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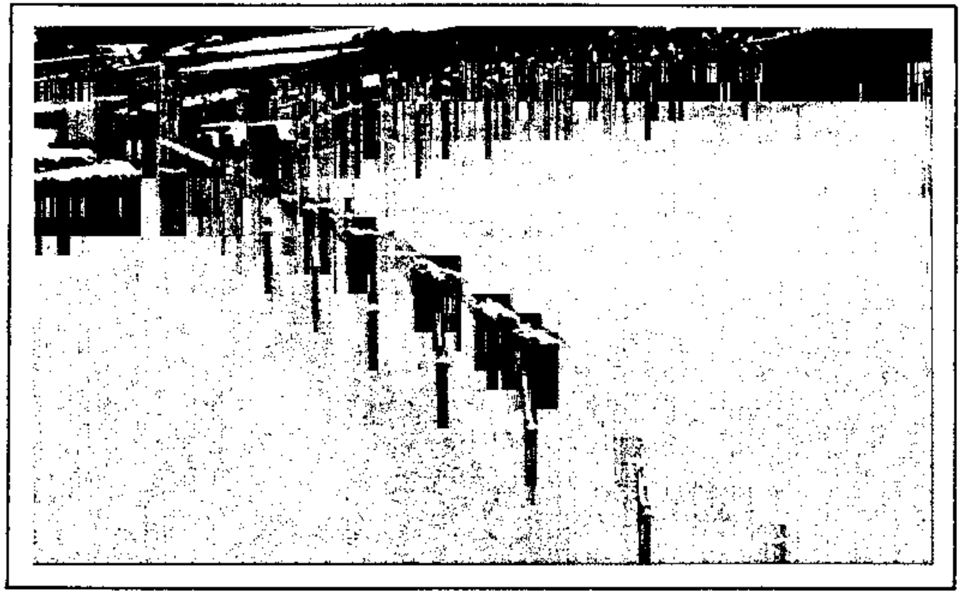

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Editor

Bringing the Concrete Industry into A New Era of Sustainable Development

P. Kumar 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 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.

Key words: Infrastructure, sustainable growth, durability, cost, industrial by-products, fly ash, slag, utilization rates, high-volume applications.

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1. INTRODUCTION

In an earlier paper, **Concrete Technology at the Crossroads**, presented in 1994 at the Mohan Malhotra Symposium (1), the author discussed some of the challenges confronting the concrete industry. The following three issues were addressed in some 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 preservation of the ecological balance on the planet earth. There is 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. One of the objectives of this paper is to show how seemingly unrelated issues, such as those listed above, are found to be closely interconnected when examined from a holistic standpoint.

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 builder 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. Projected yearly cement consumption rates in different parts of the world in the years 2000 and 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 (2) reported that, in 1989, 562 million tons of coal ash were produced, from 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 (3). 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 utilization rate of the product as a cementitious material is quite low because, in many countries, only a small portion of the slag is available in granulated or cementitious form.

The author has made an interesting observation 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 up all or most of the available coal ash and iron blast-furnace slag, either in the form of blended portland cement or as supplementary cementing materials 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 away 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 (4), 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 away from a cement mortar when the total content of the metals present in the mortar was 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 watertightness 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 shrinkage 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 strain 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 mix 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.

Driven by the high speed of construction, concrete mixtures today tend to contain a high content of normal or even high-early strength portland cements. Obviously, as shown in Fig. 3, the extensibility or crack resistance of such concretes would be low because of an 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 less than one month old, Rogalla et al. (5) 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 among 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.

Based on the holistic approach to concrete deterioration, a two-stage model of the damage process may be constructed (Fig. 4). Such models should not be used for making exacting predictions of the service life of concrete structures. Nevertheless, as discussed next, they can be helpful in decisions regarding cost-effective strategies for prolonging the service life of concrete exposed to aggressive environments.

Gerwick (6) 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. Addition 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. Note that the first four options influence durability through prolonged watertightness, namely, through their effect on Stage 1 of the concrete damage model.

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 are expected to prolong Stage 2 of the damage model. 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 (7), 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 (7), 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% (7). 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 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 excellent review of alkali-aggregate attack in concrete, Swamy (8) 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, it is not necessary to reject high-alkali raw materials for cement making, or a reactive aggregate in concrete mixtures, provided the concrete structure would remain dry during its service life. To this end, the use of fly ash or other pozzolanic materials has already been discussed.

