CURRENT INNOVATION IN CEMENT-BASED MATERIALS

By Tarun R. Naik and Rakesh Kumar

Report No. CBU-2003-09
REP-504
March 2003

Department of Civil Engineering and Mechanics
College of Engineering and Applied Science
THE UNIVERSITY OF WISCONSIN - MILWAUKEE
1.0 INTRODUCTION

At the present time, concrete infrastructures experience deterioration at a much faster rate than expected. This may be due to the fact that structures are subjected to aggressive chemical environments. Such structures include bridge decks, pavements, ocean piers, offshore platforms, pipes, and structures for confinements of solid and liquid wastes containing hazardous materials, etc. Recent investigations in cement-based materials have led to development of a special class of materials called high-performance concrete (HPC). This material may be proportioned to have both high-strength and high-durability related properties. This is accomplished through the use of innovative mixture proportioning technology, high-quality constituent materials, good quality control, mineral admixtures, and chemical admixtures.

Currently, high strength concrete (HSC) with and without mineral admixtures can be proportioned to attain strength in the range of 70 to 80 MPa at a low water-to-cementitious materials ratio using conventional materials and production technology, with chemical admixtures. HPC above 80 MPa requires the use of special aggregates (small size, closely graded, high-strength aggregates), high-performance low heat of hydration cement, silica fume, special chemical admixtures, and special care in mixing, handling, placing, and early curing. Ultra-high strength concrete with compressive strength between 210 MPa and 800 MPa requires no coarse aggregate but very low water-to-cement ratio (0.15-0.25) and special production techniques.

It is now well established that a very dense homogeneous concrete microstructure, especially in the interface region between hydrated cement paste and aggregate, is required in
order to produce HPC and UHPC. This is accomplished using low waternocementitious materials ratio (0.20 - 0.35) with the help of HRWR that can produce slump in the range of 75 to 125mm. The use of mineral admixtures for such concretes is a necessity because they are needed for improving densification and homogeneity of the interfacial region. As a result, HPC attains high impermeability to aggressive agents, leading to improved durability under aggressive chemical environments and complex applied loading conditions. The recent development of self-compacting concrete is being treated the most wanted development in concrete technology for enhancing performance of concrete in its wide range of applications.

This chapter deals with current advances in manufacture of concrete constituent materials, microstructure of cement-based materials, testing of concrete, and recent advances in various types of cement-based materials, such as high-strength concrete, high-performance concrete, high-durability concrete (HDC), roller compacted concrete, high-volume fly ash concrete, fiber-reinforced concrete, self-compacting concrete, ultra-high-strength concrete, conductive concrete, self-curing concrete, and controlled low strength materials (CLSM).
2.0 CONSTITUENT MATERIALS

2.1 Portland Cement

Portland cement is defined by ASTM C 150 as, "a hydraulic cement produced by pulverizing clinker consisting essentially of hydraulic calcium silicates, usually containing one or more of the forms of calcium sulfate as an underground addition." Portland cement is truly hydraulic. Therefore, it requires only the presence of water to develop its strength gaining properties.

Portland cement is composed mainly of calcium and silica oxides along with alumina and ferrous oxides. Smaller amounts of other oxides such as magnesium oxide, titanium oxide, and sulfur trioxides are also present. These oxides are present in the form of compounds consisting primarily of tricalcium silicates (C₃S), dicalcium silicates (C₂S), tricalcium aluminates (C₃A), and tetracalcium aluminoferrites (C₄AF). The strength development characteristics within a given cement type, different brands may vary because of the variation in compound composition and fineness that are permitted by ASTM C 150.

Cement is a gluing agent that is used to glue together coarse aggregate and sand to produce concrete. The worldwide consumption of the portland cement is around 1.6 billion tons per year (Mehta 2002). The United States consumes approximately 110 million tons of Portland cement annually (Holland 2002). The manufacture of cement is not only energy-intensive, but is also responsible emissions for large amount of carbon dioxide. It requires approximately 3000 kJ of energy per kg of cement (Schmidt 1993). Large amounts of fossil fuels are burned to meet the energy requirements in the production of portland cement. Combustion of these fuels results in...
emissions of particulate matters and gaseous pollutants such as SO$_x$, NO$_x$. Both SO$_x$ and NO$_x$ contribute to the formation of acid rain when hydrolyzed in the atmosphere. Additionally, combustion of the fossil fuels emits large amounts of greenhouse gases, especially CO$_2$. Such gases are also produced due to use of limestone (CaCO$_3$) as a raw material in cement production, which is then converted into lime (CaO), and CO$_2$. It is estimated that 1 tonne of CO$_2$ gas is produced for every tonne of portland cement (Davidovits 1993).

Use of industrial by-product materials in the production of cement-based materials not only provides energy saving, and economic and ecological benefits but also several technical benefits. The technical benefits include: increased strength, improved workability, reduced heat of hydration, decreased permeability, increased freezing and thawing durability, increased resistance to chemical attack.

Generally, blended cements are produced using portland cement (PC) and supplementary materials such as blast furnace slag (BFS), fly ash (FA), silica fume (SF), and natural pozzolans (NP). During hydration of cement, Ca(OH)$_2$ is produced. When a three-component (ternary) system (PC+BFS+FA) is used, initially Ca(OH)$_2$ is consumed by the more reactive BFS and then by FA. However, the rate of pozzolanic reaction is significantly lower than PC+FA (Mehta, 1994a). Thus, this system is probably more suitable where low-heat of hydration is required, especially in mass concrete systems. Hinczak et al. (1992) reported that concrete mixtures made with ternary and quaternary cement systems consisting of combinations of portland cement, blast furnace slag, fly ash, and silica fume show lower amounts of heat of hydration compared to control mixture containing only portland cement. When a PC+BFS+SF blending system is used,
reactions of BFS follows reaction of SF due to lower reactivity of BFS compared to SF. The ternary component in such blended cements made with 60% or more portland cement exhibits a setting time comparable to that of portland cement concrete.

Concrete incorporating PC+BFS+SF blended cement shows higher strength gain per unit heat of concrete compared to concrete made with PC+BFS+FA blended cement for a given portland cement content. Davidovits (1994) reports development of alkali-blended cements containing no portland cement. The cements were composed of three components: kaolinetic clay calcined at 750°C, blast furnace slag, and alkali disilicate powder (Na₂K₂)H₂SiO₂. These cements exhibited a high rate of setting and hardening. Such cement can develop compressive strength in the 20 MPa range at 4 hours and in the range of 70-80 MPa at 28 days.

Guisani and Malhotra (1995) developed a blended cement using high volumes of ASTM Class F fly ash. This blended cement was composed of 55% fly ash, 45% ASTM Type I clinker, 3% gypsum by weight of clinker, and a high dosage of a dry, naphthalene-based superplasticizer. Four different sources of fly ash representing a wide range of chemical compositions were used in this investigation. All fly ash had low CaO content (less than 3%), an alkali content (Na₂O equivalent) varying from 1.5 to 2.5% and the Blaine fineness ranging between 2100 and 3100 cm²/kg. The ingredients were ground in a laboratory grinder to produce the cement. With a view to evaluate the effect of incorporating a naphthalene-based superplasticizer during the grinding of fly ash and clinker, three different grinding methods (Mode I, Mode II, Mode and III) were used. These include: fly ash and clinker ground together with the superplasticizer (Mode I), fly ash and clinker ground without the superplasticizer (Mode II), and clinker and superplasticizer ground
together and then fly ash added (Mode III). The result showed improved performance in Mode I compared to Mode II. Mode III was found to be the least efficient because fly ashes did not receive the benefit of grinding. The test data revealed that grinding of the portland clinker together with fly ash and the dry superplasticizer was the most effective procedure to manufacture blended cement using large amounts of fly ash.

Recently, Naik et al. (1995b) conducted an extensive lab investigation to develop low-cost, high-performance blended cements. They used portland cement, six additives, and two chemical admixtures (Table 1) in manufacture of blended cements. Over 150 blends of portland cement, additives and admixtures were proportioned and tested for compressive strength development. Based on both strength development characteristics as well as economy of the blends tested in this work, six performance groups were made. They are described below. An economic analysis was carried out to determine cost-effectiveness of each blended cement.

