Editorial Guidelines

1. Use **W/C** not W/C ratio
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3. Use **Fig.** not Figure
4. Use **Figs. 1,2** not Fig. 1,2
5. Use **data are** not data is
6. Use **mixture** not mix
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11. Cite references numerically as they appear
    - **do not** use "Author Name and Year" style
12. Use **fly ash** not PFA
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SAMPLE

ROLE OF SUPPLEMENTARY CEMENTING MATERIALS IN REDUCING GREENHOUSE GAS EMISSIONS

by

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Role of Supplementary Cementing Materials in Reducing Greenhouse Gas Emissions

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ABSTRACT

The World Earth Summits in Rio de Janeiro, Brazil, 1992 and in Kyoto, Japan in 1997 have, in no uncertain terms, emphasized the dangers associated with the unchecked increase in CO_2 and other greenhouse gas emissions to the atmosphere, and their undesirable effects on climate change. As a result, most industrialized countries are in the process of formulating regulations to stabilize these emissions to 1990 level by the year 2010. This paper describes the amount of CO_2 being contributed by the portland cement industry, and discusses how these emissions can be reduced considerably by the increased use of large volumes of fly ash and other supplementary cementing materials in concrete industry.

Keywords: cement, CO_2 emissions, concrete, fly ash, greenhouse gas, supplementary cementing materials.

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INTRODUCTION

The environmental issues will play a leading role in the sustainable development of the cement and concrete industry in the 21st century. The World Earth Summits in Rio de Janeiro, Brazil in 1992 and Kyoto, Japan in 1997 have made it abundantly clear that unchecked increase in the emission of greenhouse gases to the atmosphere is environmentally and socially no longer acceptable for overall sustainable development. The primary greenhouse gas emissions discussed in the deliberation of the above conferences are the CO_2 emissions. The other greenhouse gases such as NO_x and CH_4 are of serious concern, but the amount involved is relatively small compared with that of CO_2. As a consequence, the developed countries are considering regulations and mandatory quotas on the emission of these gases, and the main thrust is to stabilize these emissions to the 1990 level by the year 2010. As the manufacture of portland cement contributes significantly to the CO_2 emissions, this paper discusses the role of the increased use of large volumes of fly ash and other supplementary cementing materials in the construction industry in reducing these emissions.

PORTLAND CEMENT PRODUCTION

Portland cement is a major construction material worldwide and will remain so for the foreseeable future. The net cement production in the world is expected to rise from about 1.4 billion tonnes in 1995 to almost about two billion tonnes in the year 2010 (Table 1). It is expected that the production will not increase significantly in North America and Western Europe but the major increases will take place in China, India, Eastern Europe, and Africa. In view of the huge tonnage involved, it is imperative that the manufacture of cement be made as environmentally friendly as possible. If this is not possible, then ways and means must be found to reduce significantly the consumption of portland cement by the increased use of supplementary cementing materials in concrete.

ENERGY CONSUMPTION, CO_2 EMISSIONS, ASSOCIATED COSTS IN THE MANUFACTURE OF PORTLAND CEMENT AND SITUATION IN DEVELOPING COUNTRIES

Energy Consumption

After aluminum and steel, the manufacture of portland cement is the most energy-intensive process. The manufacture of portland cement requires about 4 GJ of energy per tonne of the finished product. Over the past decades, the cement industry has made major strides in reducing the energy consumption. This has been achieved primarily by replacing wet production facilities with new modern dry-processing plants and by moving away from the petroleum-based fuels. For example, in the U.S.A. the cement industry has been able to reduce the average energy use per tonne of cement from about 7 Gigajoules in 1974 to about 5.5 Gigajoules per tonne in 1991 (Figure 1). However, it has reached about the limit beyond which it is extremely difficult to reduce further energy use in the cement production process. Obviously, the existing cement plants cannot be shutdown. This leaves only one option, and that is to limit the installation of new plants, and phasing out of the old inefficient installations. The loss in capacity due to this change can and must be met by the increased use of supplementary cementing materials such as fly ash, blast-furnace slag, natural pozzolans, rice-husk ash, and silica fume. Most of these materials happen to be available in large amounts as industrial by-products.

