countries. Present cement production growth ranges from 5% (China, Japan) to 16% (Korea, Thailand) and suggests that in 25 years from now, world cement CO_2 emissions could equal 3,500 million tonnes. Eco-taxes when applied would have a spectacular impact on traditional Portland cement based aggregates industries. Taxation based only on fuel consumption would lead to a cement price increase of 20%, whereas taxation based on actual CO_2 emission would multiply cement price by 1.5 to 2. A 25-30% minor reduction of CO_2 emissions may be achieved through the blending of Portland cement with replacement materials such as coal-fly ash and iron blast furnace slag. In year 2015, assuming that world Global Climate treaties might authorize an amount of this Portland blended cement production in the order of 1850 million tonnes, the complementary need for new low-CO_2 cementitious materials, in the range of 1650 million tonnes, requires the introduction of a different technology. Novel geopolymeric poly(sialate-siloxo) cements, which do not rely on the calcination of limestone (and accompanying release of CO_2), are low-CO_2 cementitious materials providing similar properties than current high-CO_2 Portland cement. The technology reduces CO_2 emission caused by the cement and aggregates industries by 80%.

Global Warming Impact on the Cement and Aggregates Industries

1.0 INTRODUCTION: CO_2 Emissions during Portland cement manufacture

The EC Commission, seeking to limit carbon-dioxide emissions linked to global warming, recommended on September 25, 1991, that member states adopt a new energy and fuel tax equal to $10 per barrel of oil, in the year 2000. Crude oil now costs about $20 per barrel. Half the tax would be a general energy tax, with the other half tied to a fuel's carbon content. For example, a $10 per barrel oil tax would correspond to a $14 tax on coal and a $5 tax on nuclear and hydroelectric power, based on equivalent amount of energy produced by the respective sources. In the year 2000, when the tax is fully in place, it would lead to a gasoline price increase of only 6 percent, but a 61 percent rise in coal prices to industry. Six energy-intensive industries - steel, chemicals, glass, paper, cement and non-ferrous metals - would receive some «special treatment» under the new tax.

Yet, the tax is based on energy and fuel consumption, not on actual carbon-dioxide emission measured at the chimneys. Chemical reactions which produce carbon dioxide -chemical-CO_2 as opposed to the carbon-dioxide which results from the combustion of carbon-fuel- are not taken into account, even though chemical-CO_2 emissions could represent, in the near future, 15% to 20% of today's total carbon-dioxide emissions. This is particularly the case for cement and iron manufacturing. Very few papers are dealing with the issue of carbon-dioxide produced during Portland cement manufacturing [Davidovits, 1991]. In 1990, the US D.o.E. Carbon Dioxide Information Analysis Center, endorsing the validity of chemical-CO_2 emissions, provided data which included carbon-dioxide emissions from fossil-fuel burning *and* cement production [Zurer, 1991]. The topic was also discussed at a recent Portland Cement Association Conference with supplementary world statistics and technical data [Schmidt, 1993], and at the 1993 American Ceramic Society Meeting [Davidovits, 1993].

Cement (ordinary Portland cement) results from the calcination of limestone (calcium carbonate) and silico-aluminous material according to the reaction:

$$5CaCO_3 + 2SiO_2 = (3CaO,SiO_2)(2CaO,SiO_2) + 5CO_2$$

The production of 1 tonne of cement directly generates 0.55 tonnes of chemical-CO_2.

Iron metallurgy involves reduction of iron ore Fe_2O_3 into FeO and Fe, combustion of the coke and decarbonation of limestone. The by-product, blast furnace slag, is a molten material which appears above the pig iron at the bottom of the blast furnace. The main component of slag, melilite, is a solid solution of

$$(2CaO.Al_2O_3.SiO_2)(2CaO.MgO.2SiO_2),$$

comprising 40% by weight of CaO. The production of 1 tonne of iron results in the by-production of 0.6 tonnes of iron slag and generates 0.19 tonnes of chemical-CO_2.

Table 1 displays the world production of cement and iron for 1987 and the associated chemical-CO_2 emissions. For iron, about 1/3 of the production represents recycled metal which, therefore, does not generate any slag and chemical-CO_2. In terms of chemical-CO_2 emissions, the 1987 iron world production of 500 million tonnes corresponds to 330 million tonnes of blast-furnace iron.

Table 1: 1987 World production in million of tonnes (MT.) for cement, iron and resulting chemical-CO_2.

Contrary to general belief, chemical-CO_2 emission from cement manufacturing is 8 times higher than emissions resulting from metallurgical activities. The production of 1 tonne of cement which directly generates 0.55 tonnes of chemical-CO_2, requires the combustion of carbon-fuel to yield an additional 0.40 tonnes of carbon-dioxide.

To simplify: 1 T of cement = 1 T of carbon-dioxide.

The 1987 1 billion metric tonnes world production of cement accounted for 1 billion metric tonnes of carbon-dioxide, i.e. 5% of the 1987 world carbon-dioxide emission. This is equivalent to the carbon-dioxide generated by the entire Japanese industrial activity.

Recognizing the need to save energy and raw materials, the iron-, glass- and chemical industries are presently involved in programs aimed at increasing the use of recyclable materials. Indirectly, these industries may present programs which demonstrate their effort to contribute in the slow-down of chemical-CO_2 emissions. On the other hand, the recycling of Portland cement will actually remain a hypothetical task for decades. It is probably inevitable, given this situation and the influence of D.o.E.. data, that some environmentalists and politicians will again look at the cement and concrete industries in unfriendly terms.

2. The basic needs for Concrete and Cement in developing countries

But the greatest difficulties concern the developing countries, which are in urgent need of implementing a framework capable of producing the necessary alimentary goods, concrete and building houses, and covering the entire fundamental needs of their population. The stage of any national economic development is reflected by the growth rate of infrastructures and highlighted by the growth rate of the cement production. Fig. 1 displays the atmospheric carbon-dioxide concentration increase for the time range 1840-2000 and the development of world Portland cement manufacture since its invention in 1840. Since the 1970 decade, due to the exponential uses of concrete, cement production has increased at a much higher speed than atmospheric carbon-dioxide concentration, i.e. than all major carbon-dioxide emissions caused by human activities, such as energy and transportation. As time goes by, it will thus have a greater influence on the trends of CO_2 emissions and the predicted BaU values for future atmospheric carbon-dioxide concentration should be corrected accordingly. Predicted values for cement production are those obtained according a BaU scenario (Business as Usual), which assumes a continuation of present demographic and industrial trends, without any major technological revolution and other particular restrictive measures.

Figure 1: Atmospheric CO_2 concentration (ppm) and world Portland cement production (million tonnes) for the time frame 1840-2000 (BaU). Sources: IPCC and Cembureau.