Based on performance, blended cements developed in this investigation were classified in six different groups presented below.

**Group 1: Low Early-Age Strength, Low Later-Age Strength, and High Economy**

A number of cement blends were found to provide exceptional economy (30 to 40% cost savings), but their compressive strengths were relatively low. The majority of the cement blends in this group contained large amounts of additives (50% to 80%), primarily Additive 1 and Additive 3.
Group 2: **Low Early Age Strength and Equivalent Later-Age Strength**

Several cement blends were found to provide excellent economy (up to 45% cost savings) with reduced early-age strength and equivalent later-age strength compared to the control mixture. The most economical of these blends contained 40% Additive 1, 25% Additive 3, and 6.5% Admixture 2. This blend showed very low 1-day and 3-day strengths but had strength equivalent to the control at 28 days. This blend also provided a materials cost savings of nearly 45%.

Group 3: **Low Early-Age Strength and High Late-Age Strength**

Several cement blends provided lower early-age strengths and higher later-age strengths compared to the control mixture. The most economical blend in this group contained 40% Additive 5 and 4% Admixture 1. This cement blend showed one of the highest 28-day strength results, exceeding the control mixture by more than 35%.

Group 4: **Equivalent Early-Age and Later-Age Strength**

Numerous cement blends with strengths equivalent to the control mixture at both early-age and later-age were also produced with cost savings of up to 35%. Several other blends containing Additive 1, Additive 3, and the admixtures produced similar results but with decreased economy.
Table 1 Material Cost Estimates

<table>
<thead>
<tr>
<th>Material</th>
<th>Unit Price ($ / Ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I Portland Cement</td>
<td>80</td>
</tr>
<tr>
<td>Additive 1</td>
<td>25</td>
</tr>
<tr>
<td>Additive 2</td>
<td>25</td>
</tr>
<tr>
<td>Additive 3</td>
<td>10</td>
</tr>
<tr>
<td>Additive 4</td>
<td>0</td>
</tr>
<tr>
<td>Additive 5</td>
<td>0</td>
</tr>
<tr>
<td>Additive 6</td>
<td>65</td>
</tr>
<tr>
<td>Additive 7</td>
<td>800</td>
</tr>
<tr>
<td>Admixture 1</td>
<td>280</td>
</tr>
<tr>
<td>Admixture 2</td>
<td>100</td>
</tr>
</tbody>
</table>
Group 5: Equivalent Early-Age Strength and High Later-Age Strength

Some cement blends exhibited strengths equal to the control mixture at early ages and higher than the control mixture at later ages. These blends provided savings up to 30%. The best performance of these blends was attained using Additive 5 with Admixture 1. This blend provided higher strength than the control at 28 days by 25% and an economic savings of 15%.

Group 6: High Early-Age Strength and Equivalent Late-Age Strength

Many cement blends exhibited high early age strengths and equivalent later-age strengths. The most economical blend was produced by blending Additive 1, Additive 2, Admixture 1, and Admixture 2. This blend provided the 1-day strength exceeding the control mixture by over 40% and material cost savings of over 15%. The highest 1-day strength was achieved by using blend containing Additive 1, Admixture 1, and Admixture 2. This blend produced 1-day strength exceeding the control by nearly 65% but with only about 10% decrease in material cost. All blends containing Admixture 1 provided high 1-day strengths. However, these blends were also the least cost effective.

2.2 Pozzolanic Materials

A pozzolanic material is defined by ASTM C 618 as, "a siliceous or siliceous and aluminous material which, in themselves, possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties." Pozzolans exist in both natural and man-made forms. Volcanic ash is the most common form of natural
pozzolans. The most effective and widely used pozzolans include coal fly ash, blast furnace slag, silica fume, and other combustion ashes.

When pozzolanic material is combined with cement, the compound calcium silicate hydrate C-S-H is formed (due to its reaction with calcium hydroxide (CH), which is a by-product of cement hydration). Generally, pozzolanic reaction occurs much more slowly than the hydration reaction. Moreover, because CH is a by-product of cement hydration, cement hydration must occur before pozzolans can form C-S-H. For these reasons, strength development is often slower in low-lime pozzolanic material and portland cement than plain portland cement. However, when the pozzolanic reaction consumes CH, it generally produces denser, less permeable concrete. This leads to improved strength and durability-related properties for such concretes containing pozzolanic material and portland cement.

Small amounts of additional chemical admixtures can be used to increase performance of blended cements. Pozzolans and slag contain large amounts of glassy phases (amorphous phases). The addition of alkaline admixtures can increase the solubility of these glassy phases. It has been observed that both alumina and silica, the primary compounds present in pozzolans, become soluble at a pH of 13.3 or greater. Therefore, activation can be achieved by the use of chemical admixtures, which will increase pH of the mixture. Salts of weak acids and strong bases are the most effective activating agents (Ramachandran and Mailvaganam 1992).

The following are the most commonly used alkaline admixtures in blends of portland cements with pozzolanic material:

1. Calcium Hydroxide (Ca(OH)$_2$ or CH),
(2) Sodium Hydroxide (NaOH),
(3) Sodium Sulfate (NaSO₄),
(4) Gypsum (CaSO₄),
(5) Calcium Chloride (CaCl₂),
(6) Sodium Carbonate (Na₂CO₃), and
(7) Sodium Silicate (Na₂O·SiO₂).

2.2.1 Natural pozzolans

Ash produced because of volcanic activity is called a natural pozzolan. The chemical oxides composition of most volcanic ash is similar to that of coal fly ash. Volcanic ash, however, generally contains larger amounts of crystalline (non-reactive) particles rather than (reactive) glassy particles. Also, natural pozzolans generally exhibit a greater loss on ignition (LOI). For these reasons, natural pozzolans are generally less effective in cement-based materials than other typical coal ash-based pozzolans.

2.2.2 Fly ash

Fly ash is a by-product generated due to combustion of coal at thermal power plants. It is removed from the combustion gases by particulate collecting devices such as cyclone separators, electrostatic precipitators, fabric filters, or wet scrubbers. Most of the fly ash particles are spherical in shape, with particle sizes ranging from 1 to 150 μm (1 μm = 0.001 mm = 1 x 10⁻⁶ m),
with a specific gravity varying between 2.1 and 2.8. Fly ash is composed primarily of SiO\(_2\), Al\(_2\)O\(_3\), Fe\(_2\)O\(_3\), CaO, and MgO.

Fly ash is being used on a worldwide scale in cement and concrete because of economy, resource and energy savings, and some added technical advantages in concrete at both fresh and hardened states.

ASTM C 618 has broadly classified ashes into the following three classes:

Class N: Raw or calcined natural pozzolans that comply with the applicable requirements for the class as given herein, such as some diatomaceous earths; opaline cherts and shales, tiffs and volcanic ashes, or pumicites.

Class F: Low-lime fly ash is normally produced from burning anthracite or bituminous coal, which typically contains less than 5% calcium oxide. This class of fly ash has pozzolanic properties.

Class C: High-lime fly ash is normally produced by burning lignite or sub-bituminous coal, which typically has lime contents exceeding 10%. This class of fly ash has cementitious as well as pozzolanic properties.

Generally, Class F and Class C coal ashes are used in advanced-cement based materials as a pozzolan. The pozzolanic reaction of the ash results in formation of pozzolanic C-S-H, similar to that formed by the hydration of cement. Thus, pozzolanic reaction contributes to the formation of the denser concrete. In fact, it causes both pore and grain refinements of the
hardened concrete mass. For a given strength requirement, it is possible to replace a part of the cement requirement with fly ash. The higher calcium content of the Class C fly ash allows greater replacement rates of cement than that of a Class F fly ash. It is now well established by Naik et al. (1986-1997) that the typical acceptable rate of Class C fly ash in structural grade concrete is 30 to 40% of total cementitious materials. Naik and Ramme have also used up to 70% cement replacement concrete mixtures for roadways. Naik and Singh (1991) have studied the performance of concrete containing ASTM Class C fly ash up to 70% for the replacement of cement and suggested that have shown that it possible to manufacture structural grade concrete having compressive strength more than 6000 psi, with 70% replacement of cement by ASTM Class C fly ash.