Greenhouse Gas Emissions

Not only is the manufacture of portland cement highly energy intensive, it also is a significant contributor of the greenhouse gases. The production of every tonne of portland cement contributes about one tonne of CO_2 into the atmosphere. Minor amount of NO_x and CH_4 are also released into the atmosphere. The total CO_2 emissions per tonne of cement range from about 1.1 tonne of CO_2 from the wet process to 0.89 tonne from a precalciner kiln. About half of the CO_2 emissions are due to the calcination of limestone (a major raw material) and the other half are due to the combustion of the fossil fuels. According to Cahn et al. (1), the emissions from the calcination of limestone are fairly constant at about 0.54 tonne of CO_2 per tonne of cement; the emissions from the combustion depend on the carbon content of the fuels being used and the efficiency of the fuel usage.

Globally, in 1995, the amount of production of cement was about 1.4 billion tonnes. This means that the manufacture of portland cement contributed about 1.4 billion tonnes of CO_2 to the atmosphere. According to IEA[*] World Energy Outlook 1995, the worldwide CO_2 production from all sources was 21.6 billion tonnes. On the basis of the above figures, the worldwide production of cement accounts for almost 7% of the total world CO_2 production, and from the projections made by the cement companies, this proportion is expected to remain steady in the next decade (1). Obviously, the cement companies are not expecting the emergence of environmentally-friendly cement manufacturing technologies in the near future.

Cost Considerations

The cost of a new portland cement plant is in the order of 175 million dollars per million tonnes of installed capacity. Till recently, a one million tonne capacity plant was considered to be the most efficient installation. However, lately huge cement plants with capacities of about 3 million tonnes have come on line in Thailand and South Korea. The above cost considerations,

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[*] International Energy Authority.

combined with the CO_2 emission and energy consumption issues, cast doubts that many new installations will be brought on line in the developed world. Instead, the government regulations on greenhouse gas emissions would force the cement industry to look for supplementary cementing materials that could be used to produce blended cements or could be used as separate ingredients at concrete batch plants. The developed countries would also attempt to import more cement from the developing countries. The export of cement from Mexico to the U.S.A. is one such example.

Situation in Developing Countries

The infrastructure needs of the developing countries have led to huge increases in demand for portland cement (Table 1). This has led to the installation of a large number of new cement plants in China, India, and countries in South America. Paradoxically, these are the same countries that are also installing huge coal-fired power stations to supply electricity to meet the growing needs of the population and the manufacturing industries. For example, it is anticipated that in the year 2002, India will produce about 109 million tonnes of portland cement, and the coal ash from thermal stations will reach about 130 million tonnes annually. Unfortunately, the much needed industrial developments in these countries are adversely affecting the environment in two ways. The installation of the new cement plants is increasing tremendously the CO_2 emissions, and the construction of the monstrous thermal-power stations is resulting in huge amounts of fly ash, bottom ash, and boiler slag that are not being used in any significant manner. Most of the fly ash is being dumped in lagoons, land-fill sites, abandoned quarries, and in some instances being slurried directly to the open sea. Thus, potential valuable cementing resources are being wasted in precisely the countries that need it most to reduce the greenhouse gas emissions, and to make economical and durable concrete infrastructures.

ROLE OF FLY ASH AND OTHER SUPPLEMENTARY CEMENTING MATERIALS IN SUSTAINABLE DEVELOPMENT OF CEMENT AND CONCRETE INDUSTRY

In view of the energy and greenhouse gas emission concerns in the manufacturing of portland cement raised above, it is imperative either new environmentally friendly cement-manufacturing technologies be developed or substitute materials be found to replace a major part of portland cement for use in the concrete industry. At present, there are not many major new technologies on the horizon for manufacturing environmentally-friendly portland cements that are economically acceptable to the cement industry. This leads to the question whether other supplementary cementing materials and technologies are available to replace significant amounts of cement in concrete. These issues are discussed below.

