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Report No. CBU-2005-17
REP-588
August 2005

Presented and Published at the CANMET/ACI Three-Day International Symposium on Sustainable Development of Cement and Concrete, October 5-7, 2005, Toronto, CANADA

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Konstantin Sobolev* and Tarun R. Naik**

ABSTRACT

Following the growing demand for cement, the world production of cement has significantly increased in the past 10 years. This trend is the most significant factor affecting technological development and updating manufacturing facilities in the cement industry. At the same time, the existing technology of production of cement clinker is ecologically unfriendly: it consumes much energy and natural resources, and emits a number of undesirable air pollutants.

A new approach to the production of blended or High Volume Mineral Additive (HVMA) cement helps to improve its ecological compatibility. HVMA cement technology is based on the intergrinding of the portland cement clinker, gypsum, mineral additives, and a special complex admixture. This new method increases the compressive strength of ordinary cement, improves durability of the cement-based materials; and at the same time it permits the utilization of a high volumes of inexpensive indigenous mineral additives or industrial by-products. This phenomenon leads to the reduction of the energy consumption per unit of the cement produced. Higher strength, better durability, reduction of pollution at the clinker production stage, and decrease of the landfill area occupied by industrial by-products, all provide ecological advantages for HVMA cement.

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INTRODUCTION

According to Cembureau and other reports (1-3), the world production of cement has increased by about 50% in the past 10 years (Fig. 1). The growing demand for cement is the most significant factor affecting technological development and the updating of manufacturing facilities in the cement industry (2-12).

It is generally agreed that the production of cement is expensive and ecologically harmful. CO_2, a principal gas contributing to the "greenhouse effect", NO_x and SO_x are among the hazardous emissions generated in relatively high volumes by the conventional portland cement process. If the production of cement is further expanded based on the existing technologies, products of the same performance will be obtained, but at a cost of increasing the consumption of raw materials and energy. Such expansion would, therefore lead to a substantial degradation of the environment. As a result, the demand of developing and growing markets cannot be met by simply extending the capacity of the current cement industry based upon existing technology (11).

Sustainable development is the answer to this challenge and main way ahead. The environmental damage due to construction materials can be measured and factored as an economic cost (13-18). New products must either have better performance or use less raw materials and energy.

SUSTAINABLE DEVELOPMENT AND ECO-EFFICIENCY

The definition of "sustainability", following the World Commission on Environment and Development, emphasizes the importance of ensuring the satisfaction of the present needs without compromising the ability of future generations to meet their own requirements (13). As a business model, this means businesses try to balance inputs and outputs to maintain a profitable enterprise. Sustainable development also includes the issue of environmental impact, resource use, and social effects. Sustainable development can be defined as achieving social, economic, and environmental objectives in parallel (14-15). For the construction industry sustainability means:

- Progress that meets the needs of the society;
- Economic development;
- Preservation of the environment; and
- Efficient use of resources.

Engineers and other professionals working together must take care of the health of the beautiful earth ("La Bella Terra") by recycling and sustainable management of resources derived from the earth (7). The concept of eco-efficiency was formulated at the 1992 "Earth Summit". The World Business Council for Sustainable Development (WBCSD) has proposed the following definition: "Eco-efficiency is reached by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle, to a level at least in line with the earth's estimated carrying capacity" (15-18). WBCSD has identified seven elements to achieve eco-efficiency:

- Reduce the material intensity of products;
- Reduce the energy intensity of products;
- Reduce toxic emissions;
- Enhance material recyclability;
- Maximize sustainable use of renewable resources;
- Extend product durability; and
- Increase the service life of the products.

For the cement industry these components can be presented in the following guidelines (11):

- Implementation of low temperature technologies for manufacturing clinker (including belite and mineralized clinkers) with consequent energy/fuel savings;
- Production of stronger cement and consequent application of stronger concrete in structural members with reduced cross-sections and consequent reduction of the amount of concrete raw materials, structural steel, and energy used leading to reducing bulk consumption of cement and concrete;
- Production of more durable cement-based materials with a significantly prolonged service life and reduced cost of maintenance;
- Application of mineral additives or industrial by- products in blended cements and reducing energy consumption and the corresponding emissions per unit of cement produced;
- Implementation of modern technologies for saving energy and recovery of materials leading to a reduction of heat, dust, and pollutant emissions;
- Development and application of new types of cement based on alternative (different from conventional portland cement) binders.