Aimin and Sarkar (1991) investigated the influence of gypsum (CaSO₄) activation on portland cements containing fly ash. In the study, two mortar mixtures containing portland cement, Class F fly ash, and gypsum were compared to a control mixture as well as mixtures containing portland cement and Class F fly ash without gypsum. The fly ash mixtures containing gypsum outperformed the mixtures without gypsum. However, the control mixture showed higher strength than the mixtures tested with or without gypsum. Beneficiated fly ashes or superfine fly ashes are highly reactive. A superfine fly ash from Australia (Mehta 1994a) had 4.6 μm particles and 1560 m²/kg surface area. This fly ash showed better performance than silica fume.
2.2.3 Condensed silica fume

Condensed silica fume is a by-product of ferro-silicon alloys or silicon metal, which is removed from silicon-based ore processing flue gases by oxidation. Condensed silica fume is composed of superfine particles, which are spherical in shape with a very high fineness. Typical particle sizes are on the order of 0.1 μm, which is approximately 100 times smaller than the average cement particle. The SiO$_2$ content of silica fume generally exceeds 90%.

Due to the high fineness and high reactivity, silica fume is a highly active pozzolan, making it a suitable substitute for portland cement in high-strength or high-performance concrete. Silica fume is highly effective in increasing the density of concrete microstructure, resulting in production of very high strengths. However, the large specific surface area of the silica fume also increases the water demand greatly, by about one pound of water per pound of silica fume added for a given workability of the concrete. Optimum amounts of silica fume vary between 5 and 10% of total cementitious materials. Both laboratory and field experience indicate that concrete incorporating silica fume has an increased tendency to develop plastic shrinkage cracks. Thus, it is necessary to quickly cover the surface of freshly placed silica-fume concrete to prevent rapid water evaporation (Neville 1995). The most cost effective use of silica fume is in combination with other pozzolans (Naik et al. 1997d and 1998).

The supply of silica fume is relatively small compared to that of fly ash or blast-furnace slag. The United States produces approximately 120,000 tonnes annually; nearly all of which is utilized in cement based materials (Malhotra 1992). Due to the relatively small rate of production and high demand, condensed silica fume is relatively expensive. For this reason,
silica fume is used primarily to produce high-quality, high-durability, high-strength, or high-performance concrete.

2.2.4 Blast-furnace slag

Blast-furnace slag is a product of the manufacture of pig iron from iron ore in a blast furnace. The molten slag can either be slowly cooled to a crystalline (non-reactive) form or rapidly cooled to a granulated glassy (reactive) form. Although the crystalline slag has no hydraulic properties, the granulated slag contains chemical compounds similar to portland cement, and when ground, the granulated slag displays latent hydraulic properties. ASTM C 989 defines granulated blast-furnace slag as "the glassy granular material formed when molten blast-furnace slag is rapidly chilled by immersion in water." The granulated blast-furnace slag is produced in the form of small-grained particles, similar to fine aggregate (i.e., sand). Granulated slag must be dewatered, dried, and ground in a process similar to that used for grinding cement clinker. The slag is less reactive than portland cement. It is normally ground finer than portland cement to improve its reactivity. The specific gravity of slag is similar to that of portland cement. The latent hydraulic properties of ground granulated blast-furnace slag make it an appropriate substitute for portland cement. Ground granulated blast-furnace slag has only latent hydraulic properties and, therefore, must be used in combination with portland cement, or alkaline activators, to gain sufficient strength for structural applications.
The principal constituents of the blast furnace slags are silica, alumina, calcia, and magnesia, which accounts for 95% of the composition (Miller and Collins 1976; Kalyoncu 2000).

Wu et al. (1990) studied the activation of slag cements using sodium sulfate ($\text{Na}_2\text{SO}_4$), potassium aluminum sulfate ($\text{KAl(SO}_4\text{)}_2\cdot2\text{H}_2\text{O}$), and calcium aluminate cements (AC). In the study, mortar mixtures containing 30% slag, 70% portland cement, and various chemical activators were compared to a similar inactivated slag mixture and a control mixture containing only portland cement. The results revealed that at early ages, a combination of calcium aluminate cement and sodium sulfate provided the best activation. This mixture attained compressive strengths comparable to the control mixture at 1 day age and exceeded the control mixture strength at 3 days. At 7 days and beyond, sodium sulfate and potassium aluminum sulfate provided the best activation, with strengths exceeding the control mix at all ages beyond 7 days.

Douglas and Brandstetr (1990) carried out research on the activation of ground granulated blast-furnace slag in an attempt to completely eliminate the need for cement in the hydration process. In their study, strengths of mortar cubes made with 100% portland cement were compared to activated slag mixtures using no portland cement. All slag mixtures were activated with a sodium silicate solution. Additional activators and supplementary materials were also used in an attempt to increase performance. The activators used were calcium hydroxide ($\text{Ca(OH)}_2$) and sodium sulfate ($\text{Na}_2\text{SO}_4$); and, the supplementary materials were portland cement, lime, and silica fume. The slag mixture activated by only sodium silicate showed 28-day strengths exceeding the control mixture by more than 150%, but did not attain sufficient strength.
to be measured at 1 and 7 days. The sodium silicate activated slag mixtures incorporating silica fume, Ca(OH)$_2$, and portland cement mixture displayed improved strengths. However, the 1-day strengths of these mixtures were considerably lower than the control mixture.

2.2.5 RICE HUSK ASH (RHA)

Rice-husk is an agricultural based by-product material. It constitutes about 20% of the weight of rice. Rice husk ash is produced through controlled combustion of rice husks. This ash is a highly active pozzolan. It is sometimes called a "superpozzolan" (Mehta 1994a). In cement-based materials, the effect of this ash is similar to that of silica fume.

Partially combusted rice husk is black in color due to the presence of carbon. Whereas, fully incinerated RHA can be gray, purple, or white, depending upon combustion conditions and impurities present in rice husks (Mehta 1994a). Fully combusted rice husk is primarily composed of non-crystalline silica, ranging between 90 and 95%. Both K$_2$O and Na$_2$O are also present in RHA as impurities. The K$_2$O content varies between 1 and 5%. Other minor impurities (less than 1%) such as CaO, MgO, and P$_2$O$_5$ are also found (Mehta 1994b). The surface area of this ash varies between 50 and 100 m$^2$/g. The bulk density of rice husk is about 0.2 g/cm$^3$.

The particle size of rice husk varies between 10 and 75 μm. Although particle size of rice husk ash is larger than typical coal fly ashes (1 to 150 μm) and silica fume (0.01 to 1 μm range),
its surface area is two to five that of silica fume. Among all pozzolans, rice husk ash is exceptional in contributing to strength development at early ages of one to three days.

Due to pozzalanic, homogeneous size distribution of nanometric particles, and very high siliceous properties of rice-husk ash, several efforts have been made to utilize RHA in cement-based materials including cement (Mehta 1992; Zhang and Malhotra 1996; Ismail and Waliuddin 1996; Cisse and Laquerbe 2000; Chandrasekhar et al. 2002; Ajiwe and Okeke 2000). Zhang and Malhotra (1996) used rice-husk ash as a supplementary cementitious material for 10% replacement of cement (by weight) in the manufacturing of high-performance concrete and reported higher compressive strength and higher resistance to chloride-ion penetration for concrete containing RHA in comparison with the control portland cement concrete at the same water-to-cementitious material ratio. Study by Wada et al. (1999) has shown higher compressive strength of RHA mortar and concrete than the control mortar and concrete. They have further reported excellent strength development at the early stages even without steam curing for RHA mortar and concrete.

Slow reacting pozzolans, such as Class F fly ash, can be combined with RHA to obtain improved results. Up to 70% of cement can be replaced without significantly affecting compressive strength (Mehta 1994b). Use of rice husk ash and fly ash in combination may offer complementary and synergistic effects on the properties of concrete. It is reported that use of rice husk ash increases water demand of concrete (Zhang and Malhotra 1996). Fly ash compensates the reduction in workability due to high water demand of rice husk ash, while its progressive reaction with calcium hydroxide contributes to the later-age strength. The combined used of
fly ash and rice husk ash allows producing high-performance concrete with compressive strength levels of 80 to 90 MPa at 28 days (Bui and Stroeven 2001). Even small amounts of cement replacement (10 to 20%) with RHA cause significant improvement in strength as well as resistance to chloride-ion penetration. Inclusion of rice husk in concrete is highly effective in controlling alkali-silica reaction. The properties of rice husk ash make it suitable for use in manufacture of high-performance concrete or other advanced cement-based products.

