Concrete : Construction Material for the 21st Century

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1. Introduction

During the 20th century, portland cement concrete has played a major role in the development of the infrastructure of modern society. Society has relied on concrete to provide safe, long lasting and fire resistant structures. Indeed, concrete has been the material of choice for the construction of long-span bridges, tunnels, airports, port and harbor facilities and high-rise buildings. With a rapid pace of development of the infrastructure, the demand for concrete increased dramatically. In terms of the worldwide consumption of portland cement, the demand increased 650 times from mere 2 million tons in 1890 to 1.3 billion tons in 1990. It is being projected that by 2010 the demand will increase to 1.95 billion tons. Thus, it is reasonable to expect that the demand for concrete will continue.

Since the first concrete made with portland cement in 1824, concrete has gone through many technical breakthroughs. We have seen the compressive strength of concrete steadily increased from 14 MPa (140 kgf/cm^2) to100 MPa (1000 kgf/cm^2). Development of flowing concrete eliminated the use of vibrators for consolidation of concrete. Pumping concrete through pipelines at 200 m^3/hr made possible to deliver concrete at high volume to shorten the duration of construction. These breakthroughs made possible to build economically concrete skyscrapers, long-span bridges, and large offshore structures (Fig.1).

In recent years, the heavy expenditure for repair and replacement of the infrastructure has become a major concern in most industrialized countries as too many concrete structures are found suffering from deterioration problems. For example, we have seen many deteriorated bridge decks, elevated highway structures, tunnel linings, and buildings. In the United States, until the 1970s, cases of premature deterioration of concrete were treated as exceptions. Durability of concrete attracted serious attention when it was reported that approximately 253,000 concrete bridge decks were in varying degrees of deterioration and about 35,000 were being added to this number every year. Some of the causes of the deterioration were the corrosion of reinforcing steel, exposure to cycles of freezing and thawing, alkali-silica reaction of aggregate, and chemical attacks. These signs of deterioration are simply perceived by the public as evidence of non-satisfactory performance, and serious questions have been raised as to whether concrete can be trusted as a durable construction material.

In response to durability problems of concrete structures, the concrete industry began to address developing a new class of concrete, high performance concrete. Such a class of concrete should have characteristics to meet the demand for strength, durability, and workability. It is recognized that extrapolating knowledge of conventional concrete is not adequate to deal with the development of high performance concrete. This paper examines several key areas requiring research and development, so that many of the problems encountered with the performance of existing concrete structures could be avoided in future construction.

2. High Performance Concrete

While there is no generally agreed upon definition of "high-performance concrete," one definition that has been accepted by the American Concrete Institute is that "Concrete meeting special performance and uniformity requirements which cannot always be achieved routinely using only conventional constituents and normal mixing, placing and curing practices." These requirements may involve enhancements of the following:

- Ease of placement and compaction without segregation.
- Long-term mechanical properties.
- Early age strength.
- Toughness.
- Volume stability.
- Long life in severe environments.

These properties may be used individually or in combination to describe high-performance concrete [1]. This definition recognizes that performance should be defined in terms not only of strength, but other attributes that are important for a given application. It is not necessary that high performance concrete be a high strength concrete. However, in general, high performance concrete is perceived as concrete having high strength, high durability and/or good workability.

3. High Strength Concrete

For structural applications, the strength of the material is an important factor. If the strength can be increased, the cross sectional dimensions of structural members can be decreased, as well as the dead load. As a result, the use of high strength materials is highly desirable for the design of a structure, especially a concrete structure.
During the last twenty years, with the advent of chemical and mineral admixtures for use in concrete mixture, the concrete strength has increase remarkably. Nowadays, it is not uncommon to see 70 MPa (710 kgf/cm^2) concrete used in major projects worldwide. For example, high strength concrete has been used for such famed projects as Two Union Square in Seattle Washington in 1988 (135 MPa or 1370 kgf/cm^2), Petronas Twin Towers in Kuala Lumpur in 1998 (80 MPa or 810 kgf/cm^2), Confederation Bridge at Prince Edward Island, Canada in 1997 (60 MPa or 610 kgf/cm^2), and Hibernia Platform at Newfoundland, Canada in 1996 (69 MPa or 700 kgf/cm^2) (Fig.1). Without the availability of high-strength concrete, the construction of these structures would not have been possible.

