Greening of the Concrete Industry for Sustainable Development

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Change is inevitable. However, it is the rapid rate of change that often becomes disruptive. This is why, all of a sudden, we are confronted with the present situation. Our current ways of economic and industrial development seem to be unsustainable. Population growth, urbanization, technology choices, and their environmental impact are unquestionably among the key forces that are shaping today's world.[1] Although these factors are interrelated, it is useful to view them separately with regard to their historical data and future trends.

At the beginning of the twentieth century, the world's population was 1.5 billion people; at the end of the twentieth century, it had grown to 6 billion people. Considering that it took 10,000 years after the end of the last ice age for the world's population to reach the 1.5 billion mark, the rate of growth from 1.5 to 6 billion people *during the short span of 100 years* is truly explosive.

Statistics show a direct correlation between population growth and the urbanization of the planet. At the beginning of the twentieth century, about 10% of the world's population lived in cities; in 2001, nearly half of the world's 6 billion inhabitants lived in and around cities. According to recently published statistics by the United Nations,[2] the planet hosts 19 "megacities," each with 10 million or more people, 22 cities with populations of 5 to 10 million, 370 cities with 1 to 5 million inhabitants, and 430 cities with one-half to 1 million people.

Population growth and urbanization have contributed to enormous expansion of the energy, manufacturing, and transportation sectors of the economy during the twentieth century. Unfortunately, our technology choices have been *reductionistic*, because decisions were made based on short-term and narrow goals of an enterprise rather than on the full range of consequences from the use of a technology. For instance, according to Hawken et al.,[3] only 6% of the total global flow of materials, some 500 billion tons (450 billion tonnes) a year, is actually ending up in consumer products, whereas many of the virgin materials are being returned to the environment in the form of harmful solid, liquid, and gaseous wastes.

Environmental pollution is not a new phenomenon. However, due to the rapidly growing volume of the pollutants, the environmental challenge we face now is not regional but global. According to scientists, the greatest environmental challenge today is that of man-made climate change due to global warming, which is caused by the steadily rising concentration of greenhouse gases in the earth's atmosphere during the past 100 years. Consequently, since the 1990s, the Worldwatch Institute has recorded an unusually high number of extreme weather-related disasters in many parts of the world.[4] Thus, we may not be running out of natural resources, but we are running out of the environment that sustains life as well as the entire economy.

ENVIRONMENTAL IMPACT OF CONCRETE

Portland cement, the principal hydraulic binder used in modern concrete, is the product of an industry that is not only energy-intensive, but is also responsible for large emissions of carbon dioxide (CO_2)—a greenhouse gas. Typically, ordinary concrete contains about 12% cement, 8% mixing water, and 80% aggregate by mass. This means that, in addition to the 1.6 billion tons (1.5 billion tonnes) of cement used worldwide, the concrete industry is consuming 10 billion tons (9 billion tonnes) of sand and rock, and 1 billion tons (900 million tonnes) of mixing water annually.[5] In total,

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the concrete industry, which uses 12.6 billion tons (11.4 billion tonnes) of raw materials each year, is the largest user of natural resources in the world. Mining, processing, and transporting huge quantities of aggregate, in addition to about 3 billion tons (2.7 billion tonnes) of the raw materials needed every year for cement manufacturing, consume considerable energy and adversely affect the ecology of the planet.

How can we reduce the environmental impact of the concrete industry? The long-term approach to lower the environmental impact of using any material is to reduce its rate of consumption. For reasons that are discussed in the following sections, the rate of concrete consumption probably cannot be reduced for some 50 years. In the short-term, we must begin practicing industrial ecology for sustainable industrial development. Simply stated, the practice of *industrial ecology* involves recycling the waste products of one industry by substituting them for the virgin raw materials of another industry, thereby reducing the environmental impact of both.