THE INTEGRAL EFFICIENCY OF THE CONSTRUCTION MATERIALS

The formula for the integral efficiency of the construction material or structure can be presented in the following equation (18):

$$L_i = \frac{\Sigma \mathbf{L}_{1..n}}{\Sigma \mathbf{M}_{1..n}} * D * W$$

In this formula $\Sigma \mathbf{L}_{1..n}$ represents the total engineering benefits as a sum of individual efficiency parameters $\mathbf{L_1, L_2, .. L_n}$. $\Sigma \mathbf{M}_{1..n}$ relates it to the sum of the expenditure $\mathbf{M_1, M_2, .. M_n}$. The integral efficiency L_i of the construction material increases with increasing of useful life **D**. The fourth important efficiency variable is the reusability ratio **W**. This describes the proportion of the structure that can be appropriately reused after the end of the structure's service life.

Corresponding to these main parameters there are four approaches for improving integral efficiency (18):

- Increase the engineering or ecological benefit,
- Reduce expenditure;
- Improve durability and service life; and
- Raise the recycling ratio.

TECHNOLOGICAL TRENDS IN CEMENT AND CONCRETE INDUSTRY

The most recent developments in cement and concrete technology can be summarized as follows (19):

- Strength: Following a historical trend of cement and concrete development, there is a strong trend to increasing strength. Continuous breakthroughs in knowledge allow the design and application of ultra high-strength concrete with a compressive strength of 130-250 MPa, high flexural strength, and high ductility (2-6, 8, 11, 19-22). As a result, research and application of effective structures, utilizing high strength concrete, is accelerating in past years, demonstrating strong growth potential.

- Chemical Admixtures: The use of chemical admixtures has become one of the essential parts of modern concrete. Added to the concrete mixture, relatively small amounts of the chemical admixtures radically alter the behavior of fresh or hardened concrete. Modern admixtures provide a solution for overcoming or improving almost any problematic property of concrete (4-8, 23).

- By-Products Utilization: The utilization of industrial by-products and post-consumer waste (IBPW) as mineral additives comprises a valuable segment of the cement and concrete technology. According to wide-scale investigations (2-11, 24-38), the performance of concrete with controlled volumes of IBPW can be significantly improved. Well-investigated mineral additives include granulated blast furnace slag, fly ash, and silica fume. These mineral additives not only yield concrete with improved properties and, at times economical effectiveness, but they also improve the eco-balance of these materials (39).

As a result of these developments the concept of high-performance concrete (HPC) has been put forward and successfully applied worldwide. It is generally accepted that concrete with properties better than conventional levels (considering its workability, strength, permeability, durability, and other properties) could be called High-Performance Concrete (HPC). According to Forster (40) HPC is “a concrete made with appropriate materials combined according to a selected mix design and properly mixed, transported, placed, consolidated, and cured so that the resulting concrete will give excellent performance in the structure in which it will be exposed, and with the loads to which it will be subjected for its design life”.

To realize the HPC concept, a variety of chemical admixtures and mineral additives are necessary, and a modern concrete batching plant must use adequate equipment for precise control, dispatching, dosing, and batch processing (19, 24). The technology of high performance (HP) cement was developed to simplify the production of HPC and to extend its range of application (11).

PROS AND CONS OF BLENDED CEMENT

The earliest reference to Roman cement and concrete with remarkable durability was made by Vitruvius (100 A.D.). The secret of the durability of Roman cement was to mix slaked lime with pozzolana, a volcanic ash from Mount Vesuvius, near Pozzuoli. This resulted in a binder that was able to harden under water. Modern blended cements also utilize pozzolan as a mineral additive or cement-replacing material, which is interground or blended with portland cement.

According to (26, 41), pozzolans can be defined as “siliceous or siliceous-and- aluminous materials which by themselves possess little or no cementitious value but, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties”. Pozzolans can be divided into two major groups (26):

- natural pozzolans (naturally occurring materials: volcanic ash/tuff, thermally activated clay/shale, diatomaceous earth); and
- artificial pozzolans (including IBPW).