The introduction of superplasticizers (high-range water reducers) and mineral admixtures, particularly silica fume, is the most important factor that made it possible to produce high strength concrete economically. Superplasticizers increase the slump of concrete significantly from about 70 mm to 200 mm while the mixture remaining cohesive. Thus, superplasticizers not only allow concrete to be placed with little or no compaction, but also more significantly, permit to produce concrete with a very substantial reduction in the water/cement ratio. Water/cement ratios of 0.2 have been used to produce concrete with the compressive strength of about 150 MPa (1500 kgf/cm^2) [2]. Recently, it has been reported in Japan that a new type of admixture is being developed to produce concrete having a water/cement ratio less than 0.15.

In today's production of high-strength concrete, it is common to use a combination of mineral admixtures. The most common mineral admixtures being used are silica fume, fly ash and ground granulated blast-furnace slag. Because these mineral admixtures are much finer than Portland cement (as much as 100 times smaller than cement particles), they improve particle packing in the concrete. When adequately cured, mineral admixtures reduce permeability, thereby inhibiting intrusion of undesirable materials into concrete.

The beneficial effects of mineral admixtures have been well documented in numerous concrete materials-related journals and conference proceedings. Particularly, many research papers are found in the proceedings of the *International Conferences on High Performance Concrete* sponsored by the American Concrete Institute and in the proceedings of the *International Conference on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete* sponsored by the Canada Center for Mineral and Energy Technology (CANMET) [3,4,5,6].

Fire Endurance Characteristic

Because high-strength concrete is more densely packed with fine particles than normal strength concrete, questions have been raised as to the fire behavior of structures made with high-strength concrete. Studies have shown that high-strength concrete loses its compressive strength as temperature rises at a much higher rate than normal strength concrete (Fig. 2), and is susceptible to explosive spalling when exposed to temperature above 300°C [7].

Recent laboratory tests [8] of high-strength concrete specimens have exhibited explosive failures when they were heated to temperatures greater than 400°C. On November 18, 1996 a section of the 52 km long Channel Tunnel connecting Britain and France sustained severe fire damage. The compressive strength of the tunnel lining was about 100 MPa (1000 kgf/cm^2). The temperature of the fire was estimated to have reached between 1000°C and 1200°C. Figure 3 shows fire induced spalling up to 150 mm to 200 mm.

A number of techniques have been tried to improve the performance of high-strength concrete at elevated temperatures. One technique deals with the application of fire-resistant coating on the concrete surface, and the other deals confining high strength concrete in steel tube thereby preventing explosive spalling. Recently, laboratory tests have been made on high strength concrete mixed with synthetic fibers such as polypropylene fibers. Synthetic fibers would melt at about 140°C, which is considerably less than temperatures at which high-strength concrete begins to spall. This melting action creates continuous conduits for vapor to escape to the concrete surface. When the pore pressure is relieved in this manner, spalling is avoided. It should be noted that when fibers are used, the workability of concrete is reduced, especially in the pumping process. Further research is needed to optimize the quantity and size of synthetic fibers for reducing pore pressure build up and, at the same time, to improve the workability of concrete.

Curing

Proper curing of concrete is one of the most important requirements to obtain the desired structural and durability properties of concrete. Even when good quality concrete is placed on the job site, curing is necessary to ensure the concrete provides good service over the life of the structure. Good concrete can be ruined by the lack of proper curing practices.

relationship between time and depth of carbonation, and the relationship between concrete permeability and carbonation.

The permeability criterion is based on achieving a certain level of impermeability as measured by a specific test method. One difficulty in using the permeability criterion is the selection of the critical level of impermeability because there is insufficient knowledge of the relationship between measured permeability values and long-term durability.

The degree of hydration criterion is based on the concrete reaching a specified degree of hydration. At present, there is insufficient data to relate the minimum degree of hydration at the end of the curing period with long-term performance.

