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Concrete Technology at the Crossroads—Problems and Opportunities

by P.K. Mehta

Synopsis: The future of the concrete industry appears to be bright from projections based on current trends in population growth, and increasing industrialization and urbanization. However, this optimism must be tempered with changing attitudes in the society on ecological issues such as conservation of natural resources, durability of engineering materials, and environmental pollution. Due to the increasing public concern with durability of concrete as a construction material, this subject is discussed in detail with reference to deficiencies in the science of concrete durability, methods of testing for quality assurance and service-life prediction, and education in concrete technology.

Keywords: Air pollution; concrete technology; conservation; deterioration; durability; education; models; quality assurance; research; service life; urban development; waste management.

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1. INTRODUCTION

We are at the crossroads. In a few years, a new century will begin and the twentieth century will become a part of history, leaving behind many accomplishments as well as disappointments. This is an appropriate juncture in time to look into the future because, due to a heightened public awareness of energy, resources, and ecological issues, unhindered industrial growth cannot be taken for granted.

Predicting the future is never easy; however, we can always speculate about the future prospects of any industry if we have a clear understanding of current trends in both opportunities and problems before our society. In other words, we can assure a bright future for the concrete industry by bringing its goals into line with the changing needs and aspirations of the society. Accordingly, in this paper, first, some of the changes taking place that are shaping the future world, are described. Next, an overview of the state of the concrete industry and technology today is presented. This is followed by a discussion of the deficiencies in modern concrete technology that must be resolved before the concrete industry can respond effectively to the needs of tomorrow's world.

This subject is not being addressed for the first time. The earliest report "Concrete - Year 2000," was published 23 years ago.[1] Among the recent are a paper by Neville,[2] and the proceedings of an international symposium held last year at University of Dundee, Scotland.[3] It would indeed be a fitting tribute to Mohan Malhotra if the deliberations of this symposium in his honor were to make a significant contribution in setting the agenda of the concrete industry and technology for the 21st century.

2. TOMORROW'S WORLD

Compared to the world we inherited at the beginning of the twentieth century, the world at its end is much different. Among the powerful forces that are shaping tomorrow's world and are expected to have a great influence on human attitudes in the future are population growth and urbanization, pollution and waste management, technological innovations and globalization, and a paradigm shift in scientific research. They are briefly discussed below.

2.1 Population Growth and Urbanization

The twentieth century has seen an unprecedented population explosion, mainly as a result of sharp decline in infant mortality due to immunization and availability of antibiotics. For example, during the 50-year period, 1925-1975, the world population rose from 2 to 4 billion. Although the rate of population growth has slowed down significantly in some countries, the overall rate is still so high that the current world population, which is nearly 6 billion, is projected to increase to 9 billion by the year 2025. The search for more food, energy, and other resources to support the additional population means a continuation of pressure for further industrialization. As oceans cover twice as much surface as the combined surface area of the seven continents of the earth, the world is already becoming increasingly ocean-oriented for the recovery of energy and mineral resources. More than 25% of the world's hydrocarbons are being extracted from coastal and offshore deposits. During the last two decades many marine construction projects involving sophisticated structures, such as offshore oil platforms, undersea tunnels, and superspan bridges have been successfully executed. Many more are underway, as discussed by Gerwick and by Hoff at this symposium.

As a result of population growth and industrialization, by the end of this century, for the first time in history, more people will live in and around cities than in rural areas. According to a projection by the United Nations, shown in Table 1,[4] there will be at least 20 **megacities** with 11 million or more inhabitants in addition to numerous big cities of more than 1,000,000 people. The infrastructure, both new construction and rehabilitated old structures, to support these megacities and big cities, such as buildings for housing and industry, mass transit for moving people and goods, and facilities for handling water and sewage will require large amounts of construction materials.

2.2 Pollution and Waste Management

During the last quarter of this century, many individuals and organizations have contributed to public education on the state of our environment. The U.N. sponsored Earth Summit at Rio de Janeiro in 1992 was a milestone in this regard. Industries causing excessive pollution of air, land, or water are being scrutinized and controlled in many countries of the world. Considerable research is ongoing to develop methods for safe disposal of nuclear and hazardous chemical wastes. In the future, engineers responsible for the selection of materials will be expected to exercise social responsibility by considering not only the engineering properties and cost but also the ecological friendliness of a material.