In spite of the evident savings from energy and raw materials, there is a limit to the volumes of pozzolan utilized as cement/concrete additives. These volumes are controlled by the possible detrimental effect of pozzolanic additive on concrete performance (especially, early-age strength, permeability, and durability). Among the major concerns of the misuse of mineral additives are: reduced early strength, increased water demand of concrete mixtures, and reduced freezing and thawing resistance due to inadequate air-entrainment. The possible adverse effect of blended cements on the properties of concrete must be evaluated; to assure that the specific requirements of the particular construction project can be met.

TECHNOLOGY OF HP/HVMA CEMENT: HIGH STRENGTH AND DURABILITY

A new reactive silica-based complex admixture was developed (11, 24) to provide an improvement of cement properties. When added during the cement grinding process, the complex admixture modifies the surface and size distribution of cement particles; it also leads to the formation of highly reactive amorphous structures and pre-hydrates. The process named "high-performance (HP) cement technology" was found to be very effective for the development of an additional feature of normal cement. HP cement can be defined as a product manufactured by the mechano-chemical activation of certain proportions of clinker, gypsum, complex admixture, and optionally, a mineral additive of industrial or natural origin, which imparts a high-strength and extreme durability to the concrete or mortar made from it (11). The flowchart for the grinding unit for manufacturing HP/HVMA cement is presented in Fig. 2.

The high-strength phenomenon was used to engineer cement with a high-volume of mineral additives (HVMA). Because of its high strength, a large amount (up to 70%) of portland cement clinker could be replaced with mineral additives. A wide range of natural pozzolanic materials, sand, limestone, granulated blast furnace slag (GBFS), fly ash, and broken glass and ceramic, all can be used as mineral additives in these cements (24, 42 - 45). There are two types of HP cement:

- Basic HP cement (Type A) and
- Blended HP cement (Type B).

Basic Type A cement involves intergrinding the clinker, gypsum, and a complex admixture. Blended Type B cement covers wide range of HP cements with a mineral additive. The content of a mineral additive in blended HP cement varies with the specified level of the properties and with the type of additive used. Wide-scale research (11, 42 - 44) has demonstrated that HP cements with a mineral additive content within the standard limitations (25 - 50%) could be produced. Furthermore, the range of mineral additive utilization in HVMA cement can be extended. New types of mineral admixtures (such as sand, and broken glass and ceramic) can be used as an ingredient in the blended HP cement (24, 44).

The chemical composition of HP cement depends on the type and composition of the raw components. The chemical composition of HP cements (HPC) in comparison with normal portland cement (NPC) and GBFS is presented in Table 1.

The test results of HP cement (HPC) and normal grade cement (NPC) in accordance with the corresponding ASTM procedure are summarized in Table 2. HP cement possesses high 28-day compressive strength, which is at least 65% higher than the strength of NPC. The early age strength development of the HP cement classifies this cement as super-rapid hardening cement. HP cements demonstrated an increase in the long-term strength, especially, in case of Type B based on 50% of GBFS (Fig. 3). The application of granulated blast furnace slag (GBFS) in blended HP cement provides a very high resistance to chemical attack (30, 39, 42). Test results have demonstrated the possibility of producing blended HP cement with a compressive strength of more than 80 MPa and the GBFS content of up to 50% (Fig. 3).

As a result, HP cement technology helps to overcome the challenges related to the application of blended cements.

IMPACT OF HP/HVMA CEMENT ON THE ENVIRONMENT

Blended cements incorporating different mineral admixtures or industrial by-products and post-consumer waste (IBPW) can partly replace the cement clinker. Clearly, blended cements meet the challenges of modern society by increasing bulk production and conserving energy (2-11, 24, 36, 37). In the case of CO_2 emissions, “frozen” by the EU and others at the level of 2000, the share of conventional portland cement in the market must be drastically reduced by the year 2015 (Fig. 4).