Reportedly, over 1 billion tons (900 million tonnes) of construction and demolition wastes are generated every year. Cost-effective technologies are available to recycle most of these wastes as partial replacement for the coarse aggregate in fresh concrete mixtures.[5] Similarly, industrial wastewaters and nonpotable waters can be substituted for municipal water for mixing concrete, unless they are proven harmful by testing. Blended portland cements containing fly ash from coal-fired power plants and ground-granulated slag from the blast-furnace iron industry provide excellent examples of industrial ecology because they offer a holistic solution for reducing the environmental impact of several industries.

The concrete construction industry already uses concrete mixtures containing cementitious material replacements with 15 to 20% fly ash or 30 to 40% slag by mass. Malhotra and his colleagues[6-8] have shown that, with conventional materials and technology, it is possible to produce high-performance concrete mixtures containing 50 to 60% fly ash by mass of the blended cementitious material. An article in this issue of *Concrete International*, written by V. M. Malhotra, describes the high-volume fly ash (HVFA) concrete technology. Note that fly ash is readily available in most parts of the world. China and India, the two countries that consume large amounts of cement, produce over 300 million tons (270 million tonnes) of fly ash per year.[9]

DURABILITY AND SUSTAINABILITY

In the long run, sustainable development will happen only if we are able to make dramatic improvements to our resource efficiency. Hawken et al.[3] describe a movement launched in 1994 by the Factor Ten Club, a group of scientists, economists, and businesspeople. The declaration of the Factor Ten Club states that, within one generation, nations can achieve a tenfold increase in their resource efficiency through a 90% reduction in its use of energy and materials. Obviously, large future savings in materials can result if we produce products that are much more durable. For example, the resource efficiency of the concrete industry would increase by a factor of five if the service lives of most structures built today were 250 years instead of the conventional 50.

First, let's review the state of durability of modern concrete structures built during the second half of the twentieth century. Then, let's determine what steps can be taken to enhance the durability of the structures that are being built today.

In the April 1998 issue of *ASCE News*, the American Society of Civil Engineers assigned a "D grade" to the nation's infrastructure and estimated that $1.3 trillion (in U.S. dollars) was required to fix the problem. Published literature[1] contains references to numerous reports describing the premature deterioration of concrete, especially in those structures that are exposed to industrial and urban environments, de-icing chemicals, and seawater. In most cases, the degradation of concrete is associated with the corrosion of reinforcing steel; in a few cases, deterioration is due to alkali-aggregate reaction or sulfate attack.

Why do reinforced concrete structures begin to deteriorate much earlier than their designed service life? Many researchers, including Burrows,[10] have pointed out that modern portland cement concrete mixtures, which are usually designed to attain high strength at an early age, are prone to cracking. Interconnections between the cracks, microcracks, and voids in concrete provide pathways for the penetration of water and harmful ions necessary for the initiation of several types of durability problems.

From a comprehensive review of the durability of field concrete during the twentieth century, Mehta and Burrows[11] concluded that today's reductionistic concreting practice, driven solely by demand for high-speed construction, is generally responsible for excessive cracking and the reported epidemic of durability problems with bridge decks and parking garages built during the 1980s and 1990s. Since the 1930s, the tricalcium silicate (C_3S) content and fineness of ordinary portland cement have been steadily increasing. Present-day concrete mixtures contain a greater content of a highly reactive portland cement that produces high strength at an early age. But, this type of concrete also undergoes high thermal contraction and high drying shrinkage. Consequently, it cracks and loses watertightness much earlier than the concrete mixtures used 50 to 60 years ago.

I believe that, in regard to concrete durability, instead of reductionistic methods that have been tried without great success, we need to pursue an approach based on a holistic model of concrete deterioration. This approach will bring about a fundamental shift in our current concreting practice, by seeking a better end product that is free from cracks rather than pushing the envelope for higher construction speeds.

AN EMERGING TECHNOLOGY FOR *GREEN* CONCRETE

The high-volume fly ash (HVFA) concrete originally developed by Malhotra and his colleagues[6-8] provides the most promising example of how we can build concrete structures that are more durable and resource-efficient than those made of conventional portland cement concrete. Whether as a component of blended portland cement, or as a mineral admixture added to concrete during mixing, the fly ash content of HVFA concrete mixtures is typically between 50 and 60% by mass of the total cementitious material. The sidebar on p. 26 contains two examples of field application of the HVFA concrete technology.