Availability of Fly Ash

In 1989, the total coal-ash production in the world was in the order of 400* million tonnes annually (2). The former Soviet Union had the largest production of 90 million tonnes followed by China at 55 million tonnes. Other major sources of coal ash production in the world were the United States at 48 million tonnes, and India at 36 million tonnes. Since then the fly ash production has increased considerably. The production data for 1995 are shown in Table 2 . It is now estimated that both China and India will be producing more than 100 million tonnes of fly ash each by the year 2000. There has been some increases in the other countries also but not to the same extent. Based on the fragmented information available, it can be predicted safely that by the year 2000, the availability of fly ash will be greater than 600 million tonnes in comparison with the estimated production of portland cement of 1.4 billion tonnes. The vast majority of the available fly ashes for

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*Includes fly ash, bottom, ash, and boiler ash.

use in concrete are low-calcium fly ashes (ASTM Class F), and are basically the by-product of burning anthracite or bituminous coal. These fly ashes, in themselves, possess little or no cementitious value, but will in finely-derived form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. In recent years, high-calcium (ASTM Class C) fly ash has come on the market in the U.S.A., Canada, Poland, Greece and some other countries. These fly ashes are by-products of burning lignite or subbituminous coal, and have cementitious properties in addition to being pozzolanic.

Present and Potential Use of Fly Ash in Concrete and Blended Cements

It is agreed that not all the available fly ash is suitable for use in concrete. However, it is believed that technologies are available that can beneficiate those fly ashes that fail to meet the fineness and carbon content requirements, the two most important parameters of a fly ash for use in concrete. These include separation technologies, floatation technologies and grinding methods. From the published information, the current worldwide utilization rate of fly ash in concrete is about 10 per cent. In China the utilization rate approaches about 15 per cent whereas in India the utilization rate is less than 5 per cent. In North America, the utilization rate is in the vicinity of 10 per cent in concrete. The utilization of fly ash in Hong Kong and some European countries like the Netherlands and Denmark is very high, but the amounts involved are small. Thus, there is huge potential for the increased use of fly ash in concrete in the world. In this regard the following statement in 1984 from Ed Abdun-Nur, a noted U.S. concrete technologist, should be of interest (3).

> "In the real world of modern concrete, fly ash is as essential an ingredient of the mixture as are portland cements, aggregates, water, and chemical admixtures. In most concretes I use it in larger amounts (by volume) than portland cement, and therefore it is not admixture i.e. an addition to the mixture. Concrete without fly ash and chemical admixtures should only be found in museum show cases."

The writer agrees totally with the above statement, and this prophetic observation is slowly coming true.

New Technologies in the Use of Fly Ash in Concrete

One of the major developments in the area of fly ash utilization in concrete has been the technology of high-performance, high-volume fly ash concrete by Malhotra and his associates (3,4), and it is believed that in years to come, it will revolutionize the use of fly ash in concrete. Briefly, in the production of high-performance, high-volume fly ash concrete, about 60 per cent of portland cement is replaced by ASTM Class F fly ash. The water-to-cementitious materials ratio is maintained at 0.30±0.01 with portland cement and fly ash contents at about 150 and 225 kg/m^3, respectively. The water content of the mixture is kept low at about 120 kg/m^3 and flow slumps are achieved by large dosages of a superplasticizer. This type of concrete that was developed about 10 years ago has excellent long-term mechanical and durability properties, and this is supported by voluminous research data and some field data. The early-age strength (6-8 MPa at one day) is ample enough for formwork removal except in cold regions. The later-age strength of more than 110 MPa at 10 years has been achieved in demonstration blocks (see Tables 3,4). This type of concrete has been successfully used in several projects in Eastern Canada. Somewhat similar type of concretes can be produced using ASTM Class C fly ash.

Other fly ash technologies being investigated include alkali-activated fly ash concretes, ternary blends incorporating portland cement, fly ash and slag or silica fume, and high-volume fly ash blended cements.