In developing countries, especially China and India, and in the industrialized Pacific region (South Korea, Taiwan) the increase in cement production has followed an exponential trend since the seventies, contrasting sharply with western countries (USA, EC) where cement production remains constant. Potential for concrete and need for cement manufacture in developing countries are tremendous. Fig. 2 shows the cement production increase for China and India to be compared with the stagnation for USA and Italy (major European producer). In 1975, China's cement productions and that of the US were at the same level. In 1990, China produced 4 times more cement and India's production reached USA level.

Figure 2: Annual cement production for China, India, Italy, USA in million tonnes (MT.). Source: Cembureau.

The shift in world cement production from the industrialised countries towards the developing countries is illustrated in Fig. 3 which displays world cement production for the different economic regions in 1984 and 1993.

Figure 3: Shift in world cement production between 1984 and 1993.

The question now is whether this trend will continue. There can be no doubt about the on-going nature of the present evolution, since other developing countries, like Thailand and Mexico, are becoming listed in the 15 first world cement producers. In this respect, the lists of Table 2 provide interesting comparative data.

Table 2: Production of cement in major countries for 1975 and 1990 in million of Tonnes and use in kilogram per capita (Source: Cembureau).

Under these conditions, a world-wide freeze of carbon-dioxide emission or Portland cement production at the 1990 level as recommended by the EC, could easily be conceivable in industrialized countries but, in contrast, incompatible with the development needs of less industrialized countries. Bearing in mind that international actions aimed at reducing carbon-dioxide emission must be undertaken, a drastic change in the cement-based systems involved in the utilization of concrete is necessary. Fig. 4 displays the predicted annual world production of cement with the BaU scenario, and carbon-dioxide until year 2003. The freeze requires the search for alternative binders and their production. We are discussing this issue in the next chapters. Yet, concretes should utilize less calcium-based cements, the latter being replaced by Calcium-free binders (sodium- or potassium-based) providing similar cementitious properties, such as the Geopolymeric cementitious systems developed by the author (alkali-activated alumino-silicates).

Figure 4: Predicted world annual production of Portland cement and connected carbon-dioxide (BaU). Potential market for Calcium-free cements assuming freeze of Portland production at 1990 level [Davidovits, 1991].

With the assumption that Europe (EC) and USA will commit themselves to such a costly freeze, third world cement production will continue to grow and become the major source of carbon-dioxide emission. Fig. 5 illustrates BaU values for World Cement-carbon-dioxide, (years 2000, 2015), assuming a 2.5% and 5% yearly increase, respectively, and «frozen» Europe (EC) total carbon-dioxide emission at 1990 level.

Figure 5: BaU value for World Cement-carbon-dioxide with 2.5% and 5% yearly increase and «frozen» Europe (EC) total carbon-dioxide emission at 1990 level, million tonnes (MT.).

The question could be raised on the probability of having a constant growth in the 5% range. Present annual cement production statistics reproduced in Table 3 are suggesting an average growth ratio in favour of the 5% increase scenario.

Table 3: Present Cement production growth

In 25 years from now, world cement carbon-dioxide emissions could equal the 3,500 million tonnes total carbon-dioxide production of Europe (EC), -industry+energy+transportation. This addresses the need for solutions and new technologies adapted to the economy of the developing countries.

3. Minor Reduction of CO_2 Emissions with Blended Cements

Two traditional methods may help to reduce chemical-CO_2 emissions in cement manufacture.
1) reabsorption of atmospheric carbon-dioxide during the carbonation of concrete;
2) blending of Portland cement with industrial by-products;

3.1. Concrete as a sink for CO_2?

During hardening, the Portland cement paste reacts with atmospheric CO_2. Theoretically, it could be possible to keep a certain amount of concrete to recarbonate itself. This chemical reabsorption of CO_2 which is actually very slow, taking decades to fulfil, has been accelerated in CO_2 enriched precast concrete products. However, this concept is not always desirable, for any recarbonation in calcium carbonate will reduce the pH level of the cement and prevent the beneficial passivation of the iron reinforcement bars taking place and protect them against corrosion. Yet, intensive

CO_2-precast manufacture could be a partial solution to some Portland cement plants.

3.2. Blending of Portland cement

The search for Portland cement replacement materials has become a challenge for the international cement community. These minerals are either of natural origin, like natural pozzolans, or industrial by-products, sometimes considered as waste, like blast furnace slag and fly ash, a residue of the combustion of the finely ground coal in the generation of electric power. Properties of blended cements obtained by replacing a certain amount of Portland cement with these mineral additives, have been intensively studied for over thirty years in several laboratories. The results of this research are disclosed at the well established International Conference on the Use of Fly Ash, Silica Fume, Slag and other Mineral By-Products, held every third year since 1983, and initiated by CANMET (Canada Centre for Mineral and Energy Technology) and ACI (American Concrete Institute).

3.2.1 Natural pozzolans

True pozzolans are vitreous pyroclastic materials produced by violent eruptive volcanic action. The Ancient Romans used natural pozzolans for producing their famous Roman Cement, obtained by blending lime and pozzolan. Properties of blended cements obtained by replacing a certain amount of Portland cement with natural zeolitic tuffs, have been studied for over thirty years in several laboratories and in use in some countries. China, for example, is presently producing 70 million tonnes of cement containing 10% to 30% of zeolitic material, mostly clinoptilolite. The extraction of 15-20 million tonnes of zeolites in China equals the Portland cement production of the United Kingdom. In terms of mechanical strength the highest replacement is in the 30% range.

3.2.2 Iron Blast furnace slag

The quantities of iron blast furnace slag available for blending with Portland cement are rapidly evolving in industrialised countries, due to the changes occurring in metallurgical processes. For instance, in the short period 1980-1984, the US production of blast furnace slag dropped sharply from about 26 million tonnes to 13 million tonnes. Actually, conventional steel-manufacture technology provides a crystalline slag, which has no hydraulic properties, and is used as road base material or as stone-like aggregates or simply disposed of as a waste product. Hence, the use of slag for its cementitious properties requires the material to be in the amorphous vitreous state, obtained by quenching the slag from the melt, either in water or in air.

Table 4: Production and utilization rates for iron blast-furnace slag for the year 1984, in million tonnes [Mehta, 1989].

Table 4 shows that USSR, Japan, China, Germany, USA and France were among the largest producers of iron blast-furnace slag. Yet, a considerable proportion of the slag is simply air-cooled, not quenched, and therefore can not be used as a replacement for Portland cement. The utilization data are for the granulated or pelletized slag consumed by the cement and concrete industries in 1984. It is striking to discover that in industrial countries like France, Germany, USA, cementitious blast furnace slag is not as popular as in the eastern countries like Japan, China and India. Yet, from the disclosure of Table 2 and Table 4, it becomes obvious that blast furnace slag covers only 8% of China's market and 9% of the Japanese one.