A compressive strength criterion involves one of the two approaches:

1. R1 Concept - Concrete is cured until it attains a specified minimum strength.
2. R2 Concept - The concrete is cured until the in-place compressive strength reaches a prescribed fraction of the 28-day specified compressive strength so that at 28 days the concrete at a prescribed depth will attain the specified strength.

The R1-Concept offers the advantage that the use of mixtures with low water-cement ratios or having rapid early strength development can reduce the curing period. This criterion may be applicable when durability is of concern.

The R2-Concept is dependent on the rate of strength development. It is independent of the water-cement ratio. This concept is appropriate when structural strength is of concern. The basic notion is that the concrete should be cured long enough so that the in-place strength at some depth below the surface attains the specified strength used to design the structure. The concept is illustrated in Figure 4, where the solid curve represents strength development of the concrete under standard curing and the dashed curve represents in-place strength development at some prescribed distance from the

Current curing practices are based on research related to strength development of conventional concretes. Most high strength concretes are fundamentally different from conventional concrete, because they typically have a low water-cementitious materials ratio (*w/cm*) and one or more chemical admixtures. In addition, mineral admixtures such as silica fume, fly ash, and ground slag are commonly used to achieve high strength, low permeability, reduced temperature rise, and economy.

Concrete mixtures that contains mineral admixtures, which have slower reaction rate, require longer periods of curing for proper development of strength than normal strength concrete [9]. Because silica-fume concrete is more vulnerable to plastic shrinkage cracking than normal strength concrete at early age, good curing practices is necessary to control cracking tendency. Superplasticizers are used typically to provide workability. Since the composition of high strength concrete differs from conventional mixtures, early-age characteristics of the hydrating paste will also differ. Therefore, existing curing practices may not be optimal for high strength concrete.

Concrete with low *w/cm* will gain strength faster and become impermeable sooner than those with higher *w/cm*. This is an important characteristic since it may mean that curing duration can be reduced in accordance with the *w/cm*. Based on this consideration, Hilsdodrf identified that one of the following criteria may be used in establishing minimum curing duration [10].

- Depth of carbonation.
- Permeability.
- Degree of hydration.
- Attainment of compressive strength.

The depth of carbonation must be controlled to ensure that an alkaline environment surrounds the reinforcing steel. The minimum duration of curing for adequate resistance to carbonation depends on the depth of cover, the desired service life, the exposed surface. When curing is terminated, drying of the surface occurs and hydration ceases when the moisture content in the surface layer falls below a critical value. When the drying front reaches the prescribed depth, the strength increases due to drying and the rate of hydration is reduced. The objective is to ensure that the two strength-development curves cross at an age of 28 days or later.

Hilsdorf suggested that the curing period should be long enough so that at 28 days the concrete strength at the depth of the first layer of reinforcement will equal to the design strength. The rationale for this requirement is to ensure that the bond strength of the reinforcing steel will attain the value assumed in the design. However, at present, data are insufficient to establish the duration of curing that will ensure that the two strength-development curves cross at 28 days.

4. Environmentally Sustainable Concrete

Demand for concrete has steadily increased as world's population increased rapidly during the last half of the 20th century. The increasing demand can be illustrated by the world consumption of portland cement. According to World Cement Annual Review (WCAR) [11], the world cement consumption was about 1.4 billion tons in 1995. WCAR projected that the consumption will increase to about 1.66 billion tons in 2000, about 1.84 billion tons in 2005 and 1.95 billion tons in 2010. The production of every ton of portland cement contributes about 1 ton of carbon dioxide (CO_2) into the atmosphere. About half of the CO_2 emissions are due to the calcination of limestone and the other half are due to the combustion of fossil fuels. Currently, the worldwide production of cement accounts for about 7% of the total world CO_2 production. This proportion is expected to remain steady during the next decade [12]. Increased CO_2 emission into the earth's environment is a matter of serious concern to everyone on this earth. During the last one hundred years, the "greenhouse effect" caused global warming by 4°C. Thus, without the reduction of CO_2 emission, an environmental disaster would be unavoidable.