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 (9), 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.** Again, the economic and ecological implications of this conclusion are profound. For example, for burning portland clinkers, it is not necessary to stop the use of secondary fuels such as old automobile tires and petroleum coke, which usually contain a high sulfur content. From economic and ecological standpoints, a preferable solution is to reduce the chance of excessive cracking and microcracking and subsequent water penetration during the service life of concrete made with a portland cement containing higher than normal sulfate content.

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

It is obvious by now that, in order to achieve sustainable industrial development in the future and to dramatically accelerate the rate of utilization of pozzolanic and cementitious by-products in the concrete industry by the year 2005, it will be necessary to identify and remove the barriers that are in the way of increasing their use. This mission 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. To stimulate a discussion on this subject, 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 mineralogy and particle size (3).

Again, industrial fly ashes and slags happen to differ widely in both mineralogy 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 matchmaking to find suitable homes within the concrete construction industry for every type of fly ash and slag produced. Bhanumathi Das and Kalidas (10) 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 (11).

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 inhomogeneous lots of materials 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 Specifications and Codes

For historical reasons, standards on portland cements, slags, pozzolans, and blended portland cements in most countries of the world are "prescriptive" in the sense that they tend to specify limits on certain chemical constituents. With blended portland cements the prescriptive standards tends to specify maximum permissible amounts of a blending material. Although performance-based specifications are being introduced in some countries, most engineers lack the confidence to use them. This is a serious bottleneck to large-scale and innovative uses of by-products in concrete, as discussed below.

From a detailed examination of current world standards on pozzolanic and cementitious materials, it was concluded that separate standards covering them are unnecessary and that many requirements in these individual standards are obsolete and therefore can be deleted in favor of a few that might be adequate for the purposes of quality assurance (3). It will then be possible to develop a simple, performance-oriented, single standard covering all pozzolanic and cementitious materials. The Canadian Standard CSA-A23.5 has followed this approach. Restrictive limits on the maximum permissible amounts of by-product materials in blended portland cements also do not make sense in the context of studies by Malhotra and his associates at CANMET (12). As discussed later, it was discovered that, with superplasticized concrete mixtures, strength and durability characteristics required for high quality structural concrete can be attained with up to 60% cement replacement with fly ash. Note that the current Indian standard specification for portland-pozzolan cements restricts the amount of fly ash to 25% by mass. Obviously, 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. It will also help the development of ternary and quaternary cementitious systems containing two or more supplementary cementing materials added to portland cement.

5.3 Effect on Properties of Concrete

The water-reducing properties of fly ash and ground granulated iron blast-furnace slag are well established. Therefore, it is generally observed that their use has a positive influence on the rheological properties of fresh concrete, such as pumpability. In hardened concrete the effect of incorporation of supplementary cementing materials on two interrelated properties, namely, durability and strength, needs a more detailed examination.

It is a misconception that the durability of reinforced concrete containing fly ash or slag exposed to sea water or de-icing chemicals would be less than plain portland-cement concrete. Overwhelming evidence both from theoretical considerations as well as from field experience shows that pozzolanic and cementitious materials, when of proper quality and when used in correct proportion followed by proper curing of concrete, have a very positive influence on concrete properties. Use of pozzolanic materials results in concrete with reduced permeability and reduced expansive stresses, and therefore reduced tendency for cracking. Concrete receives additional protection from corrosion and other expansive phenomena, including the alkali-silica reaction and sulfate attack, when supplementary cementing materials are properly used.

Regarding the effect of fly ash or slag on the compressive and tensile strengths of concrete, whereas the ultimate strengths are generally improved, the setting and hardening rates at early ages are significantly slower, especially with less reactive materials and under cold weather conditions. A higher rate of strength development similar to plain portland cement concrete may be achieved by the application of one or more of the following methods: (i) heat curing,

(ii) partial replacement of the fine aggregate rather than portland cement, (iii) finer grinding of the fly ash or slag, (iv) reduction of water-cement ratio with the help of a superplasticizer, and (v) partial replacement of a less reactive slag or fly ash with a more reactive pozzolan (such as silica fume or rice-husk ash) or with very finely ground slag. However, as discussed below, structures made with slow-hardening concrete generally show a better long-term performance than those containing fast-hardening concrete which, unfortunately, has become the common practice in modern concrete construction.