TRADEABLE EMISSION RIGHTS AND UTILIZATION OF FLY ASH

The "tradeable emissions" refers to the economic mechanisms that are expected to help the countries worldwide meet the stringent emission reduction targets established by the 1997 Kyoto Protocol. At present there are no regulations as to how this international trading of emissions is going to operate. It is being speculated that one tonne of emission will have a trading value of about $100.00 (U.S.)*. Thus, for example, if a country can replace 20 per cent of cement utilization by fly ash or slag, the country would have saved about 20 per cent of the CO_2 emissions. For a country that produces 50 million tonnes of cement, this 20% replacement by fly ash would amount to savings in CO_2 of 10 million tonnes. This, in turn, translates into a trading value of 100 million dollars. One must keep in mind that the value of the trading of emission rights is only an estimate because the international community has not yet reached a conclusion on the subject. But given the political and environmental pressures, the utilization of fly ash will pay rich dividends. The developed countries have a major stake in this issue. If the developed countries can transfer fly ash utilization technology to developing countries, and demonstrate actual slow down in the installation of new cement plants in these countries, the developed countries would rightly claim CO_2 emission credits. In order to give an idea of huge financial stakes involved, it is estimated that it will cost about $100 billion over 15 years for Canada** to cut greenhouse gas emissions by as much as it

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*T. Corcoran, "Churchill Falls not Tradeable" Globe and Mail, Toronto, March 10, 1998.

**CP News, Globe and Mail, Toronto, March 10, 1998.

promised at the Kyoto climate change conference. Canada made a legally binding pledge to cut greenhouse emissions 6 per cent from 1990 levels by 2008-2012 at the above conference.

OTHER SUPPLEMENTARY CEMENTING MATERIALS

In addition to fly ash, the other supplementary cementing materials that can be used to partially replace portland cement in concrete include granulated blast-furnace slag, silica fume, metakaolin, and rice-husk ash. Compared to the quantities of fly ash, the availability of these materials is rather limited[*]. The worldwide production of granulated blast-furnace slag is only about 20 million tonnes per year. The availability of silica fume is very limited, (total tonnage is less than 2 million tonnes/year worldwide) and this highly pozzolanic material is generally specified for specialized applications such as structures exposed to aggressive chemicals. The rice-husk ash is not yet available commercially, though the potential is of about 20 million tonnes worldwide (5). The use of blast-furnace slag has increased considerably in recent years and this trend is expected to continue. Rice-husk ash, when it becomes available commercially will along with fly ash and granulated blast-furnace slag be the most significant supplementary cementing material for use as partial replacement for portland cement in concrete (6).

Institutional Barriers Against the Use of Supplementary Cementing Materials

One of the major institutional barriers against the use of fly ash and other supplementary cementing materials is the "prescriptive" type of specifications and standards. The use of such specifications worldwide has hindered the widespread use of the materials mentioned above. The prescriptive type of specifications place limits on individual chemical constituents of these materials,

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[*] All production figures are approximate only. Several producers of supplementary cementing amterials are reluctant to divulge accurate data because of corporate policy. This is rather strange because it has actually hindered the use of these materials in market place.

and in many instances put limit on the maximum percentage of the cement that can be replaced by the supplementary cementing materials. The solution to this dilemma is to move towards performance-based specifications. Some progress is being made in this direction but a concerted effort is needed in this direction if one is to achieve the above objectives in the near future. According to Mehta (5), getting rid of prescriptive codes and replacing them with performance-based codes will accelerate the rate of utilization of fly ash and slag in concrete, and further help the development of ternary and quaternary cementitious systems containing two or more supplementary cementing materials added to portland cement.

CONCLUSIONS

Environmental issues associated with the CO_2 emissions from the production of portland cement, energy and resource conservation considerations and the high cost of portland cement plants demand that supplementary cementing materials in general and fly ash and ground granulated blast-furnace slag in particular be used in increasing quantities to replace portland cement in concrete. Given the almost unlimited supply of good quality fly ash worldwide, and the development of technologies such as high-volume fly ash concrete, it is believed that the installation of new cement plants should be avoided as far as possible. In addition, the ageing portland cement plants should be phased-out in both developed and developing countries, and the resulting loss in capacity should be compensated for by the use of supplementary cementing materials. In this regard the following statement by Mehta (5) is worth quoting.