In the past, the HVFA concrete mixtures generally did not perform well with respect to strength development, drying shrinkage, and durability. This is because the fly ash produced by old thermal power plants was coarser and usually contained more carbon. Laboratory and field experience have shown that, when used in a large volume, fly ash from modern thermal power plants—generally characterized by low carbon content and high fineness—is able to impart excellent workability to concrete at a water content that is 15 to 20% lower than concrete without the fly ash. Further reductions in the mixing water content can be achieved with better aggregate grading and with the help of superplasticizing admixtures. As described next, a large reduction in the mixing water content has a highly beneficial effect on the cracking and durability characteristics of concrete.

The typical proportions of two concrete mixtures shown in Table 1 help to illustrate why HVFA concrete resists cracks better. The mixtures are designed to achieve a 25-MPa (3600 psi) strength and a 125- to 150-mm (5 to 6 in.) slump. Compared to the conventional concrete mixture, the HVFA system contains one-third less mixing water. As a result, the water-cementitious materials ratio (*w/cm*) of the HVFA concrete is lower and the total volume of the cement paste is nearly 16% less. Consequently, the drying shrinkage, which is directly related both to the *w/cm* and the proportion of the cement paste present in concrete, is greatly reduced. At the same time, due to a drastic reduction in the amount of portland cement, the HVFA concrete generates nearly 40% less heat of hydration at an early age and, therefore, the potential for thermal cracking in massive structural members is also greatly reduced.

Table 1: Comparison of mixture proportions for 25-MPa (3600 psi) concrete

	Conventional concrete		HVFA concrete	
	By mass lb/yd^3(kg/m^3)	**By volume ft^3(m^3)**	**By mass lb/yd^3(kg/m^3)**	**By volume ft^3(m^3)**
Cement	517 (307)	2.65 (0.075)	260 (154)	1.33 (0.037)
Fly ash	—	—	260 (154)	1.73 (0.049)
Water	300 (178)	4.81 (0.136)	200 (120)	3.21 (0.091)
Entrapped air (2%)	—	0.54 (0.015)	—	0.54 (0.015)
Coarse aggregate	1750 (1040)	10.40 (0.294)	2030 (1210)	12.10 (0.343)
Fine aggregate	1390 (825)	8.60 (0.244)	1300 (775)	8.00 (0.228)
Total	3957 (2350)	27.00 (0.764)	4050 (2413)	27.00 (0.764)
w/cm	0.58	—	0.38	—
Paste volume: percent:	—	8.00 (0.226) 29.6%	—	6.81 (0.192) 25.0%

BARRIERS TO GREEN CONCRETE

Architects and engineers are increasingly getting involved with building "green" structures that are more energy- and resource-efficient. Greening of the building industry cannot be complete until the materials used for construction are also green. Despite the fact that cost-effective and proven technologies are already available for producing green concrete, the rate at which these technologies are being adopted by the concrete construction industry is extremely slow. We must identify and address the barriers to green concrete before we can expect any change in the situation.

Current construction business practice is the first formidable institutional barrier. The building industry's profitability is largely determined by fast construction schedules, not by the life-cycle cost savings from the conservation of energy and materials. Experience shows that faster construction is not always less expensive. Poor-quality concrete, with its honeycombs and many cracks, frequently requires costly repairs and results in litigation. Poorly built structures have a tendency to deteriorate faster, especially when exposed to today's industrial and polluted environments. Thus, owners must pay a high life-cycle cost. Furthermore, we know of concrete structures that have failed prematurely during heavy storms or severe earthquakes due to pre-existing cracks and microcracks. It is evident, therefore, that today's construction economy is afflicted with considerable waste of capital and materials, and requires a fundamental restructuring.

Building codes are another institutional barrier discouraging the use of recycled materials. Out-of-date codes specify the use of particular materials and mixture proportions for a job rather than specifying a particular standard of performance. For instance, federal, state, and municipal codes for concrete mixtures often prescribe a maximum fly ash content (typically 15 to 25% by mass of the cementitious material) or a minimum cement content. High-performance concrete mixtures being produced with HVFA concrete prove that prescriptive specifications are obsolete and must be replaced with performance-based standards.