From a review of performance of concrete during the period 1930-1980, it was concluded by the author (13) that many problems with premature deterioration of concrete structures were attributable to the acceleration of construction speeds, increase in the water content of concrete mixtures, and production of portland cements with high early strengths and, consequently, low cement content in concrete. In response to concern for durability, especially under aggressive environmental conditions, the pendulum may have swung toward the increasing use of concrete mixtures containing high cement content and very low water-cement ratio. As explained earlier, these concretes are characterized by low creep and high elastic modulus even at early ages and, therefore, are quite susceptible to cracking induced by thermal and drying stresses. Structural cracking, of course, can be controlled by the use of reinforcing steel. However, this does not help the durability of concrete because it is the unseen and unmeasurable microcracks which eventually would enlarge with time and become interconnected.

In conclusion, **if durability is of primary interest, then the slow rate of setting and hardening associated with the incorporation of fly ash or slag in concrete is an advantage, not a disadvantage.** Any economic disadvantage as a result of delay in the removal of formwork would be easily offset by the lower life-cycle cost of the structure, and by the ecological impact associated with enhancement of the durability of concrete as well as the safe and cost-effective disposal of large amounts of hazardous industrial wastes.

6. EXAMPLES OF HIGH-VOLUME FLY ASH APPLICATIONS

Due to its large size, the construction industry is the primary focus of attention throughout the world in efforts to accelerate the rates of utilization of fly ashes and slags. The concrete industry, in particular, appears to be the ideal home for safe and most beneficial disposal of millions of tons of these hazardous by-products. These by-products actually serve as **complementary cementing materials** with portland-cement concrete because without them the concrete would not be as energy-efficient, ecologically friendly, and durable. Although examples of high-volume fly ash alone are given below, it is understood that, in general, similar or even larger portions of granulated blast-furnace slag can be substituted for fly ash.

For use in general construction, it is helpful to divide fly ashes into two

categories, namely those meeting any of the physical-chemical or performance standards for fly ash as a pozzolan, and others that do not meet the standards. A fly ash complying with a standard specification is permitted for use as a supplementary cementing material in concrete or as a component of blended portland-fly ash cements. In such applications, the current construction practice generally restricts the proportion of fly ash to 20% by mass of the total cementitious material. As stated earlier, studies by Malhotra (12) with superplasticized concrete mixtures have shown that, when the water/cementitious ratio is limited to 0.3 or less, up to 60% cement can be replaced with a Class F or Class C fly ash (ASTM C 618) to obtain excellent strength and durability characteristics. For instance, a test mixture containing 150 kg/m^3 ASTM Type I cement, 200 kg/m^3 ASTM Class F fly ash, 102 kg/m^3 water, 1220 kg/m^3 coarse aggregate, 810 kg/m^3 fine aggregate, and 7 L/m^3 superplasticizer gave 8 MPa, 55 MPa, and 80 MPa compressive strengths at 1, 28, and 182 days, respectively. This innovative, high-volume application of fly ash unquestionably signals the best value-added use of the material in the construction industry.

If complete utilization of all coal ash is our goal, then we must also identify the segments of the construction industry which can profit from the use of nonstandard fly ash and pulverized bottom ash. A coal ash may not meet certain minimum chemical or physical requirements prescribed by a standard specification, but it may still be useful on account of its fine particle size. Examples of these applications are cited next.

Roller-Compacted Concrete Dams: Since the 1980's, roller-compacted concrete (RCC) has been accepted worldwide as the most rapid and economical method for construction of medium-height dams. According to Dunstan (11), until the end of 1992, 96 RCC dams had been built in seventeen different countries and 82 of the RCC mixtures contained a pozzolan. The high-paste type RCC mixtures typically contain 250 kg/m^3 cementitious material of which 70-80% is a pozzolan. Fly ash has been used as a pozzolan in 90% of the 82 RCC mixtures. The Upper Stillwater Dam in the U.S. contains 1.24 million m^3 of concrete with 79 kg/m^3 portland cement and 173 kg/m^3 fly ash. In all, over 200,000 tonnes of low-calcium fly ash from six different power plants was used. Imagine the volume of pozzolanic materials needed for the Zungeru Dam in Japan which contains 5 million m^3 RCC, and the 217-m high Longton Dam in China that will contain 7.5 million m^3 RCC. Further, according to Dunstan (11), even nonstandard fly ash is beng successfully used a component of RCC mixtures. For instance, the RCC mixture for the construction of 95-m high Platanovryssi Dam in Greece contains 35 kg/m^3 portland cement and 250 kg/m^3 of treated (pulverized and hydrated) fly ash which has an unusually high calcium content (42% total CaO). The fly ash is generated from thermal power stations using lignite as fuel.

