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Role of Pozzolanic and Cementious Material in Sustainable Development of the Concrete Industry

by P. K. Mehta

Synopsis: Among the major problems facing the concrete industry at the end of the twentieth century are the enormous infrastructural needs of a rapidly urbanizing world, the premature deterioration of many concrete structures, the need to improve concrete durability in a cost-effective way, and increasing public interest in finding ecological solutions for safe disposal of millions of tons of industrial by-products that might be suitable for incorporation into cementitious materials and concrete. In this paper the author has shown that all these problems are interrelated and can be resolved by adopting a holistic approach.

Keywords: cementitious materials; cost; durability; fly ash; infrastructure; industrial by-products; slags; utilization rates.

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1. INTRODUCTION

In a paper, **Concrete Technology at the Crossroads**, which the author presented in 1994 at a symposium honoring Mohan Malhotra (1), the following three issues confronting the concrete industry were addressed in detail:

1. Enormous infrastructural needs of a rapidly urbanizing society in the world.

2. The need for a balance between industrial development and environmental protection.

3. The crisis in the area of concrete durability.

Since the advent of the industrial revolution, approximately four hundred years ago, not much attention has been paid to the environmental and social costs of technology. This is changing now. With the beginning of the twenty-first century in less than three years, **we are entering into an era of sustainable development**. This means that, in the future, it will not be possible to pursue technological goals without giving equal importance to the public interest in preserving the ecological balance on the planet earth. There is a heightened awareness now that this planet is too small to contain the wastes of our industrial civilization. In the context of this awareness, only a holistic approach in concrete technology can help us meet the material needs of an increasingly urbanized world. Therefore, one of the objectives of this paper, which is based on a presentation made last year at a symposium in honor of Professor Mario Collepardi (2), is to show how seemingly unrelated problems such as those listed above are found to be closely interconnected when examined from a holistic standpoint and therefore can be addressed with a common solution.

2. INFRASTRUCTURAL NEEDS OF THE WORLD

The twentieth century has seen unprecedented growth in human population which, during the last seventy-five years, has risen from two to six billion. By the year 2025, it is expected to increase to nine billion. Industrialization of the world occurred primarily in response to the search for sources of energy, minerals, and food as a result of population growth. Industrialization has led to urbanization. For the first time in the history of the world, more people are now living in and around cities than in rural areas. According to a U.N. report, in addition to numerous cities with a population of more than one million, there are now twenty megacities with eleven million or more inhabitants.

The infrastructure for industrial and urban areas, such as buildings, mass transit, and facilities for handling water and sewage, obviously requires large amounts of construction materials. For numerous structural applications concrete has unquestionably become the material of choice due mostly to its low cost, easy availability, versatility, and adequate engineering properties. At the same time, during the last one hundred years, portland cement has emerged as the principal hydraulic binder for concrete mixtures. The 1994 world consumption of approximately 1.3 billion tons of cement consisted mostly of portland cement because, unlike the old lime-pozzolan cements, it possesses faster setting and hardening characteristics, which are more suited to modern construction speeds. The current and the projected yearly cement consumption rates in different parts of the world up the year 2005 are shown in Table 1. Note that nearly 370 million tons out of the projected 500-million-ton total increase in cement consumption during the period 1994-2005 (i.e. 75% of the world's total) comes from Asia, and South and Central America. Due to the capital-intensive nature of the portland cement industry (U.S. $200 per ton of annual installed capacity of cement), many poor countries will be hard pressed to find the financial resources for constructing new cement plants.

3. SUSTAINABLE INDUSTRIAL GROWTH

Limestone and clay, the basic raw materials for making portland cement, are plentiful throughout the world. The major bottlenecks in increasing the portland cement production by almost five hundred million tons annually by the year 2005 appear to lie in the high energy requirements and the high rate of CO_2 emissions. It is estimated that, with every ton of portland cement produced, one ton of CO_2 is released to the environment. Increased CO_2 loading of the earth's environment is a matter of serious concern to the intergovernmental panels on climate change. During the last one hundred years, the "greenhouse effect" has already resulted in global warming by 4° C. By the middle of the twenty-first century, CO_2 emissions from the combustion of hydrocarbon fuels and other sources, if unchecked, are expected to rise by 100%. This will have the effect of raising the average atmospheric temperature of the world to an unacceptably dangerous level. An environmental disaster would be unavoidable if China, India, and developing countries of South and Central America start consuming as much energy and materials (such as portland cement) as the West did in its march to industrialization.