As discussed in earlier papers,[9,11] the present-day codes of recommended practice imply that low-*w/cm* concrete, irrespective of the cement content, is a cure for most durability problems, in spite of the fact that many recently built structures have suffered severe thermal and drying-shrinkage cracking, which has made them vulnerable to early deterioration from physical and chemical attacks. A holistic approach to durability of concrete recognizes that it is not the strength and the impermeability of laboratory-size specimens, but that of the entire structure that is essential for long-term durability. Therefore, the durability of concrete would not be enhanced by prescribing a low *w/cm* unless, at the same time, both the water content and the cement content of the concrete mixture were lowered.

A third institutional barrier is the lack of a holistic approach in engineering education and research. The shift from reductionistic to holistic construction practices must begin by reforming the present system of education and research in the fields of concrete science and technology.[9] Clearly, greening of the entire concrete construction industry will have to proceed before green concrete replaces conventional concrete as the material of choice for general construction.

LIGHT AT THE END OF THE TUNNEL?

How much time do we have before the global climate situation becomes irreversible? This discussion requires a review of the future impact of population growth, urbanization, and wasteful consumption of natural resources.

According to the latest population forecasts, the populations of Europe and North America have stabilized, while the growth rate in Asia, Africa, and South

HVFA CONCRETE TECHNOLOGY PRACTICE

Note that the HVFA concrete system is not a laboratory curiosity. Mixture proportions, field practice, and properties of concrete used for the construction of several structures in North America are described in various publications.[12-13] I have been associated with two recently built structures in the western United States that are discussed herein. The first structure, designed to endure for at least 1,000 years, consists of a massive, unreinforced, monolith foundation composed of two parallel slabs, each measuring 36 x 17 x 0.62 m (120 x 56 x 2 ft). The slabs were built with a 20-MPa (3 ksi) HVFA concrete mixture containing 106 kg/m^3 (180 lb/yd^3) ASTM Type I cement and 142 kg/m^3 (240 lb/yd^3) Class F fly ash.[13] When inspected last—two years after the construction—the exposed surfaces did not reveal a single crack in the concrete and the strength was nearly double the specified value.

Representing the other end of the strength spectrum, the second structure is composed of heavily reinforced shearwalls and a massive, post-tensioned, reinforced concrete foundation, 11 ft deep and 6 ft wide (3.4 x 1.8 m). The primary goal of the structural designer and the contractor was to build a crack-free, *green-concrete* structure. The HVFA mixtures for the shearwalls, as well as that for the foundation, were designed to have a 150-mm (6 in.) slump and a 35-MPa (5 ksi) strength at 56 days. Additionally, to facilitate the reuse of formwork, the wall concrete was designed to obtain a 20-MPa (3 ksi) strength in 7 days. In the case of the foundation concrete, the primary concern was thermal cracking; therefore, the goal was to keep the temperature difference between the interior and the surface of the concrete within the desired limit of 25 °C (77 °F). Superplasticized HVFA concrete mixtures, with 0.32 *w/cm*, 195 kg/m^3 (329 lb/yd^3) Type I portland cement, and 195 kg/m^3 (329 lb/yd^3) Class F fly ash, met the shearwall concrete requirements satisfactorily. However, for the foundation mixture, the cement content was reduced to 160 kg/m^3 (270 lb/yd^3) to control the heat of hydration. Due to the excellent workability of the HVFA concrete, the finished surface of the walls and the foundation showed no honeycombing and no bug holes. Also, the most recent inspection of the walls, 9 months after the construction, has revealed no cracks.

America is slowing. Experts now believe that, by the year 2050, the world's population will increase to about 10 billion before it enters a stable phase. Due to the direct linkage between population growth and urbanization, it is projected that about three-quarters of those 10 billion people will live in urban areas. The most recent United Nations' "State of the World Cities"[2] reported that, in the year 1980, almost half of the largest 20 cities in the world were located in developed countries. Today, except for four cities (Tokyo, Osaka, New York, and Los Angeles), all of the megacities (those with more than 10 million people) are located in the developing world. This rise of megacities in developing countries has created tremendous pressure on their building and infrastructure needs, which are yet to be met.