2.2.6 Metakaolin

Metakaolin is a dehydrated product from pure kaolin clays, calcined under controlled temperature of 700 - 900°C. This material is analogous to other pozzolans. It is an off-white, amorphous, alumino-silicate, which reacts aggressively with calcium hydroxide. It consumes Ca(OH)$_2$ produced during hydration of portland cement to create cementitious C-S-H glue.

The utilization of metakaolin (MK), as a pozzolanic material for cement mortar and concrete has drawn considerable attentions in recent years. It is reported (Bai et al. 1999) that workability of concrete reduces with the increase in replacement level of cement by metakaolin. However, for concrete containing blends of portland cement, pulverized fuel ash (PFA), and metakaolin, the loss in workability due to presence of MK is compensated by the incorporation of PFA.

It is reported (Mehta 1994b) that inclusion of 20% of high-purity metakaolin in portland cement consumed most of Ca(OH)$_2$ produced during the hydration of cement. At 20% metakaolin, concrete attains a very dense microstructure, especially in the interfacial region.
Study (Poon et al. 2001) has revealed higher pozzolanic activity for metakaolin in comparison with silica fume and fly ash blended pastes. The higher pozzolanic activity of MK results in a higher rate of strength development and pore structure refinement for the cement paste at early ages. The use of metakaolin can reduce shrinkage and creep of concrete (Brooks and Megat Johari 2001). Use of High-reactive metakaolin (HRM) for replacement of cement up to 20% replacement level helps in controlling expansion due to alkali-silica reaction (Ramlochan et al. 2000; Aquino et al. 2001; Khatib and Wild 1998). A comparative study (Dubey and Banthia 1998) on the influence of silica fume and HRM on the toughness characteristics of high-performance fiber-reinforced concrete has shown an upper hand for HRM for improving the post-peak energy absorption capacity of concrete. Increased durability for concrete containing HRM in field as well as laboratory is also well documented (Gruber et al. 2001; Poon et al. 2001; Poon et al. 2003; Roy et al. 2001).

Metakaolin can be used in manufacture of high-alkali blended cements (Davidovits 1994). These cements consisted of Kaolonite clay calcined at 750°C, blast furnace slag, and alkali disilicate powder (Na₂, K₂)H₂SiO₄. This cement exhibited quick setting and hardening. The cement achieved compressive strengths in the 20 MPa range after only 4 hours of setting and hardening at 20°C.

2.3 Aggregates

Aggregates generally occupy about 80 per cent of the total volume of concrete and have an important influence on the properties of concrete (Sidney and Young 1981; Mehta and
Monterio 1993). Aggregates are classified in accordance with size, bulk density, or source of aggregates. According to size they are classified as coarse aggregates (larger than 4.75 mm) and fine aggregates (smaller than 4.75 mm). Depending upon bulk density, aggregates are categorized as normal weight (2400 kg/m$^3$), lightweight (1120 kg/m$^3$), and heavy weight (2880 to 6080 kg/m$^3$). Depending upon source, aggregates are classified as natural mineral aggregates derived from natural sources, and synthetic aggregates produced from thermal processes.

Mehta and Aitcin (1990) reported that for very high strength levels of high performance concrete (100 MPa or more), size of aggregate should be equal to or less than 10 - 12 mm. Naik et al.1998; Naik and Kumar 2002, have attained compressive strengths in the range of 100 MPa and higher using 19 mm maximum size aggregates. For high-strength concrete the quality of the aggregate is one of the main limiting factors both for obtaining good workability and high strength. To ensure good bond between the coarse aggregate particles and the matrix, coarse aggregate particles should be approximately equi-dimensional. Crushed stone produces higher strengths than rounded gravel.

Various properties of cement-based materials such as unit weight, elastic modulus, and dimensional stability are dictated by properties of aggregates, especially coarse aggregate (Mehta 1993). These properties of aggregates are greatly influenced by bulk density and strength of aggregates. The bulk density and strength of aggregates are dependent upon physical and chemical properties of aggregates. Physical properties, however, play a greater role compared to chemical properties in influencing concrete properties. The physical properties such as shape, size, and texture are known to influence properties of concrete.
Crushed aggregate obtained by quarrying and crushing of rock can contain substantial amounts of flat or elongated particles, whereas natural gravel has a rounded shape and smooth surface texture. Generally, large aggregates are known to adversely affect properties in many ways for all concretes except low cement factor mixtures. In the larger aggregate, there is greater tendency for water film to accumulate in the vicinity of aggregates. The same is true when higher proportions of elongated and flat particles are used. As a result, the interface region becomes more porous when water evaporates, thereby reducing the strength of the interfacial region. This, in turn, becomes a weak link in concrete, providing larger flaws that favor rapid crack propagation during loading.

For manufacture of aggregates from clay, shale, or fly ash, a process is used to pelletize the material. Then it is sintered in a rotary kiln or traveling gate at temperatures ranging from 1000 to 1200 °C (Mehta and Monteiro 1993). Fly ash aggregates are commercially produced in several countries. More recently, Minergy Corporation has developed a lightweight aggregate manufacturing technology, which used three products, fly ash, paper sludge, and sewage sludge, in various combinations, to produce lightweight aggregates.

Both sintering and fusion technologies are being used in manufacture of lightweight aggregates using fly ash or other by-product materials in the USA and other countries. This process combines clay, slate, fly ash, paper mill sludge, or sewage. The resulting mixture is fed to a high intensity mixture to obtain a homogeneous mixture. The mixture is then fed to a pan pelletizer that forms spherical pellets 9.5 to 19 mm in diameter. These pellets are then fed to a dryer to remove moisture. The pellets are then sintered in a traveling gate or rotary kiln process at
temperatures of 1000 °C and above. The resulting aggregates are cooled and screened to meet the size requirements.

2.4 Chemical Admixtures

ASTM C 125 defines an admixture as a material other than water, aggregate, cement, and fiber reinforcement, used as an ingredient of concrete mortar and added to the batch immediately before or during mixing. There are several admixtures including water reducers, accelerators, antifreezing admixtures, air entraining admixtures, alkali-aggregate inhibitors, and corrosion inhibitors. The incorporation of admixtures in concrete mixtures has been recognized as an important and integral means to improve performance of concrete at both fresh as well as hardened states. The use of admixtures requires an understanding of their actions and not a blind following of the advice of the salesman. 2.4.1 Water reducer

The modern construction industry uses a variety of chemical additives/admixtures to concrete, to reach desirable qualities. The most usable additives are water reducing agents, rendering the concrete highly plastic at reduced water content, saving cement and production time and expenses. Normal water reducers (NWR) or high-range water-reducing (HRWR) admixtures called superplasticizers are used to increase workability of concrete or to reduce the
amount of water for a given workability. Normal water-reducing admixtures are used at a dosage of 0.05 to 0.1% of cement to reduce water requirements in the range of 5 - 12%. Higher dosages of normal water-reducing admixture tend to cause excessive set retardation and air entrainment. In contrast, higher dosages of superplasticizer (1 - 2% by weight of cementitious material) can be used to reduce the water requirement by 20-30% for a given workability without adversely affecting the setting and air entraining of concrete mixtures created by NWR. The superplasticizers are composed of synthetic water-soluble polymers. These include sulfonated melamine formaldehyde (SMF) or sulfonated naphthalene formaldehyde (SNF) condensate. Due to the lower cost of lignosulfates, attempts have been made to make lignosulfate-based superplasticizers. Performance of lignosulfate-modified superplasticizers has been found to be similar to unmodified melamine or naphthalene-based superplasticizers (Ramachandran 1994).