As stated earlier, nearly 370 million tons, or 75% of the total projected increase in cement consumption by the year 2005, will come from the countries of Asia, and South and Central America. Because the process of industrialization in developing countries of the world cannot be stopped, we must find a way to guide it into environmentally friendly tracks. The 1992 Earth Summit in Rio de Janeiro defined **sustainable development** as economic activity that is in harmony with the earth's ecosystems. The goal of sustainable development of the cement and concrete industries is, therefore, very important, and it can be reached if we make a serious effort for **complete utilization of the cementitious and pozzolanic by-products** produced by thermal power plants and metallurgical industries, as suggested in the next paragraphs.

Manz (3) reported that, in 1989, 562 million tons of coal ash were produced, of which only 25 million tons were used for making blended portland cements or as a concrete admixture. Note that this amount represents only about 5% of the total available coal ash. The current annual production of coal ash is estimated to be around 650 million tons, of which at least 70% or 450 million tons is fly ash or fine coal ash that is generally suitable for use as a pozzolan in cementitious systems (4). Another industrial by-product which can be useful for making cement is iron blast-furnace slag. Although the world production of this slag is approximately 100 million tons/year, the use rate of the product as a cementitious material is quite low because, in many countries, only a small portion of the slag is granulated, i.e. quenched and therefore available in a cementitious form.

The author has made an interesting discovery that relatively huge volumes of disposable coal ash and iron blast-furnace slag are available in those countries which happen to require large amounts of cement. For instance, China and India together produce about 150 million tons of coal ash every year. European countries, mainly Russia, Poland, the former Czechoslovakia, Romania, Germany, Spain, and the United Kingdom produce approximately 250 million tons of coal ash per year. Also, at least 50 million tons of the total yearly production of 100 million tons of blast-furnace slag comes from China, India, and Europe. At the same time, note that nearly 440 million tons of the total projected increase in the cement consumption by the year 2005 is expected from these countries (Table 1). **It should be immediately obvious that if we can find ways to use all or most of the available coal ash and iron blast-furnace slag, either in the form of blended portland cement or as mineral admixtures in concrete, we would be able to meet the projected cement demand in the year 2005 without any increase in the present capacity of portland-cement clinker production.** A sustainable development of the cement and concrete industries, as defined above, can thus be assured. Considering the additional ecological benefits described next, it is hard to imagine a better solution to the problem.

Nearly 90% of the coal ashes and metallurgical slags produced today end up either in low-value applications such as landfills and road bases, or simply disposed off by ponding and stockpiling. Disposal in this manner is not only wasteful but also harmful to human health because it contributes to land, air, and groundwater pollution. These by-product materials generally contain toxic metals. The concrete industry provides a preferred vehicle for their disposal because most of the harmful metals can be immobilized and safely incorporated into the hydration products of cement. In fact, owing to its large size, the concrete industry is probably the ideal home for safe and economical disposal of millions of tons of by-products. Based on a study by Schiessl and Hohberg (5), Fig. 1 shows the excellent environmental compatibility of a mortar made with a cement-fly ash mixture. In a realistic leaching test (tank test), the authors reported that only 0.09 mg/kg zinc and 0.15 mg/kg chromium were leached from a cement mortar when the total amounts of the metals added to the mortar were 185 mg/kg and 53 mg/kg, respectively.

4. CONCRETE DURABILITY

In most countries of the world, the heavy expenditure for repair and replacement of the infrastructure has become a matter of serious concern as too many concrete structures are found suffering from deterioration problems much earlier than their expected service life. At the same time, a growing public interest in ecology requires that the earth's natural resources are conserved as much as possible through enhancement of durability of manufactured products. Consequently, with the twenty-first century approaching, it is important that we critically examine the concrete technology of today and explore how it can be improved to make concrete a truly high-performance material of the future. Also, since many materials and methods are being promoted for enhancement of durability of concrete structures, it will be prudent to evaluate their cost effectiveness. This is because material cost will continue to be an important consideration in the construction of most structures.