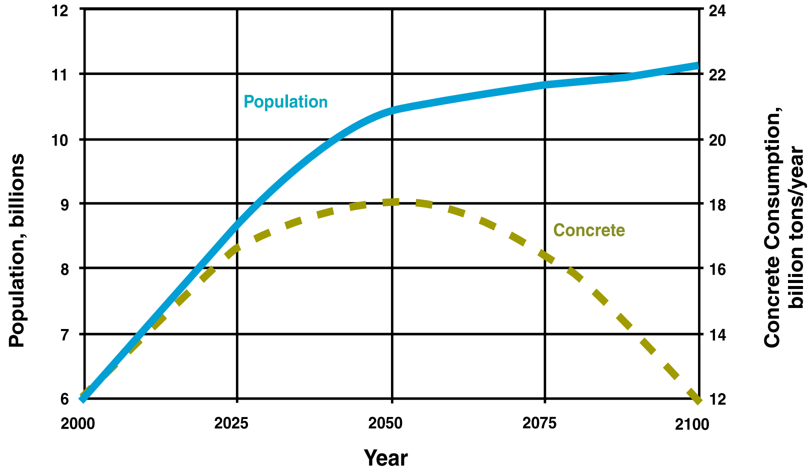

Fig. 1: Forecast of future population growth and concrete consumption

If we assume a 50% increase in population and urbanization during the next 50 years, then, at the current rate of concrete consumption, the demand for concrete will rise to about 18 billion tons (16 billion tonnes) a year by 2050. Thereafter, the consumption may drop, depending on how seriously we pursue the principles of industrial ecology and enhancement of the durability of structures during the next 50 years.

Suppose that, without delay, we implement the steps needed for the conservation of portland cement, virgin aggregates, and fresh water. By this action alone, the concrete industry can nearly double its resource productivity. At the same time, suppose that we also start building concrete structures that will not need replacement or major repairs during the next several hundred years. Then, 50 years from now, this step would have the effect of considerably reducing the concrete consumption. By the year 2050, if most of the building and infrastructure needs of the developing countries have also been met, then we can expect the rate of concrete consumption to show a downward trend, as illustrated in Fig. 1. Yes, it is possible to see the light of sustainability of the concrete industry at the end of the 50-year-long tunnel. However, this will happen only if various segments of the construction industry overcome the institutional barriers mentioned previously and embrace the task of greening the entire industry.

MOVING TOWARDS THE LIGHT

- Scientists believe that an era of unsustainable development began approximately 100 years ago. At that time, we entered into an extraordinary period of population explosion, rapid urbanization, and technology choices that have resulted in the highly wasteful consumption of energy and resources;
- As the largest consumer of natural resources and a major consumer of energy, the cement and concrete industry is one of the primary contributors to unsustainability. However, cost-effective and ecological technologies are now available that will allow the substitution of substantial amounts of industrial by-products into conventional concrete mixtures;
- Major improvements in the resource efficiency of the concrete industry are possible if, in the long run, we reduce the rate of concrete consumption by lengthening the service life of newly built structures. However, this will require a fundamental restructuring of the construction business. A radical enhancement in the durability of concrete cannot be achieved easily because of several institutional barriers; and
- According to the future demographic and urban growth patterns, the demand for concrete is expected to grow to 18 billion tons (16 billion tonnes) a year during the next 50 years, but can start to decline thereafter if we take immediate steps to greatly enhance the durability of structures that are being built now. Whether or not the concrete construction industry shall find the light of sustainability at the end of this 50-year-long tunnel depends upon how quickly we can accomplish the task of greening the entire industry.

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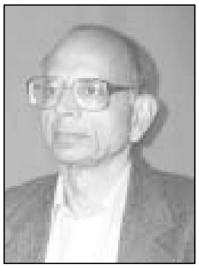

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