Current projections estimate that world population will increase from today's 6 billion to 9 billion in 2050 and to 11 billion by the end of this century. As population increases the demand for the new infrastructure for industrial and urban areas in developing countries and renewal of existing and deteriorating infrastructure in developed countries will increase substantially. For numerous structural applications concrete will become unquestionably the material of choice due to its low cost and easy availability. The question facing concrete industry is: "will it be able to meet the challenge of protecting environmental quality while projecting concrete as the construction material of choice?"

Increased demand for the development of infrastructure will require huge increase in portland cement production. The construction of new cement plants will undoubtedly increase CO_2 emissions, and construction of new high capacity thermal power stations will produce large amounts of fly ash and boiler slag, which are not being recycled in any significant way. According to Manz [13], 550 million tons of coal ash were produced worldwide in 1992 and only 35 million tons were used as a pozzolan by the cement and concrete industries, which is about 7% of the total available ash. The current annual production of coal ash worldwide is estimated to be about 715 million tons, of which about 500 million tons is generally suitable for use as a pozzolan. The worldwide annual use of fly ash by cement and concrete industries is about 38 million tons, which is very low. The annual world production of blast-furnace slag is about 110 million tons. The utilization of slag is very low as a pozzolan, however, because in many countries only a small portion of the slag is processed into the cementitious form. Thus, potential valuable cementing resources are being wasted.

Beneficial effects of utilizing fly ash and slag are well documented. Research has shown that use of fly ash and slag in concrete mixtures is not only reducing energy consumption and CO_2 emission, but it is a cost-effective way of improving durability and minimizing thermal cracking [14]. Superplasticized concrete mixture containing 60% - 70 % fly ash or blast-furnace slag by mass of the total cementitious material have shown high strength and durability at relatively early age [15]. Therefore, large-scale cement replacement in concrete with industrial byproducts and other pozzolanic materials will be highly advantageous from the standpoint of economy, energy efficiency, durability and sustainable development.

5. Recycling of Concrete

Using aggregates derived from demolition waste of concrete structures provides a great opportunity for conserving nonrenewable natural resources. In many parts of the world, virgin aggregate deposits have been depleted, and transporting aggregates over long distances can be much more expensive than using a low-cost local recycled aggregate. It is estimated that annual worldwide generation of concrete and masonry rubble from demolition is about 1 billion tons. At present, only small quantities of aggregate is being derived from recycled concrete and masonry. In Korea, about 7 million tons of concrete is demolished annually. Of this, about 2 – 3 million tons are available for recycling, [16]. The rubble can be processed in such a way that it can be used to replace natural aggregate in concrete. One of the main reasons for not using recycled-concrete aggregate is that it is more porous than natural aggregate. Thus, for a given workability, the water requirement for making fresh concrete tends to be high and as a result, mechanical properties of hardened concrete are adversely affected. One study indicates that this problem can be resolved by using water reducing admixtures and fly ash in concrete [17]. More research is needed to develop guides for using recycled-aggregate concretes.

6. Concluding Remarks

Concrete is the most widely used man-made construction material. It is generally believed that concrete structures are durable and provide a service life of 50 or more years with little or no maintenance. During the last quarter of the 20th century, we have seen many signs of early deterioration of concrete structures less than 20 years in service. At the same time society has placed demands on pollution free construction for sustainable development. It is enamours challenge for concrete industry to produce concrete more durable and economical while minimizing environmental impact. The concrete industry must seek ways to improve material properties such as strength, durability and placeability while supporting sustainability goals. Specifically, the industry should establish goals to:

- Reduce energy needed to produce cement,
- Reduce greenhouse gas emissions,
- Maximize the use of waste byproducts,
- Increase durability of concrete,
- Reduce construction time, and
- Improve service life of infrastructure.

It is clear that the concrete industry is faced with the challenge of leading future development in a way that protects environment while projecting concrete as the construction material of choice in the 21st century.