Concrete Pavements for Highways: According to Golden (14), approximately 70% of the low-volume highways and local access roads in the U.S. require upgrading. Considering the cost savings resulting from the replacement of cement with high volumes of fly ash, EPRI (Electric Power Research Institute) funded several demonstration projects. In North Dakota, during the summers 1988 and 1989, 20,000 m^2 of a 200-cm thick concrete pavement was constructed with "pozzocrete," which is a 0.43 w/c, air-entrained concrete mixture containing 100 kg/m^3 portland cement and 220 kg/m^3 high-calcium fly ash. Demonstration projects in Kansas have successfully used both low-calcium and high-calcium fly ashes in concrete pavement mixtures (10-20% fly ash by mass of concrete). An innovative feature of this project was the utilization of the crushed concrete from the old pavement as a source of coarse aggregate in the concrete mixture for the new pavement.

Base-Courses and Embankments: High-volume fly ash and bottom ash applications in highway construction may include soil stabilization, pavement base-courses, embankments, and road shoulders. According to Golden (14), in 1989, 350,000 tons of fly ash were used for the construction of a highway embankment in Pennsylvania. In Georgia, cement-treated fly ash mixtures have been used as base-courses in highway test sections. In Michigan, high-carbon fly ash is being used at the rate of 300,000 tons per year for the construction of base-courses and road shoulders.

Controlled Low-Strength Material (CLSM): CLSM is regarded as an ideal backfill material for use on street cut/repair and infrastructure rehabilitation projects. To allow for future excavation, most current CLSM applications require an unconfined compressive strength of 2 MPa or less. The upper strength limit of CLSM, 1,200 psi (8 MPa), is for those applications whose future excavation is not expected, such as structural fills under buildings. Self-compacting, flowable backfills require less labor and, therefore, often result in lower in-place cost compared to a compacted-soil backfill.

Large volumes of a nonstandard fly ash, as a substitute for fine aggregate, may be used in making a CLSM slurry. To address Boston's heavy traffic congestion problems, the new Central Artery Tunnel project provides a good example of a CLSM application. According to Sullivan (15), in the cut and cover method of tunnel construction for this project, the space between the tunnel boxes and support walls in the excavated trenches is filled with CLSM. The 0.4 MPa (28-day) CLSM is composed of 23 kg cement, 970 kg of a high-carbon fly ash, and 330 kg water. CLSM slurries containing cement-treated fly ashes typically contain 5%, 10%, and 15% cement by mass of total cementing material (cement plus fly ash) for strength levels of 0.7 MPa, 1.4 MPa, and 2.1 MPa, respectively. According to Goldbaum et al. (16), since 1990 the Colorado Department of Transportation has used CLSM for backfilling around pipes and box culverts under existing substandard bridges to convert them to on-grade roadways. Typical mix proportions for CLSM used in a Colorado project are as follows: 60 kg/m^3 cement, 240 kg/m^3 fly ash, 1,440 kg/m^3 fine aggregate, and 300 kg/m^3 water.

7. CONCLUDING REMARKS

The twentieth century will be remembered for significant advancements in the science and technology of materials. These advancements are based on the knowledge that the properties of materials can be engineered if we can understand and control their microstructure. Although concrete is a product of simple technology, it possesses a complex microstructure which is sensitive not only to the quality of component materials and mix proportions, but also to the processing methods used in construction practice. As we draw closer to the end of this century, it is apparent that this knowledge base has helped us in the development of very high-strength cement-based products using special admixtures and special processing techniques. In recent construction, with structures exposed to aggressive environments, advantage has been taken of the low permeability that is normally associated with high-strength concrete mixtures. Therefore, sophisticated concrete structures in many large projects have been constructed with high-strength concrete mixtures. However, high costs of materials and processing have prevented the application of this technology to ordinary structural concrete.

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 concrete. 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 by-products will be highly 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.**

In short, if the twenty-first century world is governed by the environmental agenda, then the future of cement and concrete industries would very much depend on our ability to interlink the growth of these industries with the goal of sustainable development on the planet earth. As presented in this paper, a holistic approach can help us achieve the goals of rising demand for concrete, enhancement of concrete durability with little or no increase in cost, and ecological disposal of large quantities of waste products from other industries.