Generally, slump loss occurs after 30 - 60 min. of addition of superplasticizers in concrete mixtures. In order to offset this effect, several methods have been used. One method uses higher doses of the superplasticizer. Other methods include redosing the superplasticizer at different time intervals with or without inclusion of retarder. Depending upon the method of application, variability in slump or strength development can occur. Additionally, total amount of superplasticizer will also vary depending upon the method of application. Consequently, to control slump accurately, a new superplasticizer is needed. Collepardi et al. (1993) reported development of a new superplasticizer, based on Carboxylated Acrylic Ester (CAE) copolymer. This contains carboxylic (COO-) groups in place of sulfonic (SO₃-) groups. This new superplasticizer showed excellent performance in controlling slump loss (Collepardi 1994).
Several other superplasticizers, as described by Ramachandran (1994) and Collepardi (1994), which can control the workability of concrete to a marked extent are also available. However, performance of new superplasticizers in concrete under a wide range of conditions is yet to be established.

Generally, slump retention is higher with sodium lignosulfate compared to other admixtures used. However, use of lignosulfate as a superplasticizer can introduce problems such as foaming, increase in air entrainment, and setting time modifications when higher dosages are used. These problems must be solved in order for the lignosulfates to be used as a reliable superplasticizer. However, at low dosages, the performance of lignosulfates is similar to that of normal superplasticizers (SMF or SNF).

2.4.2 Accelerators

Set accelerating admixtures are mostly used in cold weather conditions. For a long time, calcium chloride was used to accelerate the early cement hydration. However, the use of this accelerator is undesirable due to the presence of chloride-ions. The presence of chloride-ions in concrete can result in corrosion of the reinforcement. To avoid corrosion of the reinforcement, several non-chloride accelerators such as thiocyanates, thiosulfates, nitrites, aluminates, etc. have been developed. Additionally, organic compounds such as triethanolamine and formates have also been used (Ramachandran 1994; Collepardi 1994). The effects of these admixtures on concrete performance are yet to be established, especially long-term effects. The majority of the new admixtures promote high early-age strength, but long-term strength is generally lower.
2.4.3 Anti-freezing admixtures

These are a special class of accelerating admixtures which are used to depress the freezing point of water in concrete at very low temperatures (up to minus 30 °C), whereas many accelerating admixtures including calcium chloride, a dose of 2% can depress the freezing point by 1.5 °C (Collepardi 1994). These admixtures are useful for fabrication of precast elements, patching and repairs, foundation works. Their use increases cohesiveness, plasticity, and minimizes cold joints (Ramachandran 1994).

There are two modes of action of the antifreeze admixtures. The first mode of action is to depress the freezing points of the concrete mixture and serve as a weak accelerator or retarder. The antifreezing mixtures performing these functions include sodium nitrite, sodium chloride, weak electrolytes, and high molecular weight of alcohols and carbamide (Ramachandran 1994). The second mode of action is to accelerate the setting and hardening with good antifreezing capability. This is accomplished through the use of chemicals such as calcium chloride, sodium chloride, sodium nitrite, calcium nitrite, calcium nitrate, and urea. In Finland, dry mortar mixtures with antifreezing admixtures have been used at minus 15 °C (Ramachandran 1994).

The effects of these admixtures on concrete properties need to be established prior to their large-scale use in concrete. Additionally, compatibility of these admixtures with normal admixtures needs to be established under varying curing conditions.
2.4.4 Air-entraining admixtures

Air-entraining admixtures allow a controlled quantity of small, uniformly distributed air bubbles to be incorporated in concrete mixture during the mixing operation and which remain in it after hardening. These are surfactants whose molecules are adsorbed at the air-water and solid-water interface. Air-entrainment reduces strengths of the hardened concrete. However, this reduction can be offseted by the use of suitable water reducing admixture in the same concrete mixture (Corradi and Khurana 1999).

The amount of air-entrained, containing bubbles of the right size and spacing may control the damage to concrete caused by frost and de-icing salts. For maintaining adequate freezing and thawing resistance of concrete, air-entrainment (4-7%) with an appropriate bubble size and spacing factor is provided. Air-entrainment dosage rate is dictated by a large number of factors including variability in the material properties, pozzolans use, mixing, placing methods, temperature, etc. Thus, it is very difficult to adjust proper air content in concrete using normal air-entraining admixtures, especially in concrete containing fly ash with large amounts of unburned carbon, concrete using HRWR, etc. New air-entraining admixtures have been developed that can offset some of the negative effects of these factors. For example, a micro-air admixture has been developed that provides ultra stable air bubbles, which are small and closely spaced (Master Builder 1989). This admixture is composed of fatty acids, salts of sulfonic acid, and stabilizing agents. The admixture is appropriate for use in fly ash concrete having large amounts of unburnt carbon and concrete incorporating a high alkali cement. A stable air content is achieved after 20 minutes of mixing this admixture.
A promising approach involves the use of hollow plastic microspheres with size in the range of 10 - 50 μm (Collepardi 1994). These microspheres are deformed due to pressure generated during the freezing, thus providing air voids to accommodate the resulting expansion. This technique appears to provide more reliable air entrainment than that based on air-entrainment achieved by normal air-entraining agents. This is because doses of the microspheres can be controlled to attain the desired level of air entrainment. However, this new method is more costly compared to use of normal air-entrainment agents.

2.4.5 Alkali - aggregate reaction inhibitors

Alkali-aggregate reaction is caused due to interaction between the alkali hydroxides, usually derived from cement, and reactive silicious or carbonate aggregates. The reaction product absorbs water and swells. The stresses caused by this swelling cause cracking and/or localized pop outs. For a long time, pozzolanic admixtures have been used in concrete to inhibit alkali-aggregate reactions (AAR) by reducing alkali content in concrete mixtures. A number of chemical admixtures including salt of lithium, barium, sodium sulfate, copper sulfate, etc. have been used to inhibit AAR. It is possible to reduce expansion of concrete by inclusion of lithium and ferric chloride. The data on AAR inhibitors is very limited. Thus, recommendations for optimum dosages cannot be made at the present time.

Recent studies (Ramlochan et al. 2000; Aquino et al. 2001; Khatib and Wild 1998; Walters and Jones 1992) reveal that the use of highly reactive metakaolin for the replacement of
cement up to 20% by weight of cement is effective in suppressing the expansion due the alkali-silica reaction.

2.4.6 Corrosion inhibitors

A corrosion inhibitor may be defined, in general terms as a substance which, when added in a small concentration to an environment, effectively reduces the corrosion rate of rebar exposed to that environment. Corrosion inhibitors are liquid or powder in form. Corrosion inhibitors are chemical admixtures that can be added to concrete mixtures to prevent a rust forming reaction in the steel reinforcement. The use of inhibitors is one of the several possible methods to protect and/or delay concrete rebar from corrosion. Such chemicals include (Collepardi 1994): (1) calcium and sodium nitrate, sodium benzoate, and sodium chromate as anodic inhibitors; (2) sodium or ammonia hydroxides and sodium carbonate as cathodic inhibitors; and, (3) organic compounds having molecules that result in attraction of inhibitors to both anodic and cathodic sites. Of these, calcium nitrite is the most commonly used.

Mixed corrosion inhibitor systems are more effective relative to individual inhibitors, possibly because of synergistic effects (Ramachandran 1994). For example, a mixture of Ca(NO$_2$)$_2$ and NA-molybdate have exhibited better results than Ca(NO$_2$)$_2$ alone. Research is in progress to develop admixtures that can act as accelerators as well as corrosion inhibitors.

Suitability of inhibitor in concrete environment is utmost important. Dhouibi et al. (2002) studied the effect of two “commercial” inhibitors: calcium nitrate and alkanolamine on
the corrosion resistance of reinforcing steel as, function of time and that these inhibitors are in effective in presence of chloride on the steel-concrete interface.

2.4.7 Antiwash admixtures (AWA'S)

Placing concrete under water presents some special problems. The main problem of washout of the concrete by water is overcome by use of suitable admixtures. Recent advances have led to development of admixtures that can introduce increased cohesion in concrete mixtures. The increased cohesiveness due to inclusion of such admixtures allows placement of concrete under water with very little loss of cementitious materials. Such admixtures are called antiwash admixtures. These admixtures consist of watersoluble cellulose ethers or water-soluble acrylic-type polymers as the main ingredient (Ramachandran 1994). Dosage of these admixtures varies between 1 and 1.5% by weight of water used in the mixture.