The 1987 world production of 330 million tonnes blast-furnace iron, generated about 210 million tonnes blast-furnace slag, essentially air-cooled, unsuitable for any replacement of Portland cement. Assuming that efforts, financially and technically, will be undertaken in the future to increase the production of quenched vitreous slag, one could reasonably admit that 1/2 to 2/3 of the production, i.e., at most 150 million tonnes, would be blended with Portland cement, or used with other cementitious compounds discussed in a later chapter. A world production growth of 2.5% or 5% yearly for the next 25 years (BaU scenario), could represent the availability of respectively 290 or 560 million tonnes of blast furnace slag, in the year 2015 (see Fig. 6), for cement applications. As set forth in Fig. 5, the BaU value for 5% yearly growth, is in the order of 3,500 million tonnes. In short, cementitious slag would have, at most, 16% of the world market.

3.2.3 Coal Fly Ash

From a technological point of view, and in terms of strength properties, a certain amount of power plants coal fly ash, up to 25% by weight, may be blended with Portland cement. In the year 1988, world production of electricity generated 290 million tonnes of coal fly ash, from which only 10% to 15% have been used in blended cements. There are several reasons for the relatively low percentage of fly ash used in cements. The most relevant is the failure to provide a uniform quality product.

The tendency in world electricity production is not directed towards implementing more and more coal-fuelled power plants. It is exactly the opposite which is happening. The carbon-dioxide emissions are strongly associated with the production of electricity in coal-fuelled plants. In certain countries, for instance Poland, coal-fuelled power plants were emitting 54% of the national carbon-dioxide emission. The freezing of carbon-dioxide emission at 1990 level, definitively means the freeze of electricity production based on this technology and the stagnation at present level of fly ash quantities suitable for Portland cement replacement. Even, if power plants are successfully tackling the quality issue, in the scenario discussed above until year 2015, a maximum amount of 290 million tonnes of fly ash would be available for cement applications (see Fig. 6). This represents, at most, 8% of the cement world market.

4. The Need for Novel Low-CO_2 Cements for the Aggregates Industries

Blended cements generally comprise:

Portland cement	50-60%
blast furnace slag	20-30%
fly ash	
or natural pozzolan	15-20%

In terms of the 5% growth scenario set forth for the year 2015, 1000 million tonnes of Portland cement might be blended with 400-600 million tonnes of slag and about 300 million tonnes of fly ash or 300 million tonnes natural pozzolan. According to Fig. 5, the BaU world cement prediction for the year 2015 equals 3500 million tonnes. Based on an amount of Portland blended cement production in the order of 1850 million tonnes (1000 Mt. Portland + 560 Mt. slag + 290 Mt. fly ash), the need for new low-CO_2 cementitious materials could be in the range of 1650 million tonnes, as displayed in Fig. 6.

Figure 6: Distribution of BaU world cement market for the year 2015, total 3500 million tonnes.

These new low-CO_2 cements do not rely on the calcium silicate hydration mechanism, but provide similar cementitious properties. The chemistry involved in these low-CO_2 cements, is that of the alkali-activation (sodium or potassium based) of silico-aluminates, as briefly discussed in the case of geopolymeric cements.

4.1 Geopolymeric cements

In recent years, new alkali activated inorganic cementitious compositions were commercially introduced into the US market by the American cement manufacturer Lone Star Industries, Inc. - under the brand name PYRAMENT® blended cements - which resulted from the development carried out on inorganic alumino-silicate polymers or geopolymers [Davidovits, 1985; Heitzmann, 1987; Blumenthal, 1988], resulting from the geopolymeric reaction

$$2(Si_2O_5,Al_2O_2)+K_2(H_3SiO_4)_2+Ca(H_3SiO_4)_2 = (K_2O,CaO)(8SiO_2,2Al_2O_3,nH_2O).$$

These alumino-silicate binders are called inorganic geopolymeric compositions, since the geopolymeric cement obtained results from an inorganic polycondensation reaction, a so-called geopolymerisation yielding three dimensional zeolitic frameworks, unlike traditional hydraulic binders in which hardening is the result of the hydration of aluminates of calcium and silicates of calcium [Davidovits, 1990, 1991].

The amorphous to semi-crystalline three dimensional geopolymeric silico-aluminate structures are of the types poly(sialate), poly(sialate-siloxo) and poly(sialate-disiloxo) (Fig.7).

Figure 7: Geopolymeric molecular networks.

A patented poly(sialate-siloxo) cement [Davidovits, 1992a] is obtained by blending 3 elements produced separately:

- specific alumino-silicates of the kaolinitic clay species, calcined at 750°C;
- alkali-disilicates $(Na_2,K_2)(H_2SiO_4)_2$
- granulated iron blast furnace slag

This cement hardens rapidly at room temperature and provides compressive strengths in the range of 20 MPa, after only 4 hours at 20°C, when tested in accordance with the standards applied to hydraulic binder mortars. The final 28-day compression strength is in the range of 70-100 MPa, (see Figure 8).

Figure 8: Room temperature setting for concrete made of geopolymeric poly(sialate-siloxo) cement.

A preliminary study undertaken in 1985 by the US Corps of Engineers, Vicksburg, described the potential applications of these alumino-silicate cements [geopolymeric cements] in military operations [Malone, 1985]. The study based on tests carried out with Geopolymeric concretes and data published in the East European literature [Glukhovsky, 1980; Tailing, 1983] on alkali-activated blast furnace slags, stressed the unique characteristics of poly(sialate-siloxo) cements in terms of high early strength, high ultimate strength and adaptability in formulation and placement. According to the US Corps of Engineers «..alumino-silicate binders (cements) have the potential to become the best and in many cases the most economical binder for routine construction and may evolve into a new generation of building materials».

4.2 Comparison between Portland and Geopolymeric Cementitious Systems.

A very interesting fact arises when comparing the amount of cements which can be manufactured with an allowance of 100g chemical-CO_2 emission. Under the assumption that the fabrication process for all oxides involves the calcination of carbonates, such as calcium carbonate (limestone) $CaCO_3$ for Portland cement, sodium carbonate (soda) Na_2CO_3 and potassium carbonate (potash) K_2CO_3 for Geopolymer cement, it becomes interesting to calculate the theoretical yield for 100g chemical-CO_2 emission.

This unique comparison, displayed in Fig. 9, highlights the extraordinary potential of the geopolymeric mechanism. With similar investment, lower energy cost, and identical carbon-dioxide emission, this chemistry enables the manufacture of 5 to 10 times more cement than Portland cement technology. Introducing the former, not only for environmental uses, but also in construction and civil engineering, would reduce carbon-dioxide emission caused by the cement and concrete industries by 80 to 90%. This perspective would allow an unlimited development in the Third World.

Figure 9: Theoretical yield for cements produced with an allowance of 100g chemical-CO_2

emission, for each oxide CaO, Na_2O, K_2O.

A complete description of the chemical mechanisms involved in Portland and poly(sialate-siloxo) geopolymeric cements manufacture has been published by the Portland Cement Association and the American Ceramic Society [Davidovits, 1993]. Interested readers should contact these institutions or the author for additional information.