> "With the dawn of the twenty-first century, we are entering into an era of sustainable development. The concrete industry will be called upon to serve the two pressing needs of human society, namely, protection of the environment and meeting the infrastructural requirement for increasing industrialization and urbanization of the

> world. Also due to its large size, the concrete industry is unquestionably the ideal home for the economic and safe disposal of millions of tons of industrial by-products such as fly ash and slag. Due to their highly pozzolanic and cementitious properties, fly ashes and slag can be used in large amounts as cement replacement materials in cocnrete. In fact, superplasticized concrete mixtures containing 60 to 70% fly ash or slag by mass of the total cementitious material have shown high strength and durability at relatively early ages. This development has removed one of the strong objections to the high-volume application of fly ash and slag. It is obvious that large-scale cement replacement in concrete with these industrial byp-products will be hightly advantageous from the standpoint of cost economy, energy efficiency, durability, and overall ecological profile of concrete. In the industrial world it will be hard to find similar examples of excellent complementarity or marriage between two components of a system, one of which happens to be an industrial waste. Therefore, in the future, the use of by-product supplementary cementing materials ought to be made mandatory."

The combined use of superplasticizers and supplementary cementing materials can lead to economical high-performance concrete with enhanced durability. It is hoped that the concrete industry would show leadership and resolve, and make contributions to the sustainable development of the industry in the 21st century by adopting new technologies to reduce emission of the greenhouse gases, and thus contribute towards meeting the goals and objectives set at the 1997 Kyoto Protocol. If the above leadership and bold initiatives are not forthcoming, it is certain that the bureaucrats will impose unpleasant regulations and tax on the industries contributing significant amounts of greenhouse gases to the atmosphere. The manufacturing of portland cement is one such industry.

REFERENCES

1. Cahn, D. et al, "Atmospheric CO_2 and the U.S. Cement Industry"; World Cement, August 1997, pp. 64-68.
2. Manz, O.E., "Worldwide Production of Coal Ash and Utilization in Concrete and Other Products"; Presented at the CANMET/ACI Third International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Trondheim, Norway, 1989, Supplementary Paper, 15 pp.
3. Malhotra, V.M. and Ramezanianpour, A.R., "Fly Ash in Concrete"; 2nd Edition, CANMET, Energy, Mines and Resources Canada, Ottawa, Canada, 1994, 307 pp.
4. Malhotra, V.M., "CANMET Investigations Dealing with High-Volume Fly Ash Concrete"; Advances in Concrete Technology, 2nd Edition, pp. 445-482, CANMET, Ottawa, 1994.
5. Mehta, P.K., "Rice-Husk Ash--A Unique Supplementary Cementing Material"; A chapter in Advances in Concrete Technology, CANMET, pp. 419-444, 1994. (Ed. V.M. Malhotra).
6. Mehta, P.K., "Bringing the Concrete Industry Into a New Era of Sustainable Development"; Paper published in symposium volume: "Mario Collepardi Symposium on Advances in Concrete Science and Technology", Rome, Italy, October 1997, pp. 49-68.

Table 1. Regional and World Cement Production to Year 2010*

Summary: regional and world cement consumption to 2010

	European Union*	Other Europe*	Former Soviet Union*	North America *	C/S America*	Africa	Middle East*	East Asia*	S/SE Asia*	Oceania*	World Total
1995	168.1	65.8	58.1	92.9	89.4	64.8	63.5	623.4	161.2	8.0	1396.1
2000	187.9	80.0	80.3	94.9	106.6	74.3	75.6	732.7	219.1	10.6	1662.1
2005	194.1	90.2	110.1	94.8	127.4	80.7	76.9	798.8	255.0	11.1	1839.1
2010	189.3	94.7	128.2	94.7	145.0	85.5	73.4	844.3	279.2	11.8	1946.1
% of total 1995	12.1	4.7	4.2	6.6	6.4	4.6	4.6	44.6	11.6	0.6	100.0
% of total 2010	9.7	4.9	6.6	4.9	7.5	4.4	3.8	43.4	14.4	0.6	100.0

*million tonnes
Figures may not add due to rounding, source: Ocean Shipping Consultants Ltd.