At the same time, the extensive updating of existing facilities for the manufacture of clinker (which comprises an essential part of the inferior cements) consumes the bulk of capital investment and yields only a slow return (43). Therefore, the expansion of an existing cement plant requires a proportionally high rate of investment. The major part of this investment is associated with the installation of heavy equipment and construction. However, in the case of HVMA cement, new investments are required only to upgrade the grinding unit. This may increase production capacity by 40 - 50% with consequent increase in profit, but without any additional increase of clinker output (Table 3).

Since HVMA cement uses about 30 - 50% less clinker than inferior ordinary portland cements, it creates less ecological damage. In this way HVMA cement contributes to the reduction of carbon dioxide and other emissions at the source; and, at the same time, IBPW materials that would be otherwise transported to landfill sites are used economically.

Considering the superior level of properties of HP cement-based materials, the most important ecological and economical aspects contributing to the sustainable development are the following (42):

- reduced cross sections of structural elements for concrete raw materials, structural steel, and energy saving;
- reduced total weight of structures and foundations, reduced total energy consumption, less formwork, reduced maintenance costs and equipment loading, and increased speed of erection;
- significantly increased life-time of structures and reduced cost of repairing work because of high durability;
- replacement of generally used structural steel, polymers, and natural stone by ecologically friendly concrete;
- utilization of industrial by-products and post-consumer waste in HP/HVMA cement and reduction of energy consumption per unit of the cement produced; and
- decreasing the land spoiled landfills containing industrial by-products and post-consumer waste.

CONCLUDING REMARKS

1. HVMA cement uses less clinker than existing cements and meets the challenges of a sustainable society; it increases bulk production and conserves energy. HVMA cement contributes to the reduction of carbon dioxide and other emissions at source. Due to its better eco-compatibility, the market share of HVMA cements will increase in the future.

2. Because of its higher strength and durability, the production and application of HP/HVMA blended cement helps to reduce the environmental degradation associated with construction activities.
3. Because of its ecological and economical advantages an “ECO” prefix can be suggested for HP/HVMA cement: ECO-cement.

ACKNOWLEDGEMENT

The authors would like to acknowledge the contributions of colleagues from LAU and UWM-CBU. These were useful to improve the work reported in this article.

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Table 1 - Chemical Composition of HP Cements (42)

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	L.O.I.
NPC	19.4	4.8	3.6	63.7	1.9	0.77	0.21	2.7	2.4
GBFS	40.1	11.5	1.6	31.8	9.5	1.0	0.0	2.1	0.2
HPC-A	28.5	4.2	3.4	55.0	1.9	1.0	0.38	2.6	2.8
HPC-B	34.3	7.8	2.5	43.4	5.7	1.0	0.19	2.4	1.5

Table 2 - Physical Properties of HP Cement

	Fineness		Setting Time min		Normal Consistency %	Compressive Strength, MPa at age, days					
	Blaine m^2/kg	45μ %	Initial	Final		1	2	3	7	28	90
NPC	310	8.50	165	205	27.1	26.2	36.4	42.4	48.5	57.1	64.7
HPC-A	570	5.40	100	145	18.5	44.3	55.9	62.2	74.1	94.4	96.2
HPC-B	580	5.20	175	225	17.5	35.2	44.8	54.2	65.6	92.7	105.5

Table 3 - Expanding an Existing Cement Plant: Case of HVMA Cement (43)

Performance Parameters	**Existing Plant**	**+20% Scenario**	**+40% Scenario**
Mineral Additive Content, *%*	30	50	70
Capacity, *mil. tons per year*	1.0	1.4	2.3
Required Investments, *mil. $*	-	4.3	13.9
Unit Price, *$/ton*	45	45	45
Income, *mil. $*	45.0	63.0	103.5
Production Cost, *mil. $*	39.4	53.1	83.5
Gross Profit, *mil. $*	5.6	9.9	20.0
Extra Gross Profit, *mil. $*	-	4.3	14.4
Extra Net Profit, *mil. $*	-	3.4	11.5
Pay Back Period (10% interest rate), *year*	-	1.4	1.3