5. The Position of the Portland Cement Industry

Because the costs of controlling greenhouse gas emissions would be borne primarily by private industry in the Western Countries and Japan, while the benefits of avoiding the damage would be felt mostly in developing countries, the internal cost-benefit analyses of the US. and European cement companies show that the costs outweigh the benefits. Although US Department of Energy (D.o.E...) carbon-dioxide data do include cement manufacture, it actually does not imply any consent between US cement manufacturers to drastically reduce chemical-CO_2 emissions. D.o.E.'s data are interesting in terms of world statistics, but are not relevant for the US economy. In some countries, like USA , Germany, the former USSR, cement carbon-dioxide emissions are far below the world average of 5% from total carbon-dioxide emissions. Figure 10 emphasizes the extreme position of the US economy: major carbon-dioxide emitter (about 5000 million tonnes) and only a mere 1.5% due to cement manufacturing. For China, Japan and Italy, cement emissions are about 9-10% of their national value.

Figure 10: Total national CO_2 emission in 1000 million tonnes (Gt.) and ratio cement-CO_2/total in percent (year 1990).

An American cement manufacturer does not feel concerned in the same way as an Italian or a Japanese one. A proposal filed by the author in 1990, aimed at starting basic research and development in this field, was declined by the US Administration, simply because: «...it does not present any economic incentive for the research, which leads one to believe that it would have been actively pursued by American cement producers, if it had been economical...».

European manufacturers are confronted with the EC eco-tax proposal and are lobbying Brussels's Administration. They claim that the eco-tax would have a negative effect on the competitiveness of the European Industry. The planned eco-tax on energy is likely to induce industrials to move abroad. The representative of one of the world cement leaders argued that «.. if Europe is the only one to adopt it [the eco-tax], it will be more profitable to install our factories in Algiers (North Africa), rather than Marseille (France). Freight costs would be equivalent to the increase in manufacturing costs..» [Constanty, 1992]. This statement does not reflect the true scope of the issue, which was addressed above on actual carbon-dioxide emission (including energy and chemical CO_2). The burden would be shifted towards third countries and world cement production would continue to grow (see Fig. 5). Discussions with representatives of the Portland cement industry confirmed that taxation based only on fuel consumption would lead to a cement price increase of 15-20%, whereas any taxation based on actual carbon-dioxide emission (including combustion and chemical-CO_2) would multiply cement price by 1,5 and 2. In the mean time, Northern European countries have enacted eco-taxes based on actual carbon-dioxide emission. Any control performed at the flue gases level could hit the cement and concrete industry hard.

It is not the first time that environmental issues have hit the cement industry in Western countries. During the fifties and the sixties, tremendous efforts have been undertaken to reduce and collect the cement dust from rotary kilns. In Western Europe, USA, Canada, Japan, today's flue gases are absolutely clean of any dust. Some experts are claiming that on the energy supply side, the cement industry could examine reducing carbon dioxide emissions. Since the end of the sixties, cement plants have achieved important energy reductions, thus saving between 25% and 30% thermal energy. For the moment, energy consumption has reached its minimum. From the energy supply side, a carbon-dioxide reduction could come about by switching from high-carbon coal to low-carbon natural gas. For instance, currently 90% of cement utilities have coal-fired plants. A substantial reduction in carbon dioxide emissions due to fuel combustion is possible by replacing conventional coal-plants with high-efficiency rotary kilns fuelled by natural gas. (Coal releases about 26 g of carbon per 1000 Btu of energy, oil about 20 g per 1000 Btu, and natural gas about 14 g per 1000 Btu).

Cement engineers have always followed the changes in energy trends. French engineers for instance, (see Fig. 11), switched in the eighties from oil and gas to coal, and now from coal to industrial-wastes and by-products, even used tires and wrappings.

Figure 11: Energy types used by the cement industry in 1975, 1985 and 1990. Source: Syndicat National Fabricants de Ciments et Chaux, Paris.

6. CONCLUSION: Concrete without Portland cement?

As far as reducing chemical-CO_2, Portland cement experts rely only on studies that predict carbon dioxide emissions can be reduced significantly without major breakthroughs and little or no cost, through the intensive use of blended cements. This type of reasoning, in opposition to the demonstration carried out above, may be adaptable to the Western countries, where cement production is stagnating, but does not comply with the necessary development of the Third World.

It is likely that little or nothing will happen if the task of substantially reducing chemical-CO_2 emission in cement manufacturing remains a burden which the cement industry must endure alone. If society continues to ignore the huge amount of carbon-dioxide released during chemical reactions, the cement Chemical-CO_2 emission based on the calcination of limestone could reach BaU values of 1800 million tonnes in year 2000, or 9% of today's world total CO_2 emissions, and

3500 millions tonnes in year 2015, or 17.5% of today's world total CO_2 emissions (energy + transportation + industry).

These extremely high figures should be of concern to the concrete industry, yet the solution to this issue should not be left to the Portland cement manufacturers alone, for at least three reasons. It seems obvious that the western cement industry will go on in intensively lobbying the US and EC administrations by preventing any regulation focusing on chemical-CO_2 emission. This will restrain the flow of pertinent information. The second reason results from the basic economical nature of this heavy industry, 75% of which is founded on closed, national and subsidized, markets. The world market is not a system of open and competitive markets, in which prices do reflect the costs of all resources including ecological. During the eighties, imports increasingly originated from countries where environmental concerns (dust) have been minimized, for instance, Mexico, Poland, South Korea, and where the markets have not reflected the costs corresponding to environmental degradation. It should be remembered that, as early as 1972, OCDE member states asserted the «polluter pays» principle. But its application remained random and imprecise. The third reason is of a structural order. The production of the four biggest private cement groups, namely Holderbank, Lafarge, Blue Circle, Italcementi/Ciments-Français, all together totals only 10% of the world cement production. These international firms are too small to initiate, alone, any basic innovative development.

In preparation for the Rio Conference (June 1992), several multinational industry leaders, gathered in the Business Council for Sustainable Development (BCSD) [Schmidheiny, 1992], came to the conclusion that industrials must imperatively integrate environmental considerations into their research and development strategy. They must manufacture products and equipment goods that are less polluting, do so with cleaner processes and better energy efficiency. This concerns of course mainly high energy-consuming industries such as steel and aluminum. But it also concerns production as a whole, like the concrete industries, where chemical-CO_2 emission reduction efficiency can be improved. We have seen above that, with similar investment and lower energy cost, in terms of identical carbon-dioxide emission, the geopolymeric chemistry enables the manufacture of 5 to 10 times more cement than Portland technology. Introducing low-CO_2 Geopolymeric cements, not only for environmental uses, but also in construction and civil engineering, would reduce carbon-dioxide emission caused by the cement and concrete industries by 80 to 90%. This perspective would allow an unlimited development in the Third World.