That increasing environmental pollution can really become **a serious threat to all industrial growth** is a prospect which is being advanced by many observers from a variety of disciplines. The problem is that, driven by demographic pressure and helped by technology, recently the earth's ecosystem has come under great stress. To support more and more people and to provide better living conditions for most, the engines of the industry for converting raw materials into consumer products must be run faster and faster. Even if the technology is able to find sufficient raw materials or fuel for running the engines of industry, a cost-effective technology neither exists today nor is expected to become available in the near future to remove one bottleneck, namely **the ecologically friendly disposal of all the waste produced by the industrial activity.** For instance, CO_2 emissions from the combustion of hydrocarbons are projected to double by the middle of the 21st century and thus, through the "greenhouse effect," will result in raising the temperature of the environment to a potentially disastrous level. As the United States consumes more than 25% of the world's hydrocarbons, according to the U.S. Environmental Protection Agency, the CO_2 emissions must be rolled back to the 1950s level; otherwise there is little prospect of avoiding global warming.

Environmental pollution from industrial activity is not a new problem. However, according to Kennedy,[5] the environmental crisis we now confront is quantitatively and qualitatively different from anything before, simply because so many people have been inflicting damage to the world's ecosystem during the present century that the system as a whole - not simply its various parts - may be in danger. The author comments:

> The earth, unlike its neighboring planets, is covered with a film of matter called life... Within that film, co-existing alongside plants, animals, insects, crops, and other organisms, is the human race. It assumed the form of *Homo sapiens* some half a million years ago, well after the emergence of many of the other members of the earth's film of life. But because of the human race's growth and its economic activities, it now risks endangering the delicate envelope of matter that makes this planet unique.

2.3 Technological Innovations and Globalization

The recent **revolution in communications and information technologies** is transforming our world into a global village. As a result, the pace of technology transfer has accelerated to an unprecedented rate across both geographical and industrial boundaries. For example, developments in concrete technology in Norway are almost immediately available for use to the concrete industry throughout the world. Similarly, developments in polymer technology are quickly picked up by the concrete industry everywhere. This growing web of interconnections within and between multinational companies is the cause of rapid globalization of industry, technology, and trade. In general, our socio-economic world is increasingly governed by multinational corporations and international institutions, such as the International Monetary Fund and the World Bank. In recent times, the negative implications of this have been manifested by numerous incidents to show that the global reach of the multinational and international companies is not always matched by their global responsibility.

Two other technological revolutions, **robotics and biotechnology**, with potentially far more serious global consequences than the information technology, are discussed by Kennedy[5] in his provocative book. The use of robotics in the Japanese industry is spreading. Kennedy cites the example of a radio-cassette recorder factory where 850 industrial robots where installed to reach full production with only 16 employees compared with 340 before the automation. If the robotics revolution spreads worldwide, it would eliminate millions of jobs in factory assembly, manufacturing, and construction industries. Similarly, for the production of basic food products if we replace the currently used farming methods in the agricultural technology with the biotechnological methods under developments in many laboratories, we would cause a serious unemployment problem in the agriculture sector throughout the world.

Kennedy[5] points out that the robotics technology and biotechnology are driven by the same profit motive in the world market that has propelled technological innovations since the industrial revolution. We now seem to have arrived at a stage in the journey when further advance in the same direction may lead to disastrous results. In the past, the population increase was sustained by corresponding industrial growth because we had seemingly unlimited natural resources to feed the industry and unlimited space on earth to absorb the industrial waste products. Now that the earth apparently has reached the limit of sustainability of industrial development, we will endanger the human civilization if we do not take immediate steps to drastically reduce the rates of population increase and industrial growth, and also strictly control the use of technological innovations that have the potential of causing massive economic and social upheavals. In the remaining sections of this paper, it is assumed that collective human wisdom will somehow intervene and this "worst-case scenario," which has the potential of destroying the human civilization, will not occur.