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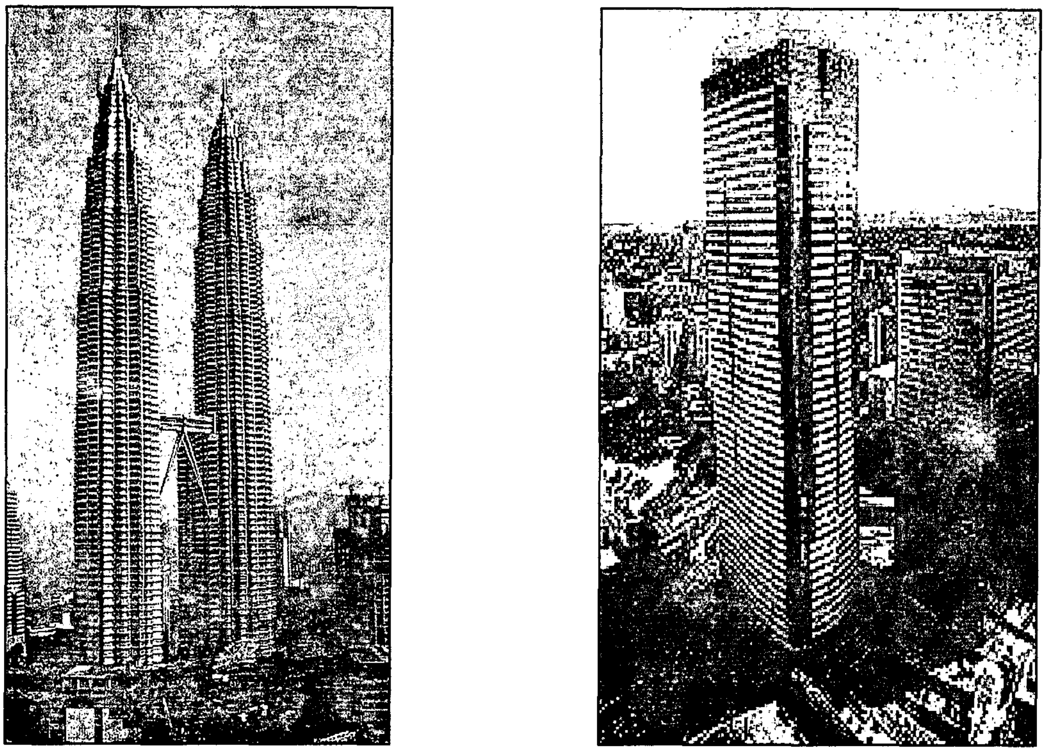
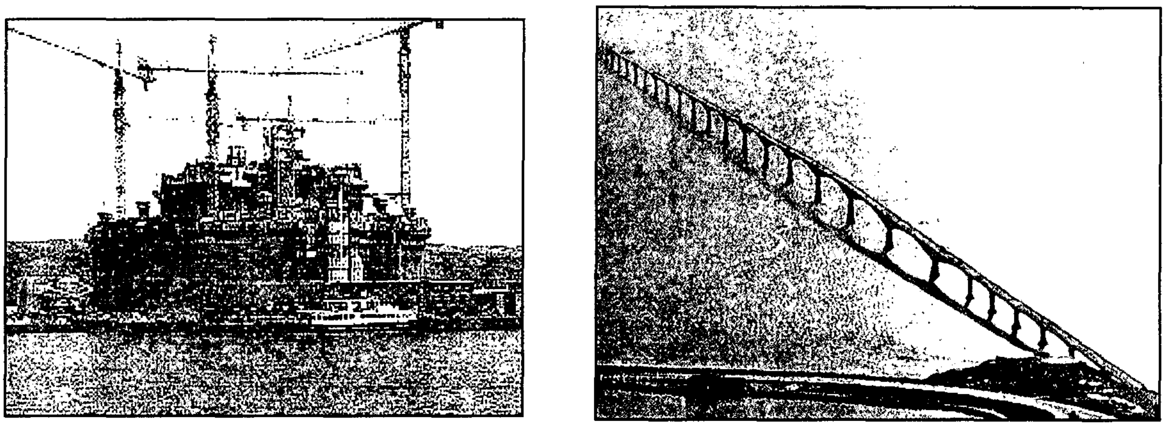