Development means implementing the use of electricity and building infrastructures and houses; in short, electricity and concrete. The by-product of electricity production with coal firing is fly-ash. The innovative step would be to produce electricity and low-CO_2 cement (geopolymeric cement), in the same plant, by adapting and implementing fly-ash production into Geopolymeric raw-material, without any supplementary chemical-CO_2 emission. In terms of the scenario set forth in section 2 (Fig. 5) for the year 2015, (see also Fig. 6), this would allow electricity utilities to produce 3500 million tonnes of low-CO_2 Geopolymeric cement «fly-ash». Today's coal-fired power plants reject 290 million tonnes fly-ash waste. In other words, implementing such a new technology would give a wide potential for any further development of electricity production with coal or lignite firing plants. Some basic research was still performed by companies involved in the development of geopolymeric binders and cements. This research resulted in patent applications disclosing alkali-activation of coal fly-ashes and inducing some processes in order to manufacture low-CO_2 cement [Engels, 1986; Gravitt, 1989; Heitzmann, 1989; Davidovits, 1992b].

Eco-taxes, when applied, would have a major impact on the evolution of production costs for construction materials. Table 5 and Fig. 12 give our estimation for Portland cement based concretes (50% increase in costs), to be compared with other materials such as steel (30% increase), wood (30% decrease) and Geopolymer cement based concretes (15% increase). Wood absorbs carbon-dioxide and it is likely that this material might be subsidized and get reduction in costs as high as 30%.

Table 5 : Estimation of cost increase or decrease for construction materials assuming CO_2 Taxes on energy alone and on energy+chemical-CO_2 emission.

Fig. 12 : Estimation of cost increase or decrease for construction materials assuming CO_2 Taxes on energy alone and on energy+chemical-CO_2 emission.

We are perfectly aware of the fact that the fostering of alkali-based geopolymeric cements will mean a dramatic change in the research and development presently carried out in USA and other countries. Alkalis are generally thought of as the cause of deleterious Alkali-Aggregate-Reaction in some concretes. As a consequence, the tendency has been to avoid any addition of alkali in ordinary Portland cement and commonly to require from the cement manufacturers the supply of low-alkali cements. However, geopolymeric poly(sialate-siloxo) cements, even with alkali contents as high as 9.2%, do not generate any dangerous Alkali-Aggregate-Reaction. Geopolymeric cements are manufactured in a different manner than that of Portland cement. They do not require extreme high temperature kilns, with large expenditure of fuel, nor do they require such a large capital investment in plant and equipment. Thermal processing of naturally occurring alkali-silico-aluminates and alumino-silicates (geological resources available on all continents) provides suitable geopolymeric raw-materials. The author is involved in the European industrial research program GEOCISTEM which is presently fostering the development of this geological route, and seeks to manufacture cost-effectively cements for applications dealing primarily with the long term containment of hazardous and toxic wastes. The technology reduces also the energy consumption during cement manufacturing. Introducing these low-CO_2 geopolymeric cements, not only for environmental uses, but also in construction and civil engineering, would reduce CO_2 emission caused by the cement and concrete industries by 80% and would allow an unlimited development of concrete infra-structures in our Global Economy .

Preliminary studies on this issue started at Materials Research Laboratory, Pennstate University, USA, 1989-1990. The industrial research program GEOCISTEM is funded by the European

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Table 1: 1987 World production in million of tonnes (MT.) for cement, iron and resulting chemical-CO_2.

	production	chemical-CO_2
cement	1,000 MT.	550 MT.
iron	330 MT.	66 MT.

Table 2: Production of cement in major cement producing countries for 1975 and 1990 (million of Tonnes) and kg per capita (Source: Cembureau).

1975		1990		kg per capita
World total	719	Word total	1 151	221
1 USSR	122	1 China	208	184
2 Japan	65	2 USSR	137	463
3 USA	59	3 Japan	85	680
4 China	47	4 USA	69	322
5 Italy	34	5 India	47	58
6 W. Germany	33	6 Italy	41	750
7 France	29	7 South Korea	33	687
8 Spain	24	8 Spain	28	704
9 Poland	18	9 W. Germany	26	420
10 Brazil	17	10 Brazil	26	179
11 UK.	17	11 France	26	448
12 India	16	12 Turkey	24	420
		13 Mexico	24	255
		14 Taiwan	19	905
		15 Thailand	18	340

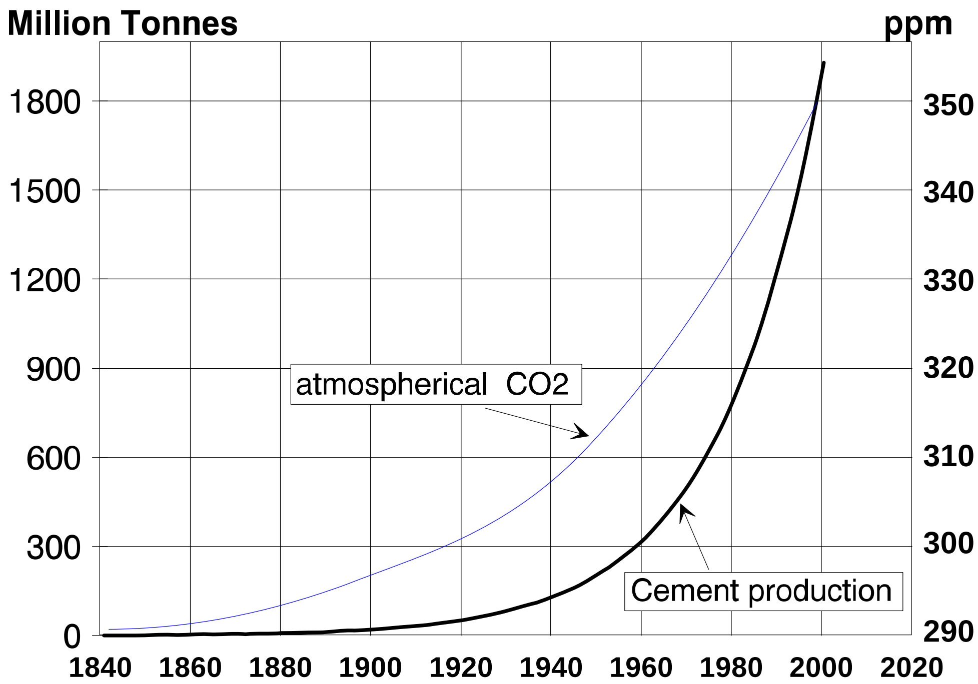

Figure 1: Atmospheric CO_2 concentration (ppm) and world portland-cement production (million tonnes) for the period 1840-2000. Sources: IPCC and Cembureau.