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Table 1 Projection of Regional Cement Consumption, million tons*

Area	Year		
	1994	2000	2005
Europe, including countries of former Soviet Union	313	393	432
Asia	680	853	1000
Middle East	65	79	82
Africa	63	71	77
North America	90	92	92
South and Central America	92	118	142
Miscellaneous	7	9	10
Total	1310	1625	1835

*Adapted from: *World Cement*, V. 27, No. 5, May 1996.

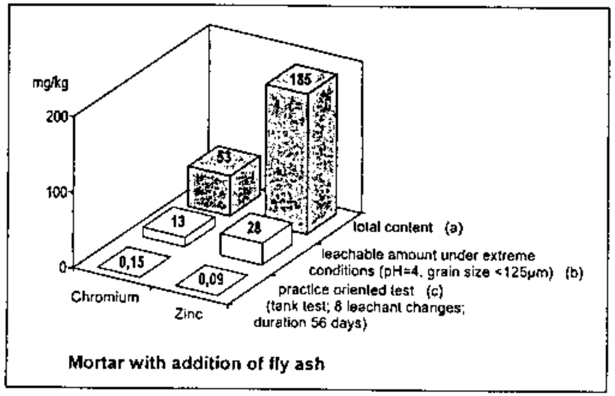

Fig. 1 Immobilization of heavy metals in a mortar containing fly ash (Ref. 4)

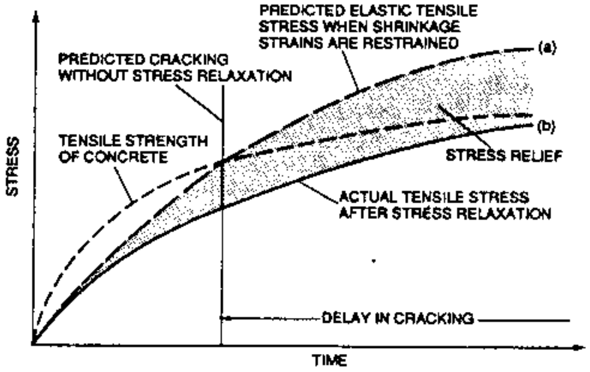

Fig. 2 Influence of shrinkage and creep on concrete cracking

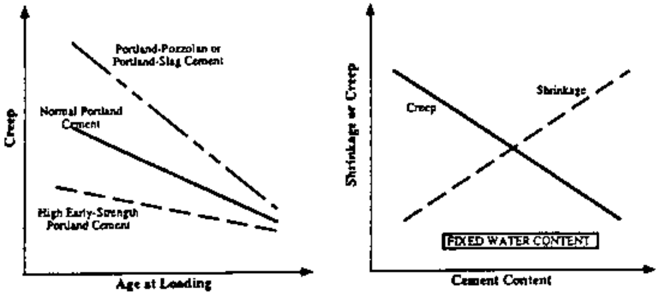

Fig. 3 Effect of cement content and type on shrinkage and creep

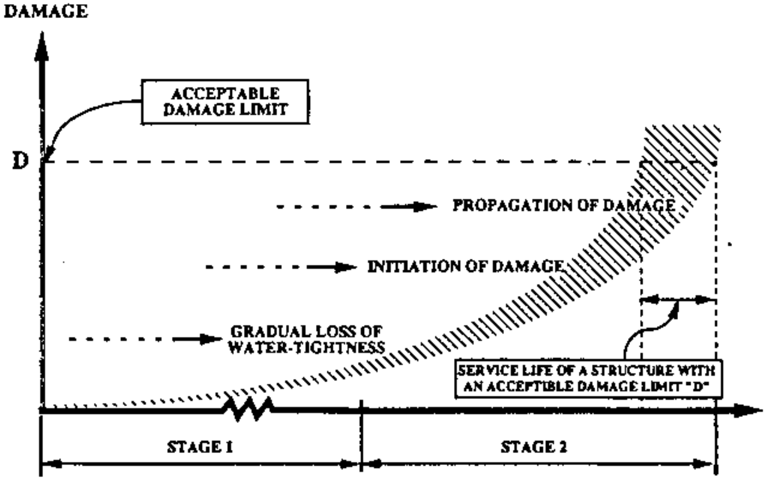

Fig. 4 A two-stage damage model for predicting the service life