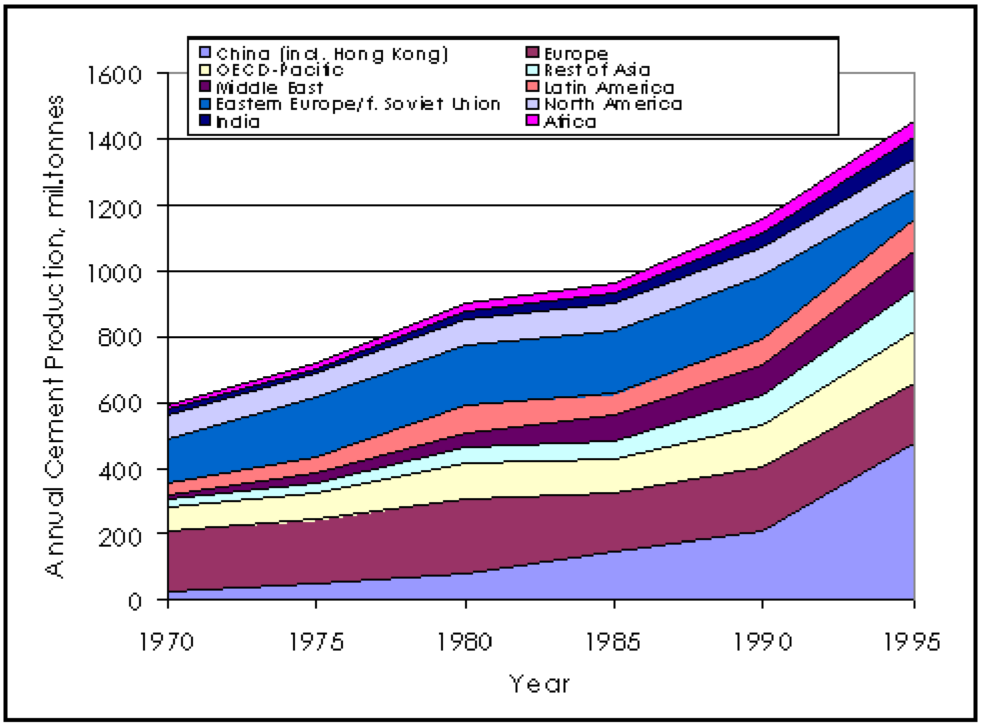

Fig. 1 - Production in the Cement Industry (1)