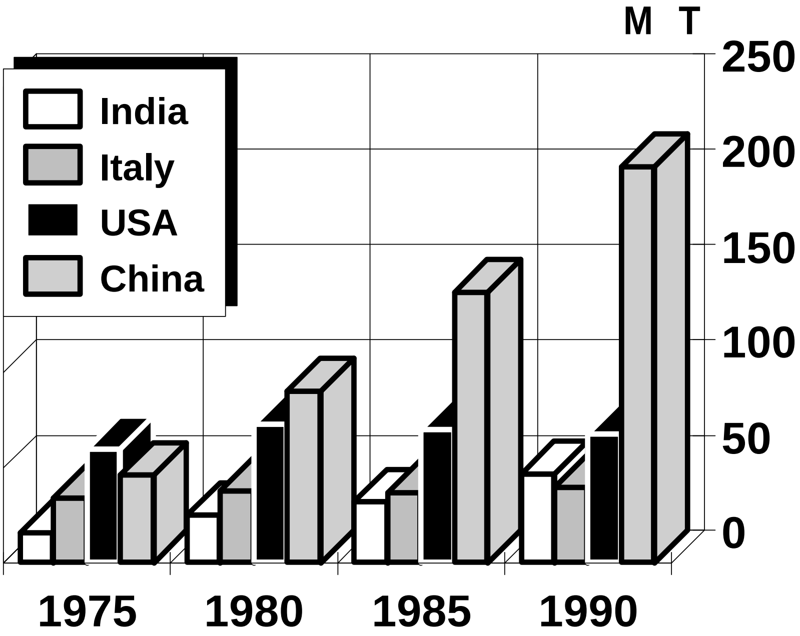

Figure 2: Annual cement production for China, India, Italy, USA in million tonnes (MT.). Source: Cembureau.

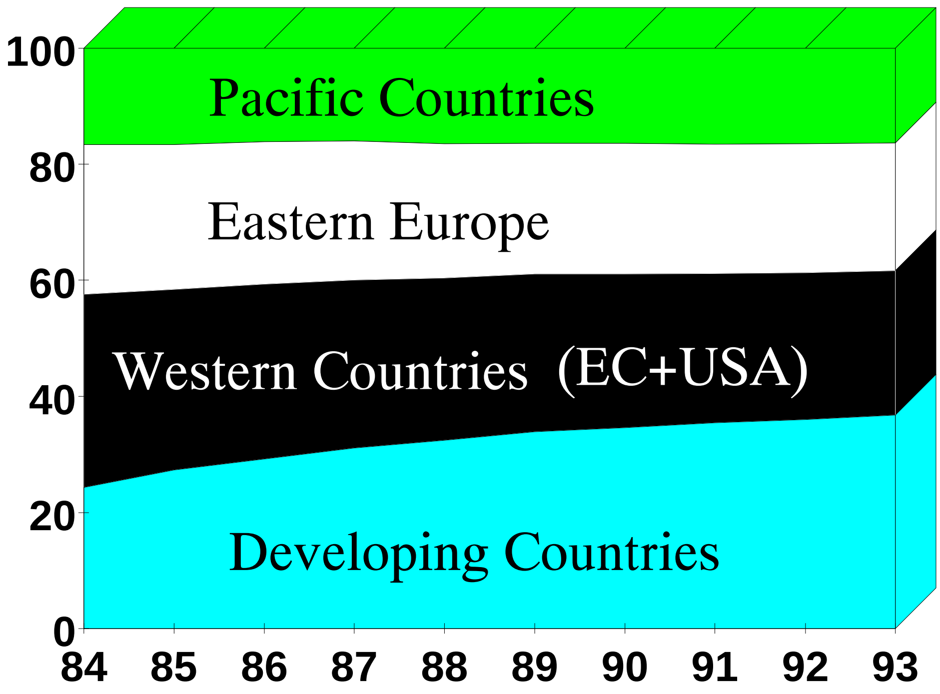

Figure 3: Shift in world cement production between 1984 and 1993.

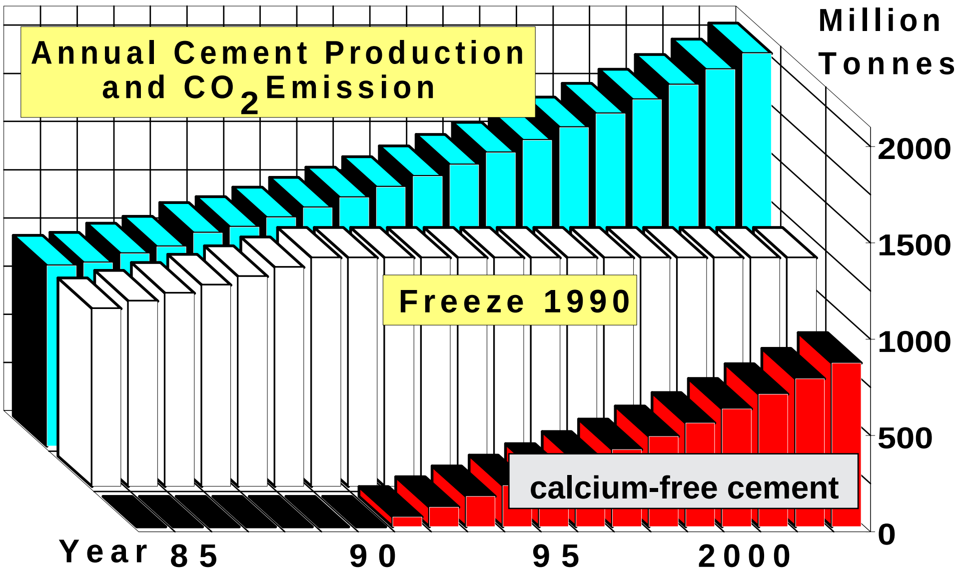

Figure 4: The uper plot shows the predicted world annual production of portland-cement and connected carbon dioxide (BaU). The lower plot shows the potential market for calcium-free cements assuming freeze of portland-cement production at 1990 level [Davidovits, 1991].

Table 3: Present Cement production growth

	China	India	Korea	Thailand	Japan	Spain	France	USSR	USA
growth	3%	5%	10%	16%	5%	4.5%	0.0%	- 1.5%	-2%

Table 4: Production and utilization rates for blast-furnace slag for the year 1984, in million tonnes [Mehta, 1989].

country	production	utilization
Australia	4.7	0.12
China	22	16
France	10.4	1.9
W.Germany	15	2.8
India	7.8	2.8
Japan	24	8.2
USA	13	1
USSR	35	?