*From World Cement Annual Review 1997. World Cement, Vol. 28, No. 7, July 1997, pp. 3-60.

Table 2. Estimated Coal-Ash Production and Utilization for Selected Countries for 1998*

Country	Production Million Tonnes	Utilization Million Tonnes
Australia	9	<1
China	>100	14
Germany	28	12
India	>80	2.0
Japan	5	3
Russia	62	5
South Africa	28	N/A
Spain	8	1
U.K.	10	6
U.S.A.	60.0	8

*The above data include fly ash, bottom ash, and slag. For every 100 tonnes of fly ash there are approximately 25 tonnes of bottom ash and slag.
The production and utilization rates have been compiled from published data. The exact figures are difficult to obtain and therefore the margin of error could be as high as 10 percent.

Table 3. Compressive Strength of 100x200-mm Cores Taken at the 10 Years from 2.0x1.2x1.35-m Thick Concrete Blocks Cast, Cured, and Left Exposed to Elements in Toronto, Canada

	Age (Days)	Mixtures					
		1	2	3	4	5	6
		Total Cementitious Content, kg/m³					
		485	484	488	486	350	485
Thick-Column Element C (2.0mx1.2mx1.35m)		cement = 65% slag = 28% silica fume = 7%	cement = 65% slag = 35%	cement = 92% silica fume = 8%	cement = 88% silica fume = 12%	cement = 43% fly ash (class F) = 57%	cement = 100%
		Compressive Strength of 100x200-mm Cores, MPa					
	1	41.7	45.6	58.4	69.4	7.8	41.5
	3	64.3	55.0	63.5	–	27.1	47.5
	7	63.2	57.2	63.4	71.8	34.0	51.4
	28	69.4	63.4	66.8	75.8	49.9	59.9
	91	70.8	63.3	69.1	72.9	82.5	75.6
	182	69.6	69.4	71.4	78.7	87.0	74.3
	365	78.5	76.2	79.2	80.8	95.6	88.2
	546	76.6	79.3	80.3	82.2	100.5	94.7
	730	78.6	84.7	85.3	85.3	99.9	95.9
	912	81.8	83.9	–	–	96.8	95.5
	1460	84.1	97.3	87.1	88.2	109.9	99.4
	3650	87.6	99.8	91.2	89.2	112.3	102.3

Table 4. Concrete Blocks, 2.0x1.2x1.35-m Thick, Cast, Cured and Left to the Elements in Toronto, Canada: Mixture Proportions and Resistance to the Chloride-Ion Penetration at 10 Years

Mix	Cementitious materials (kg/m^3)						Charge passed (coulombs)
	Total	OPC	Silica Fume	Slag	Fly Ash	w/cm	
1	485	315	35 (7%)	135 (28%)	--	0.29	102
2	484	317	--	167 (35%)	--	0.28	237
3	488	449	39 (8%)	--	--	0.27	565
4	486	427	59 (12%)	--	--	0.27	118
5	350	150	--	--	200 (57%)	0.29	0
6	485	485	--	--	--	0.27	381