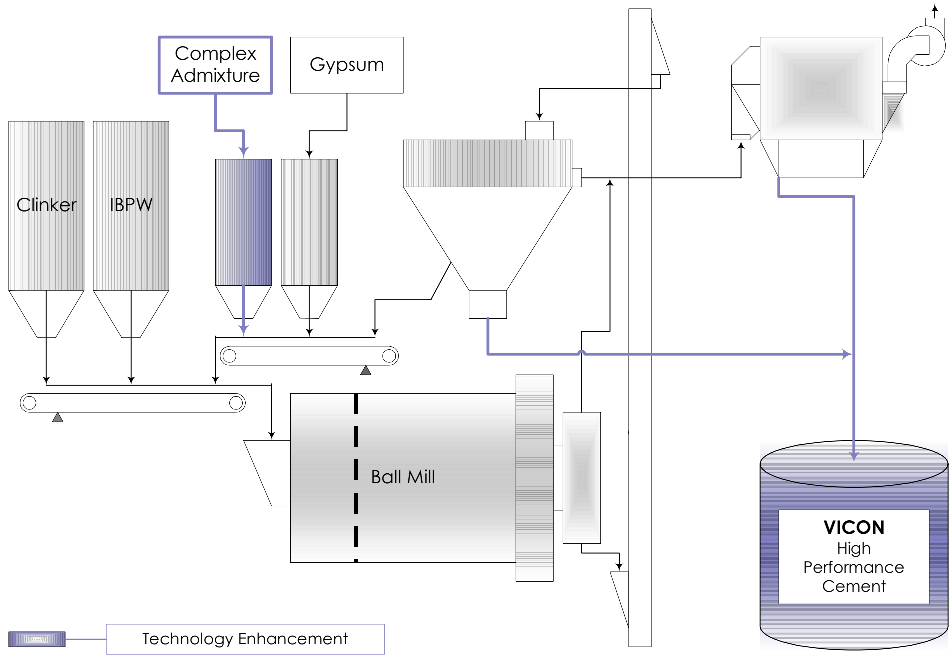

Fig. 2 - High-Performance Cement Technology

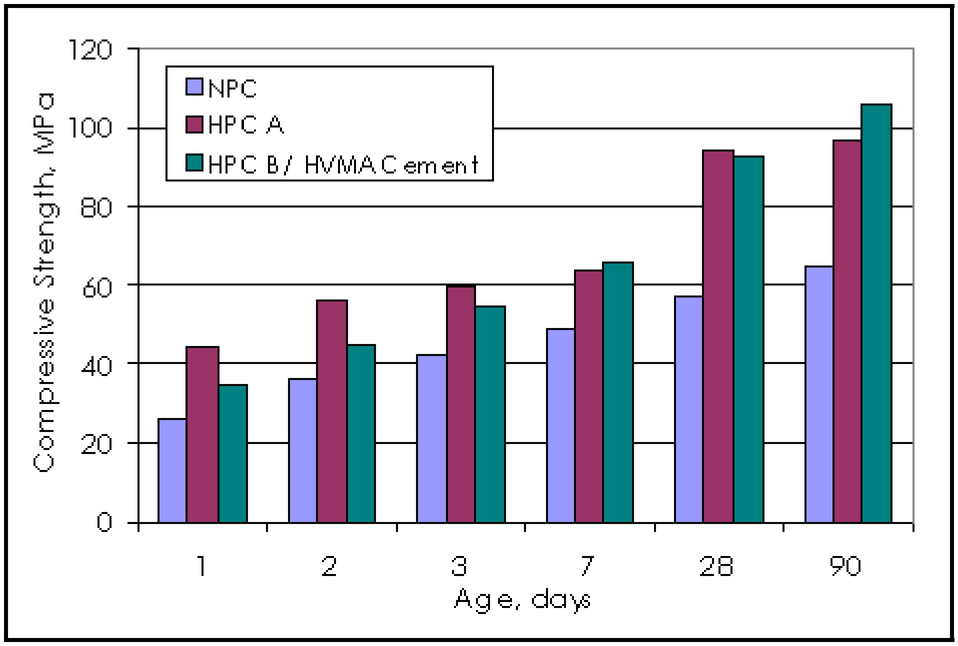

Fig. 3 - HP/HVMA Cement Strength Development

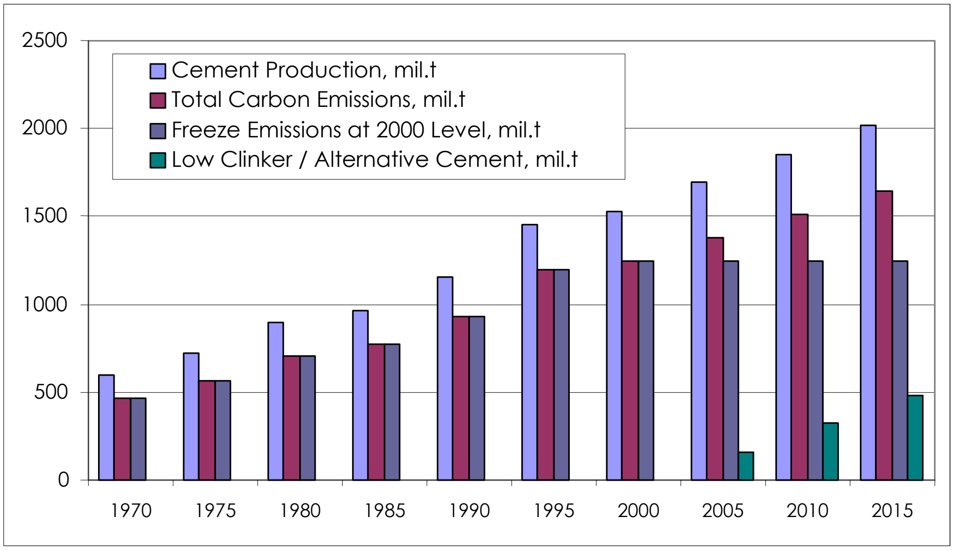

Fig. 4 - Prediction of Emissions and Market Share of Low-Clinker Cement