Table 5 : Estimation of cost increase or decrease for construction materials assuming CO_2 Taxes on energy alone and on energy+chemical-CO_2 emission.

material	CO_2 tax energy alone	CO_2 tax energy+chemical CO_2
Portland cement concrete	+ 20%	+ 50%
Blended Portland cement concrete		
50% Portland/50% by-products	+ 20%	+ 35%
steel	+ 20%	+ 30%
wood	0%	0 to - 30%
Geopolymer cement concrete	+ 10%	+ 15%

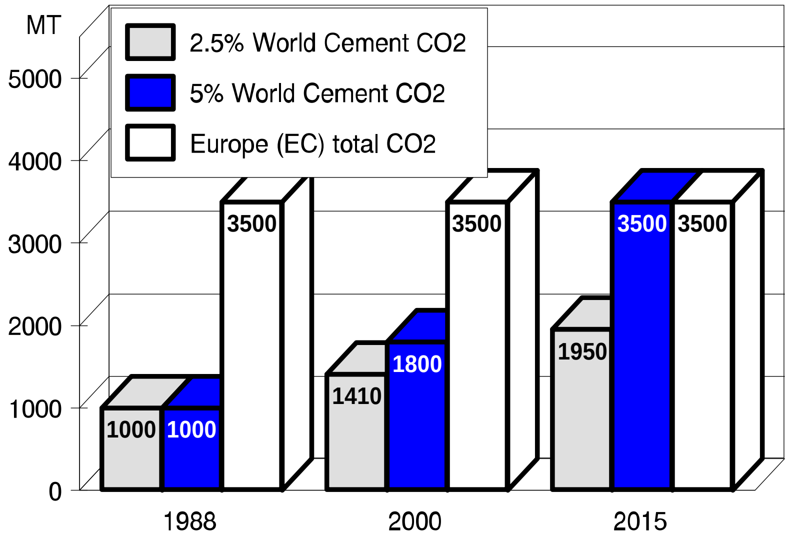

Figure 5: BaU value for World Cement-carbon dioxide with 2.5% and 5% yearly increase and «frozen» Europe (EC) total carbon dioxide emission at 1990 level, million tonnes (MT.).

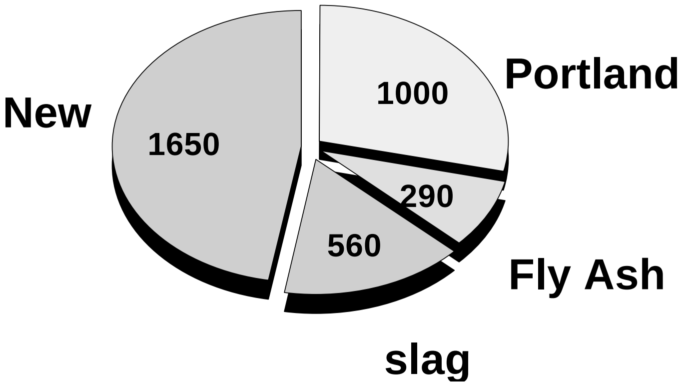

Figure 6: Distribution of BaU world cement market for the year 2015, total 3500 million tonnes.

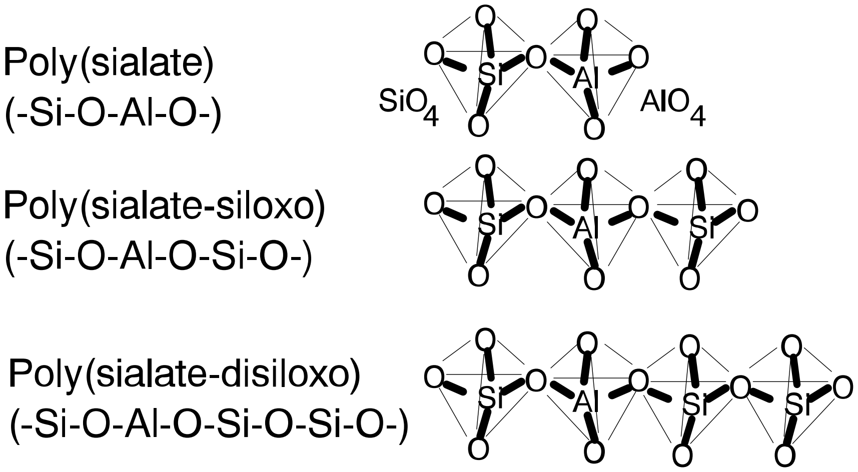

Figure 7: Geopolymeric molecular network

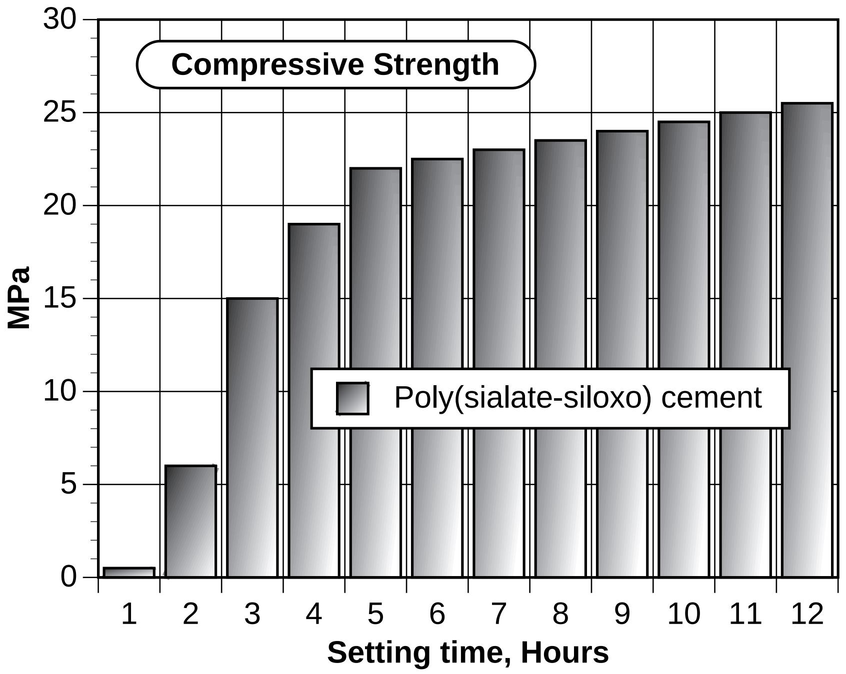

Figure 8: Room temperature setting for concrete made of potassium poly(sialate-siloxo) cement.

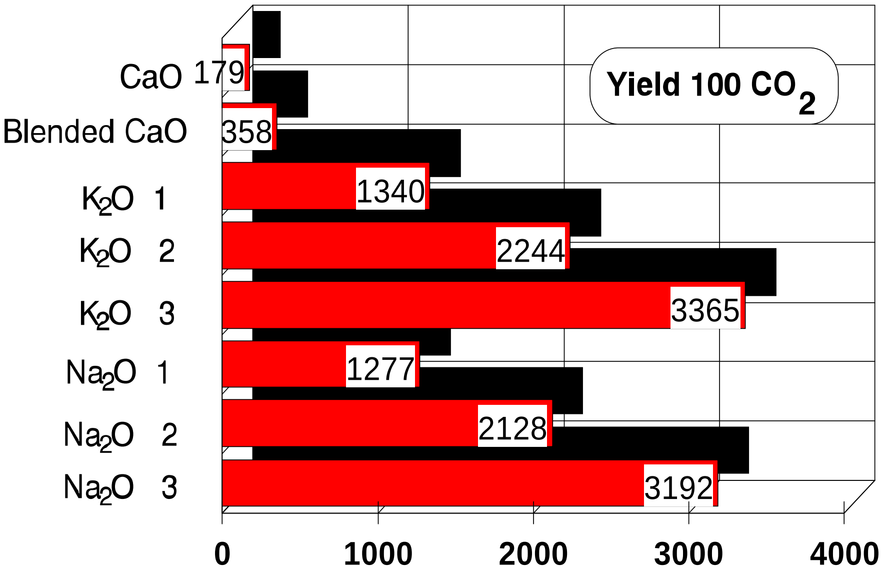

Figure 9: Theoretical yield for cements produced with an allowance of 100g chemical-CO_2 emission, for each oxide CaO, Na_2O, K_2O.