It is generally known that the major causes of deterioration of reinforced concrete structures are the corrosion of reinforcing steel, exposure to cycles of freezing and thawing, alkali-silica reaction, and sulfate attack. From a review of case histories of concrete degradation, the author developed a holistic approach encompassing the major causes of concrete deterioration (1). This approach is based on field experience that, with every one of these four causes of concrete deterioration, a high degree of water saturation is a prerequisite to the mechanisms responsible for expansion and cracking of concrete. Therefore, the water-tightness of concrete, which is its first line of defense against a hostile environment, must somehow become breached before the material is seriously damaged. This shows that, compared to other properties, the soundness of concrete, i.e. the freedom from cracking, is closely related to concrete durability. It seems that modern concrete construction practice does not pay adequate attention to the two primary causes of early cracking in concrete, namely, thermal contraction and drying shrinkage. Therefore, a brief review of the fundamental principles governing the cracking of concrete from these two causes will be helpful here.

When a freshly placed and hardened concrete is exposed to ambient temperature and humidity, it experiences both thermal and drying shrinkage strains. The type and magnitude of the shrinkage strains will depend on the temperature and the humidity of the environment, the size of the concrete element, the temperature of the concrete, the characteristics of the concrete-making materials, and the mixture proportions. Under the restraining conditions in hardened concrete, a shrinkage strain would result in an elastic tensile stress which, as a first approximation, may be assumed as equal to the product of the strain and the elastic modulus of the material. The concrete would crack when the induced tensile stress exceeds its tensile strength. However, due to the viscoelastic or creep behavior, some of the stress is relaxed, and it is therefore the residual stress which determines whether or not cracking would occur. **This interplay between the tensile stress generated by restrained shrinkage and the stress relief due to creep, as illustrated in Fig. 2, is at the heart of early cracking and microcracking in concrete structures that would later destroy its watertightness.** It is clear from the illustration of fundamental principles in Fig. 2 that the risk of cracking in concrete due to restrained shrinkage can be reduced by one or more of the following factors: a high tensile strength, a low shrinkage strain, a low elastic modulus, and a high creep strain (6).

Driven by the high speed of construction, concrete mixtures today tend to contain a high content of normal or high-early strength portland cement. Obviously, as shown in Fig. 3, the extensibility or crack resistance of such concretes would be low due to increase in the drying shrinkage, thermal shrinkage, and elastic modulus on the one hand, and a reduction in the creep coefficient on the other hand. This is the reason that high-early-strength concrete mixtures are more vulnerable to cracking than moderate or low-strength concrete mixtures. Traditionally, structural cracking is controlled by the use of sufficient steel reinforcement but, as explained below, substitution of a few wide cracks with numerous invisible and unmeasurable microcracks is not a good solution for concrete durability problems.

The preceding theoretical considerations are confirmed by field experience. In 1995 the U.S. National Highway Cooperative Research Program conducted a survey of recently built concrete bridge decks. Noting that more than 100,000 bridge decks showed transverse cracks even before the structure was one month old, Rogalla et al. (7) drew the following conclusions:

1. A combination of thermal shrinkage and drying shrinkage caused most of the cracks, not traffic loads or vibration during the hardening of the concrete.

2. Generally, decks are made of high-strength concrete. These concretes have a high elastic modulus at an early age. Therefore, they develop high stresses for a given temperature change or amount of drying

shrinkage, and most important, the concrete creeps little to relieve these stresses.

3. High-strength concretes typically contain more cement. Therefore, they shrink more and produce higher temperatures during early hydration. Modern cements are apt to cause cracking because they are finer and contain higher sulfate and alkali contents.

In conclusion, according to the holistic approach to concrete deterioration, a well constituted and properly consolidated and cured concrete will remain essentially watertight as long as the pores and cracks present in the interior do not form an interconnected network of pathways leading to the surface. Structural loads as well as weathering effects such as exposure to cycles of heating-cooling and wetting-drying facilitate the propagation of microcracks that normally pre-exist in the transition zone between the cement mortar and coarse aggregate in concrete. This happens during the first stage of the structure-environment interaction. Once the watertightness of concrete has been lost, it can become saturated and harmful ions also can move into the interior. This marks the beginning of the second stage of the structure-environment interaction during which the deterioration of concrete takes place through successive cycles of expansion, cracking, loss of mass, and increase in permeability.