2.4.8 Extended set control admixtures

Large amounts of unused ready-mixed concretes are disposed at waste dumpsites at the end of the production day. However, due to increased environmental concerns and restrictions, disposal of fresh concrete poses a great problem to the ready-mixed concrete producers. To help solve this problem, admixtures have been developed to extend set time of fresh concrete, thus allowing its storage for later uses. These admixtures employ non-chloride stabilizers and activators. The stabilizer coats cement particles in order to cease hydration for hours or days. In order to restart hydration, another activator is added. The stabilizer doses vary from 0.3 to 8.5%
per 100 kg of cementitious materials. The activator doses vary from 0.65 to 1.0% per 100 kg of the cementitious material.

3.0 MICROSTRUCTURE OF CEMENT-BASED SYSTEMS

Until a few decades back, the knowledge of the nature and behavior of concrete was restricted to a few phenomenological properties. The recent past decades have drawn considerable attention of the concrete technologists globally. On the macrostructure level, concrete is composed of two phases: a binding medium called hydrated cement paste (hcp) matrix, and particulate reinforcement dispersed in the matrix called aggregates. However, at a microscopic level, it is a hybrid composite whose properties vary from place to place in the macrostructure of the concrete due to the variations encountered in the concrete microstructure. At the microscopic level, concrete can be classified in three major phases: matrix, aggregate, and interfacial region (transition zone). Each of these phases can be further treated as composite materials.

The third phase, the transition zone, is more porous than other portions of the concrete structure (Neville 1995; Breton et al. 1993). Consequently, this zone becomes the weak link in the concrete, microstructure. Thus, most mechanical and durability related properties of concrete are dictated by the properties of the interfacial zone of concrete (Neville 1995; Breton et al. 1993). The strength of the interfacial transition zone can be improved with time as a consequence of a secondary reaction between the calcium hydroxide present there and pozzolana. Silica fume is very effective for this (Neville 1995).
Several techniques used for microstructural investigations can be classified into two categories (Sarkar 1994): direct observation techniques and indirect interpretive techniques. The direct observation techniques include optical microscopy, electron microscopy, including scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The indirect interpretive method consists of mercury porosimetry, X-ray diffraction analysis (XRDA), and thermal methods such as differential thermal analysis (DTA), thermogravimetry (TG), and differential thermogravimetry (DTG). These techniques are described in the literature (Sarkar 1994).

3.1 Microstructure of Cement Paste

Pores are inherent to the hydration products of cement. The hydration reaction between high-density cement particle and low-density water results in a solid of intermediate density with associated pore system. The hydrated cement paste (hcp) is composed of solid phases, gel pores, and capillary and other pores. Solid phases are made of unhydrated cement clinker grain, and C-S-H calcium sulfoaluminates crystals. A microstructure of hydrated cement paste is shown in Fig. 1. This figure shows non-homogeneous structure of hcp. Some of the areas exhibit dense microstructures, while others show highly porous microstructures.

The morphology of C-S-H crystal varies greatly from poorly crystalline fibers to reticular network (Mehta 1993). Size of C-S-H crystal is found in the range of colloidal dimension (1 to 100 nm) and they tend to cluster. At high magnifications, it is possible to identify microstructure C-S-H crystals or other crystals present in hcp (Fig. 1). The morphology of Ca (OH)₂ crystals are
generally in the form of stacks of large hexagonal plates or large crystals and they also tend to form hexagonal-prism morphology (Mehta and Monteiro 1993). The morphology of calcium sulfoaluminate crystals is in the form of needle-shaped prismatic crystals. These crystals are called ettringite.

3.2 Microstructure of Concrete

On the macro level, concrete is composed of hydrated cement paste, as described above, and aggregates. However, a third phase called the interfacial zone is also present on a microscopic level. In this case, the interface region between coarse aggregates and hcp becomes important as most mechanical and durability-related properties are dependent upon properties of the interfacial region. The hcp is composed of C-S-H crystals having fibrous outgrowths (Fig. 2), and large Ca (OH)₂ crystals (Fig. 3a). The CH crystals oriented at the paste-aggregate interface is shown in Fig. 3b. Other crystals include monosulfate crystals (Fig. 3c), and ettringite (Fig. 3d) of Ca (OH)₂ crystals within the interfacial zone, and the presence of ettringite in contact with aggregate (Sarkar 1994).

Monteiro et al. (1985) investigated microstructure characteristics of the interfacial region of concrete using SEM and XRD measurements. Their study revealed formation of both Ca(OH)₂ and ettringite at the interfacial region of concrete. Since the interfacial region between coarse aggregate and hydrated cement provides a weak link in the concrete microstructure, large numbers of investigations have been carried out to study structural and mechanical properties of this region (Sarkar 1994).
Fig. 1 Microstructure of Cement Paste (Mehta and Monteiro 1993)
Fig. 2 Illustrating Fibrous Type I C-S-H (Diamond 1976).
Fig. 3  Microstructure of normal concrete: (a) large tabular CH crystals; (b) oriented CH crystals at the paste-aggregate interface; (c) monosulfate crystals; and (d) ettringite needles (Sarkar 1994).
Breton et al. (1993) reviewed various models proposed by past investigations as shown in Fig. 4. These models varied with respect to the presence of C-S-H film, preferential orientation of CH crystals at the interface, and epitaxial formation.

Recent investigations by Naik and his co-workers (Naik et al. 1995; Gillot et al. 1993) evaluated the effects of Class C fly ash inclusion on concrete microstructure, with emphasis on the interfacial regions, Fig. 5. They used SEM investigations as well as computer simulation of concrete microstructure. The computer simulation involved the use of a three dimensional model developed at the National Institute of Standards and Technology (NIST). Both SEM investigations and the computer simulation model revealed that homogeneity of the interface microstructure improved due to the inclusion of Class C fly ash. This was attributed to the mechanical process of pore filling effects as well as pozzolanic reactions of the fly ash. Generally, total C-S-H crystals increased with fly ash inclusion. The maximum compressive strength was also observed at 30% cement replacement with fly ash. Beyond 30%, cement replacement (i.e., 35% fly ash to total cementitious materials) concrete microstructure was adversely affected. The mechanical performance of concrete also suffered beyond 30% cement replacement.

Some studies, as reviewed by Sarkar (1994) reported microstructural features of concrete deterioration resulting from physical and chemical causes. Based on past investigations, Sarkar (1994) reported microstructural features of deteriorated concrete as illustrated in Fig. 6.
Fig. 4 Various Models of the Interface Zone (Breton et al. 1993)
Fig. 5  Effects of fly ash on concrete microstructure (scale=10 µm): (1) Class C fly ash; (2) Aggregate-paste boundary in control concrete showing large CH crystals; (3a) 15% cement replacement with fly ash; (3b) 50% fly ash; (4) Duplex film partially surrounding fly ash particle (scale=1 µm); and (5) Polished concrete specimens showing fly ash particles filled with ettringite-like crystals (Gillot et al. 1993).
Fig. 6  Microstructure of deteriorated concrete system: (a) A carbonate layer containing brucite formed on a concrete surface exposed to arctic marine conduction for three years; (b) profusion of secondary ettringite in a severely deteriorated concrete; (c) chloroaluminate crystals in a deteriorated concrete; and (d) increased porosity in a deteriorated concrete due to leaching of CH and fine aggregates (Sarkar, 1994).
4.0 TESTING OF CONCRETE

Conventional practice of destructive and non-destructive testing is not discussed here. Only newer methods are discussed. Conventional destructive test methods are described by Mehta and Monteiro (1993); and detailed nondestructive methods are described by Malhotra and Cerino (1991).

4.1 Destructive Testing

More recent investigations regarding flexural fatigue tests (Ramakrishnan 1991; Naik and Singh 1994a) have revealed that a fatigue limit exists for plain portland cement concrete. Ramakrishnan (1991) reported that fatigue stress at 2 million cycles of non-reversed fluctuating load can be taken as fatigue or endurance limit. Test specimens were subjected to cyclic loads using a third point loading system at 20 CPS. A fixed lower limit of about 10% of the static flexural strength was used, and the upper limit was varied from approximately 90% of the static flexural strength down to the fatigue limit. Naik and Singh (1994a) used similar fatigue testing scheme to establish fatigue characteristics of Class F and Class C fly ash in concrete systems. General fatigue behavior of fly ash concrete is similar to that observed for brittle materials and plain portland cement.