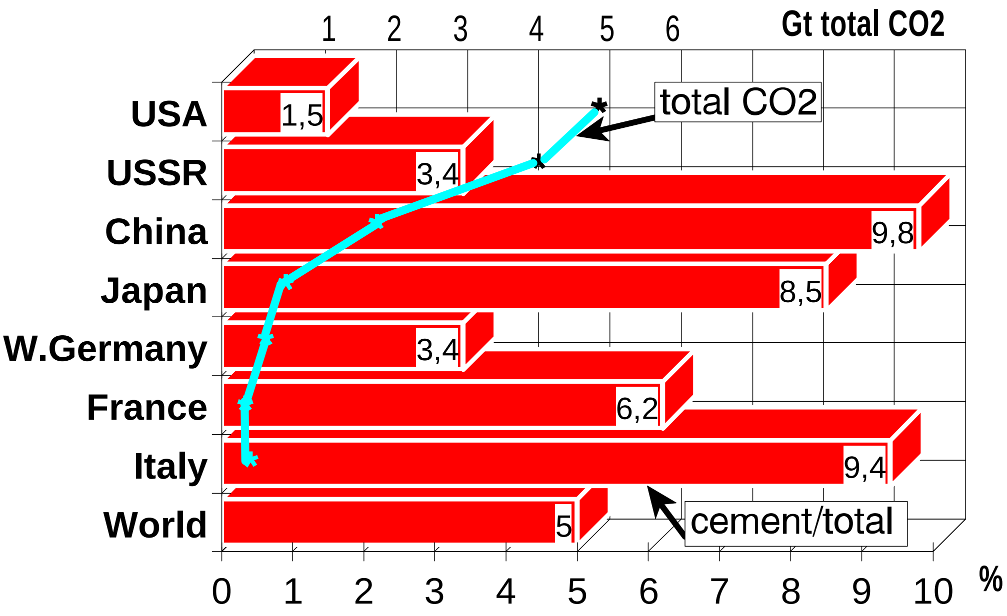

Figure 10: Total national CO_2 emission in 1000 million tonnes (Gt.) and ratio cement-CO_2/total in percent (year 1990).

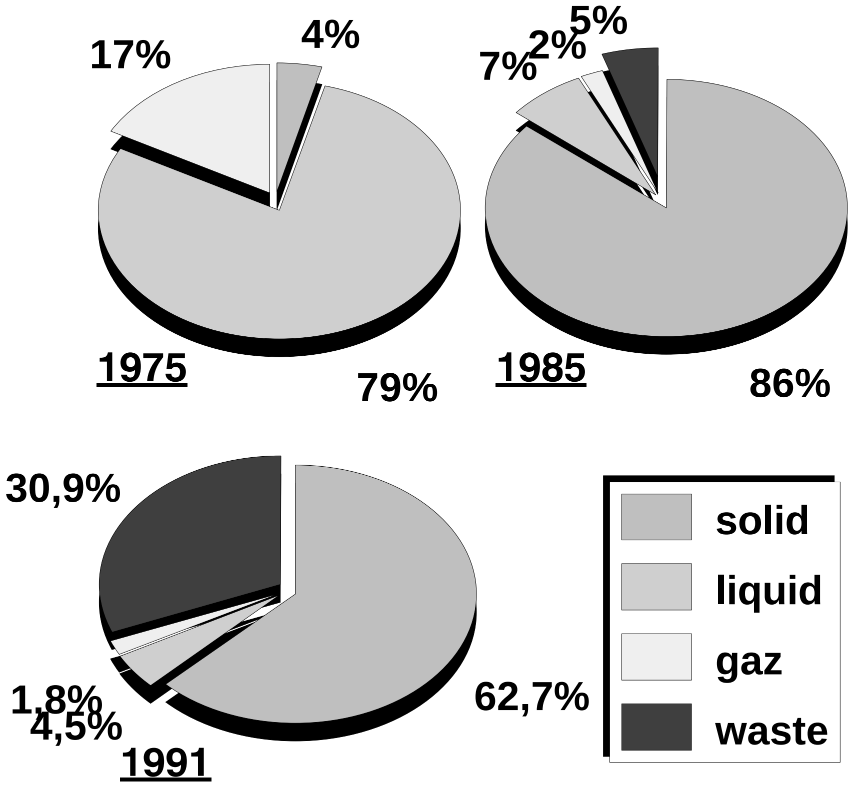

Figure 11: Energy types used by the cement industry in 1975, 1985 and 1990. Source: Syndicat National Fabricants de Ciments et Chaux, Paris.

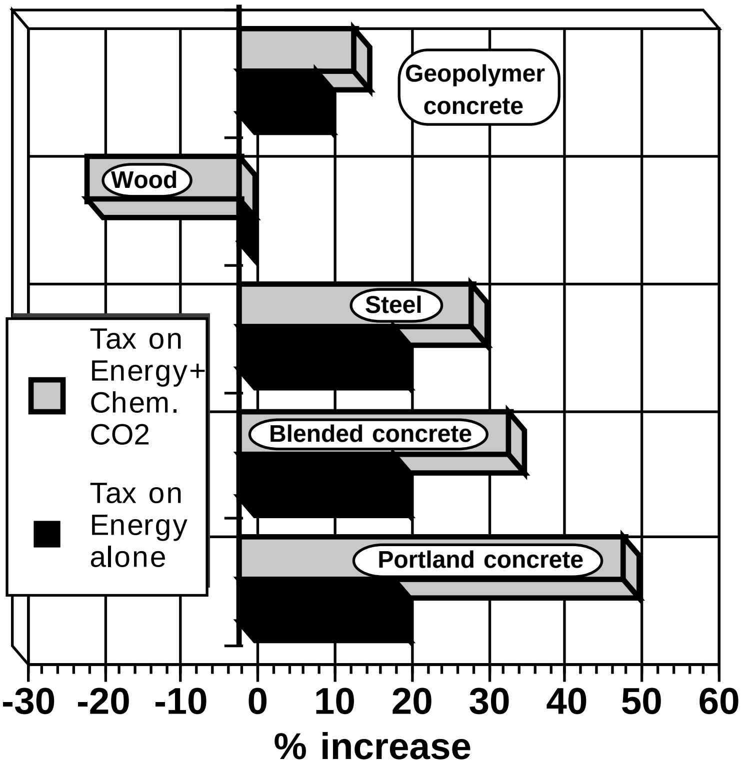

Fig. 12 : Estimation of cost increase or decrease for construction materials assuming CO_2 Taxes on energy alone and on energy+chemical-CO_2 emission.