Gerwick (8) has given a list of preventive and mitigating measures which are commonly adopted for minimizing the degradation of concrete due to corrosion of reinforcing steel, with representative values of their cost appended in parentheses (given as a percentage of the first cost of the concrete structure). A part of this list is reproduced below. These costs are valid for Western countries, and as of 1994, can be used for comparison purposes:

1. Use of fly ash or slag as a partial replacement for cement (0%).
2. Pre-cooling of the concrete mixture (3%).
3. Use of silica fume and a superplasticizer (5%).
4. Increase cover by 15 mm (4%).
5. Use of a corrosion-inhibiting admixture (8%).
6. Epoxy-coating of reinforcing steel (8%).
7. External concrete coatings (20%).
8. Cathodic protection (30%).

Obviously, where thermal cracking and durability are of primary interest, **the most cost-effective solution** is Option 1, i.e. the replacement of part of the portland cement in the concrete mixture with fly ash or slag, while meeting the setting and hardening requirements of the job under given ambient conditions. Options 2, 3, or 4 may be necessary for special structures. The last four options, namely, the use of a corrosion-inhibiting admixture, epoxy-coated steel reinforcement, external coatings for concrete, and cathodic protection are much more expensive and a relatively small extension in service life from the use of these expensive options is expected once the first line of defense, i.e. watertightness, is breached. **Experience in the field of human health shows**

that preventive measures are always more cost-effective than the remedial measures needed after the body has become afflicted with disease.

For building durable highway structures, it seems that many transportation departments in the U.S. are already showing a preference for Option 1. According to Keck and Riggs (9), since the construction of the Sunshine Skyway Bridge in 1986, the use of fly ash in bridge concrete, including prestressed concrete elements exposed to a moderately aggressive environment, has been made mandatory by the Florida Department of Transporation. A minimum cement replacement rate of 18% is specified. Also permitted are Type IP cement containing 15 to 40% pozzolan, and Type IS cement containing 50 to 70% granulated blast-furnace slag. In mass concrete replacement of up to 50% cement by fly ash is permitted. A nearly linear relationship between the rate of cement replacement by fly ash and the 7-day heat of hydration is the reason behind the use of fly ash in hot weather and mass concreting. Further, according to Keck and Riggs (9), epoxy-coated reinforcing steel was used on many projects but did not perform as well as expected in chloride exposure, for instance, the Seven Mile Bridge in Key West, Florida. Extensive evaluation of chloride permeability was done by the Florida Department of Transportation in arriving at the standard specification, making the use of fly ash mandatory in concrete exposed to aggressive environment.

Alkali-silica reaction (ASR) has been a problem in North Carolina, and the use of fly ash in concrete is mandatory if the alkalies in cement exceed 0.4% (9). At one time, fly ash usage during cold weather was prohibited, but due to the ASR problem year-round use is now permitted. ASR has also been a problem in Virginia, and concrete is required to either contain cement with alkali less than 0.4% or Class F fly ash. To address the problem of corrosion of reinforcing steel, an upper limit of 2,000 coulombs in the rapid chloride permeability test is considered; this level of permeability can be achieved economically with pozzolans such as Class F fly ash. Similarly, the South Carolina Department of Transportation requires 83 kg/m^3 fly ash in concrete to reduce permeability and reinforcement corrosion.

Among researchers in the area of concrete durability, there is now an increasing appreciation for a holistic or integrated approach. In his elegant review of alkali-aggregate attack in concrete, Swamy (10) stated, "to attack and cause damage, **all three members of the triad must be present, namely: sufficient alkali in the concrete, critical amount of the reactive aggregate, and sufficient moisture."** The economic and ecological implications of this conclusion should be apparent. For example, why should it be necessary to reject high-alkali raw materials for cement making, or reactive aggregates for making concrete mixtures, if proper steps are taken so that the concrete structure remains dry during its service life? As discussed earlier, the use of fly ash or other pozzolanic materials is one of the most cost-effective steps to achieve this end.

Similarly, in his excellent review of a highly controversial topic in concrete technology today, namely, the damage caused by the DEF phenomenon (delayed ettringite formation), Collepardi (11), using the holistic approach, has concluded that **a high risk of damage due to the DEF would occur only if all three of the following conditions are present together: late sulfate release, microcracks in concrete, and exposure to water** (Fig. 4). Again, the economic and ecological implications of this conclusion are profound. For example, for production of portland cement clinker, rather than stopping the use of secondary fuels such as old automobile tires and petroleum coke, which usually have a high sulfur content, a preferable solution is to reduce the chance of cracking and subsequent water penetration into the structure. Again, the incorporation of pozzolanic or cementitious materials into concrete mixtures can reduce the permeability and improve the crack resistance, thus resulting in enhanced durability to both internal and external sulfate attack.