Controlled Low Strength Materials (CLSM) are tested for flow, bleedwater, nail penetration, settlement, compressive strength, shrinkage, and permeability. The flow test (ACI Committee 229) is conducted by placing an open-ended 0.75 mm diameter by 150 mm length steel cylinder form on a flat surface and filling it with the slurry. The slurry form is then slowly lifted, letting the slurry spread laterally on the flat surface. After the slurry stops flowing, the
diameter of the slurry mass is measured in two directions and an average diameter is recorded as flow of the slurry. It has been established (Naik et al. 1990) that a flow/spread of 300 mm to 400 mm would provide a good flowability to the CLSM slurry.

Test specimens (150 mm x 300 mm) are prepared for compressive strength, bleedwater measurement, nail penetration for setting characteristic evaluation, etc. The depth of water accumulated on the surface of the solidified cylindrical mass is taken as a measurement of bleeding. A 50 mm nail penetration test is performed by applying moderate force (40 - 100N) on a 50 mm long (16 p) nail. Ability of slurry material to support pedestrian traffic and/or other construction loads is measured using the Kelly Ball apparatus. Compressive strength is measured in accordance with ASTM D 4832, length change is measured in accordance with ASTM C 157, and permeability is measured according to ASTM D 5084.

4.2 Nondestructive Testing

Nondestructive testing methods are divided into two major classes. The first class of non-destructive methods involves measurement of in-situ mechanical properties. The second class of testing methods evaluates hidden flaws. There are substantial advances in the second class of test methods. These methods provide valuable information in determining the condition of an existing structure. The conditions of structures are assessed by determining flaws such as voids, honeycombing, delaminations, cracks, lack of base support, etc. The techniques used for flaw detection include infrared thermography, ground penetrating radar, and stress wave propagation methods such as ultrasonic pitch-catch, impact methods, and spectral analysis of

4.2.1 Infrared thermographic technique

Infrared thermography is used to measure the temperature differences of concrete surface or other objects. The temperature measurements may be done at any time of day or night as long as heat transfer is taking place. It is based upon basic principles of thermodynamics that thermal energy will always flow from warmer areas to cooler areas. The transport of thermal energy occurs by three modes: conduction, convection, and radiation.

Thermal energy passes from the surface to the interior by means of conduction and convection within the mass. Similarly, any internal heat must be transferred to the surface by internal conduction or convection. Solid concrete is a reasonably good conductor of heat and the effects of convection are negligible within the concrete mass. If the concrete has voids caused by deterioration, delaminations, or poor placement, the conduction paths are disrupted. The disruptions in the flow of thermal energy lead to temperature differences on the surface, which can be detected by infrared thermography (IRT). During the day, subsurface anomalies cause localized increases in heat absorption, so the surface above these areas registers warmer than the surrounding areas. During the night, the anomalies cause the surface above them to dissipate heat faster than the surrounding solid areas, so they register cooler.

Maser and Roddis (1990) reported that the width of the delamination crack has a pronounced effect on the temperature differences between the solid and delaminated concrete.
One important consideration is that the temperature difference between the solid and delaminated area is only detectable if the crack is dry (i.e., air filled). A debonded area with a 0.05 inch air filled crack has up to a 4° C temperature difference compared to a solid slab. If the same crack is filled with water, the temperature difference is essentially undetectable (less than 0.2° C).

IRT detects the temperatures radiated by the surface of the pavement or any other objects. The ability of a body to radiate energy is affected by surface characteristics such as the roughness and color. The measure of the ability to radiate thermal energy is called emissivity. A perfect "black body" has an emissivity of one. This means that, at any given temperature difference with the environment, it radiates the maximum possible energy. The emissivity is higher for darker colors and higher for rougher surfaces. Naik et al. (1997c) carried out an investigation to review the available literature on infrared thermographic technique for evaluation of existing concrete structures; and, to apply the knowledge to existing concrete structures. Based on past investigations, they reported that infrared thermography (IRT) scanning can be used to inspect damage to roofs and exterior walls, deficient and missing insulations, deficient construction, air leakage, and quality of construction of buildings. Other investigators have successfully used IRT techniques to evaluate subsurface anomalies in sewer lines, wastewater pipes, and tunnels. Currently IRT scanning is more commonly used for rapid evaluations of subsurface defects of structures such as bridge decks, highways, and airport pavements to avoid costly repairs. The IRT technique is capable of locating and measuring horizontal dimensions of subsurface defects present in these structures. In order to characterize these anomalies with
respect to depth or thickness, a ground penetrating radar system is generally used along with the IRT system.

### 4.2.2 Ground penetrating radar

In this technique, an antenna on the surface of the object emits a short duration pulse of electromagnetic waves and the resulting pulses travels through the object (Carino 1994). Whenever the pulse experiences any interference due to presence of flaws, some of the pulse energy is reflected back to the antenna in the form of an echo. The antenna generates a signal based on the echo. Generally a high frequency pulse is desirable to obtain better resolution. The depth of the interference is determined by measuring the time from the beginning of the pulse till the receipt of the echo. GPR measuring system is composed of major components such as an antenna unit, a control unit, a storage device, and a display device (Carino 1994). The antenna performs both the emitting of the electromagnetic pulse and the receiving of the echo resulting from interference of flaws. A frequency of 1000 MHz is generally used for inspection of concrete bridge decks and pavements. When a pulse travels through material, attenuation of the pulse occurs due to the loss of energy. Consequently, there is a maximum depth for each material that can be inspected by the GPR under a given set of conditions. For example, dry unreinforced concrete up to 0.5m can be evaluated by GPR with 1000 MHz (Malhotra and Carino 1991). The maximum depth decreases with increasing moisture content and the amount of reinforcement. The control unit performs several functions. It monitors the frequency of the pulse and supplies power to emit the pulse. It also receives and amplifies the signal and supplies
it to the display device, usually an oscillograph. The oscillograph plots the waveforms as waterfall plot or graphic facsimile records (Carino 1994). Since metals are strong reflectors of electromagnetic waves, the GPR method is found to be effective in locating metal objects including reinforcing bars and conduits.

4.2.3 Pulse-echo method

In this method, an ultrasonic stress wave is applied on to the surface of an object using an electromechanical transducer. The pulse is transmitted through the object and is reflected when it encounters flaws or interfaces. The resulting response of the reflected waves or echoes is monitored by a receiver. In case of true pulse-echo method, the transmitter also acts as a receiver. For the pitch-catch technique, a second transducer is used (Fig. 7). In this case, the receiver output signal is displaced on an oscilloscope in time domain. From the display, the round-trip travel is determined. For a known wave speed in a material, depth of the reflecting surface can be determined as:

\[ D = \frac{1}{2} \Delta t \, C_p \]

where \( D \) = depth of the reflecting surface, \( \Delta t \) = round-trip travel time, and \( C_p \) is the speed of the P-wave (dilatational waves, commonly know as compression waves). The above equation is also applied to the pitch-catch technique when the separation between transmitting and receiving transducer is relatively small (Sansalone and Carino 1991). Generally, it is difficult to produce a
true-echo system in concrete due to the presence of paste-aggregate boundary, air voids, and reinforcing steel that also generates echoes. However, success has been achieved through the use of ultrasonic pitch-catch systems. At the present time, a pitch-catch system is capable of testing concrete structures up to 300 mm thick (Carino 1994).