2.4 Paradigm Shift in Scientific Research

There is no question that society today is enjoying many benefits from the scientific and industrial revolutions. The analytical method of reasoning has become an essential characteristic of modern scientific thinking, and has proved very useful in the development of scientific theories and realization of many spectacular technological achievements. However, an overemphasis on **reductionism in science** -- the belief that all aspects of a complex structure or phenomenon can be fully understood by reducing them to parts -- has led to fragmentation and limitation of knowledge. Professionals in many disciplines are increasingly recognizing this problem.

Commenting on the disadvantages of the reductionist approach, Capra[6] commented:

> "The rational and the intuitive are complementary modes of functioning of the human mind. Rational thinking is linear, focused, and analytical. It belongs to the realm of intellect whose function it is to discriminate, measure, and categorize. Thus rational knowledge tends to be fundamental. Intuitive knowledge, on the other hand, is based on a **direct, non-intellectual experience of the reality arising in an expanded state of awareness. It tends to be synthesizing, holistic, and nonlinear.**"

The term **holistic** from the Greek word "holos," refers to an understanding of a phenomenon or a structure in terms of an integrated whole whose properties cannot be deduced from the sum of the properties of the constituent parts. Capra predicts that this paradigm shift in science will greatly influence the directions of future research in all scientific disciplines.

3. AN OVERVIEW OF THE CONCRETE INDUSTRY AND TECHNOLOGY

In the context of the changing world, as described above, let us take a look at the present state of the concrete industry and technology. This should help us identify the problems and the opportunities lying ahead.

3.1 Demand, Supply, and Materials

Due to well known reasons, such as a low relative cost, easy availability, versatility, adaptability, and adequate engineering properties for many structural applications, portland-cement concrete has already become the most commonly used material of construction throughout the world. The estimated annual cement and concrete production rates are 1.2 and 7 billion tons, respectively. As the component materials for making concrete, namely cement, sand, gravel or crushed stone, water, and admixtures are available in abundance almost everywhere, according to current trends the concrete industry should continue to grow at a steady rate in response to growing population and urbanization in the world.

Portland cement is the principal hydraulic cement used for making concrete today. Raw materials for the manufacture of portland cement are plentiful, however the need for conservation of energy and resources has already pushed the production and use of blended portland cements containing up to 70 percent blast-furnace slag or up to 30 percent fly ash or another pozzolan. In this regard, pioneering studies by Malhotra[7] on the use of high volumes of fly ash as a mineral admixture in concrete, are noteworthy. According to these studies, 50 to 60% cement replacement with fly ash can be made in concrete mixtures containing high-range water reducers, popularly known as superplasticizers, to obtain products that are not only high in strength but also excellent in impermeability. This work takes on an added significance if the production of portland cement in the future is frozen at the current level in efforts to prevent a rise in CO_2 emissions.

In regard to concrete aggregates, as they are being consumed at an annual rate of about 5 billion tons, high quality aggregate sources close to urban and industrial areas are either already depleted or becoming rapidly depleted. Economic and environmental considerations require that in the future we learn how to live with marginal aggregates. For instance, aggregates known to cause high drying shrinkage in concrete may be used in combination with expansive cements, and those known to cause alkali-silica related expansion may be used in combination with active pozzolans. Also, there is a considerable interest in recycling demolished concrete as an aggregate, and using fly ash and metallurgical slags for making aggregate. Finally, almost all concrete made today contains one or more chemical and mineral admixtures, which are readily available and are used to achieve a variety of objectives. Several state-of-the-art reports on trends in chemical and mineral admixtures for concrete are being presented at this symposium.

3.2 Durability of Concrete

Normal concrete, typically, has 20 to 40 MPa (3,000 to 6,000 psi) compressive strength, which is adequate for most structural applications. The tensile and flexural strengths are relatively low; therefore, the material tends to crack easily under tensile stress. A concrete structure with a few visible cracks usually continues to perform satisfactorily under compressive loading; however, if the cracks are interlinked with the microcracks, the susceptibility of concrete to water penetration is greatly increased, and therefore, durability may be adversely affected depending on the environmental conditions. Consequently, concrete structures exposed to severe environments such as temperature or humidity extremes and aggressive chemicals tend to deteriorate earlier than their intended service life. For instance, in 1987 the National Materials Advisory Board[8] made a reference to the epidemic of deterioration of concrete bridge decks in the U.S. It was estimated that 253,000 concrete bridge decks, some of them less than 20 years old, were in varying states of deterioration, and about 35,000 were being added to this list every year. Premature deterioration of concrete in tunnels,[9] parking garages,[10] marine structures,[11] and railway sleepers[12] has been reported by several investigators. This offers a unique opportunity to determine what is lacking in the current state of our scientific knowledge on concrete durability and in the field practice of what is already known.