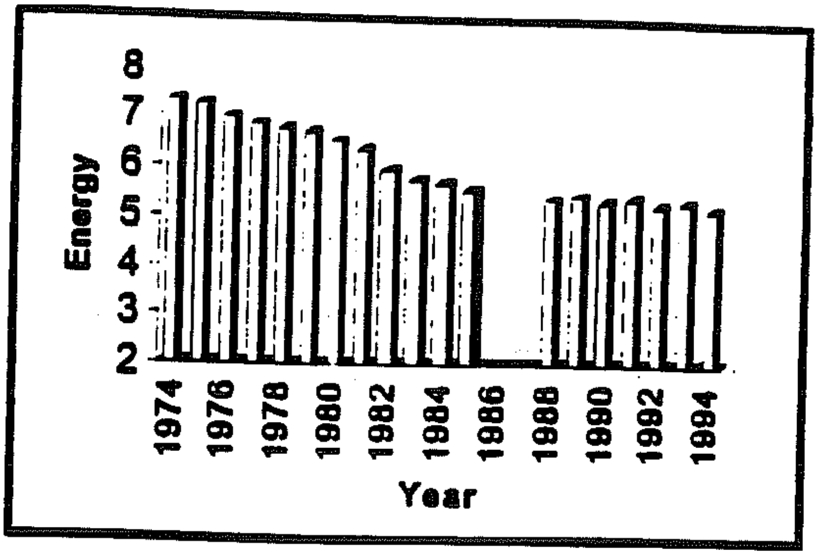

Fig. 1. Trend in energy consumption m Btu/t of cement.
Source: PCA Economic Research Dept.
US Cement Industry Fact Sheet, Fourteenth Ed.
No data available for 1986 or 1987.
From: World Cement, August 1997 p.65

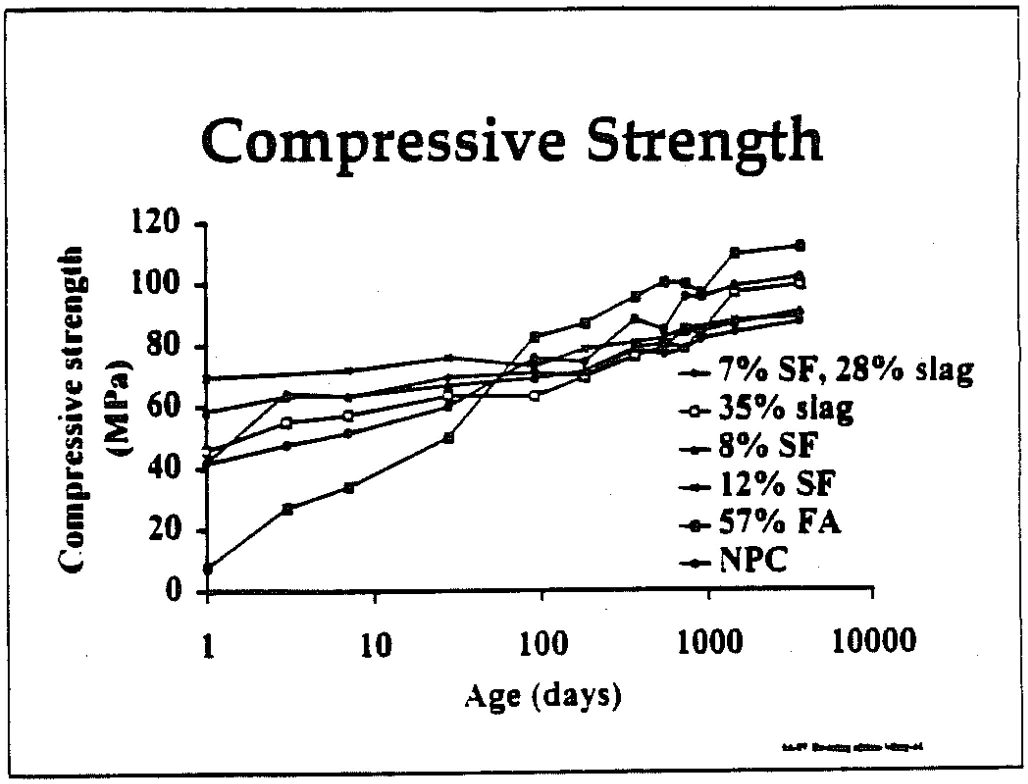

Fig. 2. Compressive strength versus age for various high-performance concretes. The strength is based on 100x200-mm cores taken from large blocks, 2.0x1.2x1.35-m in size.