Petronas Twin Towers Two Union Square



Hibernia Platform Confederation Bridge

Figure 1 Examples of Structures of High Strength Concrete

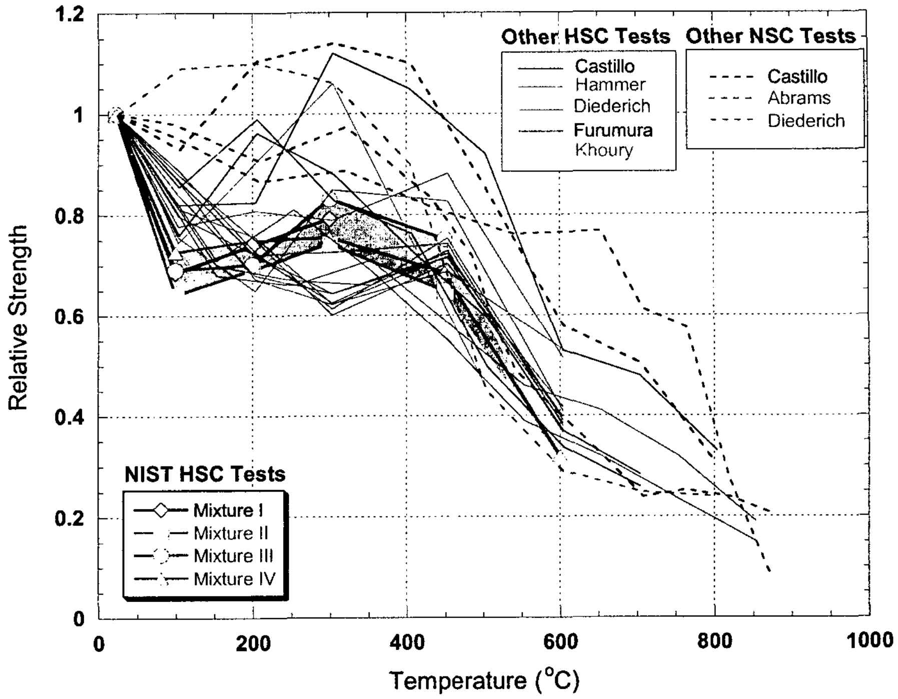


Figure 2 Compressive Strength-Temperature Relationship of Normal Weight Concrete

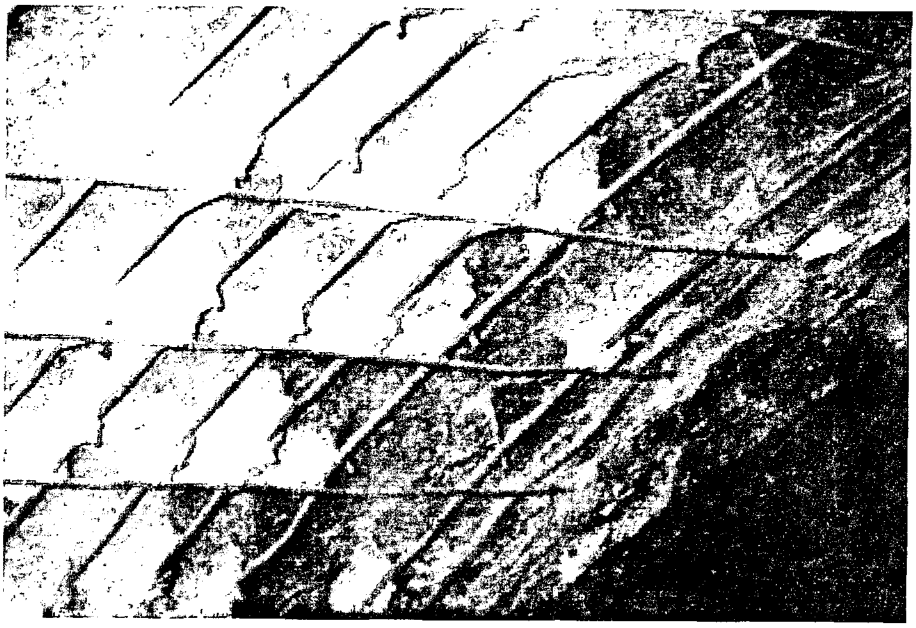


Figure 3 Fire-Induced Spalling of Concrete Tunnel Lining in the Channel Tunnel (11/18/1996)