3.3 New Technologies for Improved Performance

Some technologies developed during the last two decades have led to improved performance of the concrete construction industry; others were aimed at improving the performance of concrete as an engineering material. Roller-compacted concrete technology, which is the subject of two comprehensive reports at this symposium, offers considerable savings in construction time and cost for building concrete dams. Since 1982, when the first roller-compacted concrete dam was built at Willow Creek in Oregon, over 100 dams worldwide have been completed or under construction using this technology.

To improve the performance of concrete, numerous new technologies and products have been developed. Notable among them are high-strength concrete containing superplasticizers, fiber-reinforced concrete with steel, glass, polymer, or carbon fibers, latex-modified concrete, chemically bonded ceramics, macro-defect free cement products, and epoxy-coated reinforcing steel. These technologies are discussed in detail by other authors at this symposium. Due to high cost and special problems, many researchers including Neville[2] believe that the total volume of concrete made by the application of these technologies is not likely to be large. Due to their relevance to durabiity, the high-strength and the high-performance concrete technologies will be briefly discussed here.

High-strength concrete, with water/cement 0.35 to 0.45 and compressive strength in the 40 to 60 MPa range, is usually made using a superplasticizer and with or without mineral admixtures. It can generally be produced from locally available materials, using conventional mixing, handling, and curing methods. Depending on the physico-chemical characteristics of cement, admixtures, and aggregate, highly workable concrete mixtures with water-cementitious ratios in the range of 0.25 to 0.35 have also been commercially produced. The products show not only very high strength (60-130 MPa compressive strength) but also very high impermeability, which is the key to long-term durability in aggressive environments. From a worldwide survey of about one hundred structures made with high-performance concrete, Malier[13] estimates that compressive strength was the sole criterion for 25% of the structures; for the rest durability was the primary consideration.

It should be noted that high-strength and very-high-strength concrete in particular (> 60 MPa) is a special material requiring special aggregate (strong and closely graded), special admixtures (viz. superplasticizers), and meticulous care in mixing and handling. In a personal communication, Jan Moksnes of the Norwegian Contractors made the following observations, based on 20 years of experience of his company with the construction of high-strength concrete offshore oil platforms in the North Sea:

> High-strength concrete upgrades the unglamorous product of our youth to a more respectable, sophisticated, and high-tech. product for the future. We have acquired a fashionable material which enables us to design and build stronger, taller, longer, slimmer, and lighter structures. At the same time we are under considerable pressure to perform the work in less time; to stricter tolerances and to increasingly ambitious specification requirements. What used to be a robust and tolerant site-produced material designed with adequate redundancies is, in extreme cases, becoming a schizophrenic product balancing on a knife's edge of feasibility in terms of site performance.

High-performance concrete is the term used by some researchers for concrete mixtures which possess high workability, high strength, high dimensional stability, and high durability. This type of concrete finds application in heavily reinforced, sophisticated structural elements in high-rise buildings, offshore platforms, superspan bridges, and heavy-duty pavements. The microstructural principles underlying the composition and properties of high-performance concrete are described in several papers including those by Mehta and Aitcin,[14,15] Regourd,[16] Larrard,[17] and Gjorv.[18] It is well known that many characteristics of ordinary concrete, viz. relatively low strength and elastic modulus are related to the highly heterogeneous microstructure of the material, particularly the porous and weak transition zone which exists at the cement paste-aggregate interface. By densification and strengthening of the transition zone the properties of concrete can be improved and the risk for easy microcracking in service (and consequential increase in the coefficient of permeability) can be reduced. To achieve this end, firstly, a substantial reduction must be made in the quantity of mixing water. This is accomplished mainly by the use of a powerful cement dispersant (superplasticizer). For additional densification, strengthening, and homogeneity of the hydrated cement paste and mortar in concrete, a number of mineral admixtures possessing very fine particle size and high specific surface have been used, such as condensed silica fume, rice husk ash, fly ash, ground blast-furnace slag, metakaolin, limestone powder, and carbon black. The selection of the type and amount of mineral admixture is guided by cost, reactivity, and contribution to the packing density and workability of fresh concrete. Highly reactive pozzolans tend to reduce the curing time needed to obtain a desired level of strength and water-tightness; less reactive or non-reactive powders will improve the resistance to thermal cracking by lowering the heat of temperature rise.