5. OVERCOMING THE OBSTACLES PREVENTING HIGH USE RATES OF POZZOLANIC AND CEMENTITIOUS BY-PRODUCTS IN CONCRETE

To achieve sustainable industrial development in the future and to dramatically accelerate the rate of use of pozzolanic and cementitious by-products in the concrete industry by the year 2005, it will be necessary to identify and remove the barriers preventing their large-scale use. This task should be given a high priority not only by the developing countries of Asia, Eastern Europe, and South America, but also by the developed countries because the success or failure of this mission has global ecological implications. Discussed below are some of the well known arguments that have been advanced in the past against the use of fly ash and granulated blast-furnace slag in concrete.

5.1 Variable Chemical Composition

The chemical composition of a fly ash or slag from an industrial facility is controlled by the raw materials used and the processing conditions. These vary not only from one plant to another but also within the same plant. Large variations in the chemical composition of fly ashes and slags are, therefore, natural. However, it is generally accepted now that the pozzolanic and cementitious properties of materials are governed less by the chemistry, and more by the mineralogical or phase composition and particle size (3).

Again, industrial fly ashes and slags happen to differ widely in both the phase composition and particle size which, of course, influence their reactivity. A particular application may require a relatively reactive material; others may not require high reactivity. Thus, instead of an outright rejection of by-product materials on account of differences in reactivity, an integrated approach to safe and economical disposal of these materials would require innovative match-making to find suitable homes within the concrete construction industry for every type of fly ash and slag produced. Bhanumathi Das and Kalidas (12) at the Institute of Solid Waste Research and Ecological Balance, Visakhapatnam, southern India, have developed the technology to make fly ash-lime-gypsum or fly ash-portland cement bricks and blocks. By disregarding the standard chemical and physical requirements for use of fly ash in the cement and concrete industries, the authors found that tailor-made blends of even nonstandard fly ashes with lime and gypsum or with portland cement produced adequate strength on normal curing. With one hundred small units in operation and hundreds more on the way, it is obvious that this type of entrepreneurship is vital for making a dent in the fly ash disposal problem while conserving energy and top soil, which are the base materials used in the manufacture of fired-clay bricks.

Sometimes the reactivity of a fly ash or slag may have to be altered. Fine grinding and thermal curing are two well known methods of accelerating the pozzolanic and cementitious reactions. On the other hand, with highly reactive materials it may be necessary to retard the reactivity before use. This can be achieved by partial prehydration. For instance, for the construction of a roller-compacted concrete dam in Greece, a very reactive high-calcium fly ash with 42% total CaO (15% free CaO, and some C_3A and calcium sulfate) is being used after grinding and prehydration (13).

In short, it is not the variability from one source of supply to another which seems to be a major obstacle in the way of accelerating the use of fly ash and slag in concrete. A real bottleneck is the lack of consumer confidence in the uniformity of quality within a single source. This also is not an unsurmountable obstacle. For years the cement and concrete industries have practiced the art of blending large amounts of materials of different compositions in order to obtain end-products with acceptable uniform quality. Given the willpower and proper incentives, the producers and potential consumers of these by-products can work together to overcome this problem. The increased handling cost will be easily justified if the producers of these by-products are heavily penalized for their hazardous disposal practices.

5.2 Nomenclature, Specifications and Codes

The terms, mineral admixtures and supplementary cementing materials have been generally used for fly ash and other siliceous by-products, such as silica fume, rice-husk ash, and ground granulated blast-furnace slag. These terms imply a second-class status relative to portland cement, and therefore are denigrating. In fact, the terminology or nomenclature has probably played some role in preventing the general acceptance of these by-product materials by the construction industry.

Now that their importance is well established in sustainable development of the cement and concrete industries, and in the enhancement of durability of portland-cement concrete, with little or no increase in cost, it is strongly recommended that pozzolanic and cementitious by-products are addressed by the term, **complementary cementing materials.** These materials need portland cement for their activation; and portland cement-based products need them for improvement of their durability and ecological profile. In the industrial world, it will be hard to find similar or better examples of complementarity or marriage between two components, where each component makes an equally important contribution for the good of the whole system.