It should be pointed out here that some concrete technologists question the use of the term, high-performance concrete, to describe many recently developed high-strength products such as those with more than 100 MPa compressive strength. It is argued that in addition to strength and durability the cost of materials and processing must be taken into consideration. According to a personal communication from Idorn, in the context of the cost of making durable ordinary-concrete, it seems that many researchers have neither interest in, nor knowledge, of the exorbitant cost of production of the "high-tech." type concretes they have chosen to designate as high-performance concrete.

3.4 Ecological Profile of Concrete

Kreijger[19] predicts that materials selection in the future will be governed by their ecological profile. For a given engineering property such as strength, elastic modulus, or durability, the material with the best ecological profile is that which requires least deforestation and desoiling of the earth, consumes least energy and water for its production, and yields the least amount of harmful by-products. Using Kreijger's criteria, compared to metals, polymers, and glass, concrete has an excellent ecological profile. Also, it is generally accepted that from economic and engineering considerations there seems to be no better home than the concrete industry for the disposal of millions of tons of siliceous by-products, such as fly ash, blast-furnace slag, condensed silica fume, and rice husk ash. The use of these by-products in concrete is generally accompanied by a significant reduction in permeability and improvement in workability. Depending on the particle size, reactivity, and the quantity used, mineral admixtures can also improve the resistance of concrete to thermal cracking.

Storage of enormous quantities of these siliceous by-products, which generally contain some heavy metals, causes air and water pollution. Even low-value applications, such as landfill and sub-bases for pavements, can be hazardous because toxic metals will eventually find their way into groundwater. Incorporation into concrete either in the form of mineral admixtures or as components of blended portland cement presents a relatively safe and inexpensive method of disposal. Recent work by McCarthy et al.[20] shows that selenium and chromium can be permanently bound in the crystal structure of ettringite, which is one of the products formed during cement hydration. Also, because up to 50-60% granulated blast-furnace slag or fly ash can replace portland cement in concrete without causing any deleterious effects on the ultimate strength and with considerable potential for enhancement of concrete durability, the use of these by-products is not only energy-saving but also resource-conserving. From the above-described ecological profile, the author[21] has called concrete Lord Siva (one of the gods in Hindu mythology) of the construction materials world. Once the gods decided to drain an ocean to recover a pot of nectar lying on the ocean floor. In the process, a stream of poison was released and it started destroying the world. Whereas the other gods ran away from the poison, Siva handled the problem by drinking the whole stream of poison, which left only a blue mark on his throat.

4. PROBLEMS WITH CONCRETE SCIENCE AND TECHNOLOGY

From predictions about the nature of tomorrow's world and its needs, and an overview of the state of the concrete industry and technology today, it is possible to identify critical issues which must be addressed expeditiously if concrete is to continue occupying the position of the most favored material for general construction. It seems that **the most important issue that needs urgent attention is the durability of ordinary concrete and the growing lack of public confidence in long-term service life of the material.**

In a recent report on performance of concrete in transportation, presented at the Annual Meeting of the Transportation Research Board, Mather[22] stated, "If concrete in a transportation use fails to perform as desired, it is either due to specifications having been wrong or not being followed." Specifications can be wrong in one of the two ways; either a specifier has erred in the choice of right specifications or **the available specifications are based on a faulty science. The author would like to address the latter issue with the purpose of destroying the myth that there would not be any durability problems if the currently available specifications and codes of recommended**