4.2.4 Impact echo

This method uses mechanical impact to generate a stress pulse. As a result, it eliminates the use of bulky transmitting transducers and the associated electronics. This method generates a high-energy pulse which has high penetrability. Due to the application of the impact, stress waves are generated, which propagate into the object along spherical wavefronts as P-waves (compression waves) as well as S-waves (shear waves). Additionally, R-waves (surface waves) propagate along the surface, away from the impact point. Both P-stress waves and S-stress waves are reflected when they encounter a flaw or external boundaries. The reflected waves, or echo, produce displacement at the surface (Fig. 8). The resulting displacement is monitored by a receiving transducer and is recorded on an oscilloscope. When the transducer is paced close to the point of impact, the response is heavily dependent upon P-waves (Carino 1994). By measuring the time from the start of the impact to the arrival time of the P-wave, the depth of the reflecting surface can be determined. An investigation by Sansalone and Carino (1986) led to the successful use of impact-echo method for flaw detection for thin concrete structures.
Fig. 7  Schematic of pulse echo test technique (Malhotra and Carino 1991)
The major development of this method was the application of frequency domain instead of time domain for the observed wave signals. The recorded signal is transformed from the time domain to frequency domain using Fourier transform technique. The value of maximum frequency in the domain is used to compute the depth of the flaws or interfaces by using the following relationship:

\[ D = \frac{C_p}{2f} \]

where \( D \) and \( C_p \) have the same meanings as described before, and \( f \) = the peak frequency. The peak value of frequency in the spectrum is taken as the value of "f". This method has been successfully used for evaluation of flaws in concrete, delaminations in slabs, and voids in tendon ducts (Carino 1994). Recently, this technique was used in evaluations of prismatic members including columns and beams. A recent innovation in the interpretation of impact-echo results involves the use of artificial intelligence. This technique needs a person specially trained on a computer program to recognize amplitude spectra associated with structures with or without flaws (Carino 1994).
Fig. 8 Principles of the Impact-Echo Method (Malhotra and Carino 1991).
4.2.5 Spectral analysis of surface waves

This technique involves spectral analysis of surface waves (R-waves) produced by an impact. A shorter contact time produces a wider range of frequencies. This technique uses two receivers to monitor movements of the surface due to the R-waves. A schematic of this test method is shown in Fig. 9. The resulting signal is processed to determine the stiffness of the underlying layers. Recently, this method was used to determine the elastic properties during curing and voids in concrete slabs.
Fig. 9 Experimental arrangement for analysis of surface waves method (Malhotra and Carino 1991).
5.0 ADVANCED CEMENT-BASED MATERIALS, THEIR PROPERTIES, AND APPLICATIONS

5.1 High-Strength Concrete (HSC)

The definition of high-strength concrete has kept on changing from time to time. In the 1950s, concrete with a compressive strength of 5000 psi (34 MPa) was considered high strength. In the 1960s, concrete with 6000 and 7500 psi (41 and 52 MPa) compressive strengths were used commercially. In the early 1970s, 9000 psi (62 MPa) concrete was being produced. More recently, compressive strengths approaching 20,000 psi (138 MPa) have been used in cast-in-place buildings. For high-quality ceramic natural mineral aggregates, compressive strengths of up to 33,000 psi (230 MPa) can now be produced. If the mineral aggregate is replaced by high-quality ceramic aggregate, compressive strengths of up to 67,000 psi (460 MPa) can be achieved. Most recently, Reactive Powder Concrete (RPC)/Ultra high-strength concrete with compressive strength from 29,000 to 120,000 psi (200 to 800 MPa) has been developed (Feylessoufi et al. 2001; Reda et al. 1999; Loukili et al 1999; Dugat et al. 1996; Feylessoufi et al. 1996; Richard and Cheyrezy 1995).

Experimental investigations (Mehta and Monteiro 1993) indicate that microstructure of high-strength concrete is substantially different from those exhibited by conventional concrete (20 - 40 MPa). A relatively stricter quality control, more care in selection of constituent materials such as plasticizers, mineral admixtures, type and size of aggregates, etc. are needed compared to that used for conventional concrete. High-strength concrete has a minimal volume of capillary pores,
and these pores become segmented upon curing. At the same time, a significant proportion of Portland cement remains unhydrated, because water cannot penetrate through the pore system so as to reach the unhydrated remnants of Portland cement. These remnants can be viewed as very fine ‘aggregate’ particles, which are extremely well bonded to the products of hydration.

High-strength concrete with water-to-cementitious materials ratio of 0.35 - 0.40 can be manufactured by conventional concrete making methods using a superplasticizer with or without mineral admixtures. Generally, mixture proportioning of high-strength concrete requires minimizing water to cementitious materials ratio to produce high strength. Numerous structures made with HSC in the USA or other parts of the world have experienced rapid rate of deterioration, especially in aggressive environments. Conventional method of selection of constituent materials and mixture proportion does not guarantee long-term durability. When long-term durability is required, a special class of cement-based material is needed to assure long-term durability. Such a material is called high-performance concrete, which possesses both high-strength as well as high-durability related properties.

5.2 High-Performance Concrete (HPC)

In recent years, high-performance concrete (HPC) has become an option for structures varying from pavements to skyscrapers where reliability of performance and long-service life are sought. Various definitions exist for high-performance concrete (HPC) according to its uses. For example, Strategic Highway Research Program (SHRP 1991) has defined HPC depending on the performance requirements of a highway. The ACI Committee on High-Performance
Concrete (TR 93-5011, 1993)) defines HPC as, "Concrete meeting special performance requirements which cannot always be achieved routinely using any conventional constituents and normal mixing, placing, and curing practices. These requirements may involve enhancements of the following: ease of placement without segregation, long-term mechanical properties, early-age strength, toughness, volume stability, and life in severe environments." According to Neville (1997) “High-performance concrete is concrete selected so as to fit for the purpose for which it is required. There is no mystery about it, no unusual ingredients are needed and no special equipment has to be used. All we use is an understanding of the behavior of concrete and will to produce a concrete mix within closely controlled tolerances”. The basic fact that properties of material originate from its internal structure is also valid for high-performance concrete. This principle of modifying internal structure suitably has been used in developing a number of metals, composite, etc. (Shackeldford 1992). From material point of view, high-performance concrete is a densely packed, less permeable, concrete obtained by using low water/cementitious ratio (Mehta 1994; Naik and Ramme 1990; Naik et al. 1995; Aitcin and Neville 1993; Mehta and Aitcin 1990).

High-performance concrete mixture proportions depends heavily upon individual applications. The general potential attributes of high-quality concrete (HQC) are given in Table 2. Mixtures for HPC are proportioned to obtain dense concrete microstructure, especially at the interface region between aggregate and paste. A highly dense microstructure for HPC can be obtained through selection of high quality constituent materials and innovative mixture proportioning. A typical mixture for HPC must consist of high quality aggregate (small size,
closely graded, high strength), low heat of hydration cement, pozzolanic admixtures (fly ash, slag, natural pozzolans, rice husk ash, silica fume), and chemical admixtures. Naik and his co-workers (Naik et al. 1997d; Naik et al. 1998) and others (Committee 1993; Aitcin and Neville 1993; Aitcin et al. 1987; Beffel 1995; Naik et al. 1992; Olson 1994) have reported development of concrete mixtures in order to have high-strength and high-durability related properties. Mehta and Aitcin (1990) recommended that for very high strength levels of HPC (100 MPa or more), size of coarse aggregate should be equal to or smaller than 10-12 mm. Naik et al. (1997, 1998) reported development of strength levels up to 100 MPa and above for HPC incorporating maximum size of aggregates in the range of 12-20 mm. Naik and his associates have also developed low-cost concrete mixtures incorporating large amounts of low-cost mineral admixtures such as Class C fly ash and Class F fly ash, clean coal ash, blended ash, low amounts of silica fume, and superplasticizer. Manufacture of HPC requires special care in mixing, handling, and placing of these concretes. Moreover, strict quality controls are needed in material selection, batching, production, and testing of HPC. High-performance concrete offers several benefits over conventional concrete. In recent years, HPC has been used for the structures varying from pavements to skyscrapers where reliability of performance and long-service life are sought.
Table 2  Potential Attributes of High Quality, High Performance Concrete Systems (Committee Report 1993)

- Abrasion Resistance
- Constructability
- Corrosion Protection
- Chemical Resistance
- Ductility*
- Durability
- Energy Absorption (Toughness)*
- Fire Resistance
- High Compressive Strength
- High Early Strength
- High Elastic Modulus
- High Modulus of Rupture
- High Tensile Strength
- High Workability and Cohesiveness
- High Strength/density Ratio (Light Weight)**
- Low Permeability
- Resistance to Washout
- Volume Stability

* Fiber-reinforced concrete

** Especially with high-strength, lightweight concrete
5.3 Roller Compacted Concretes

Roller compacted concrete (RCC) is substantially different from that of conventional mass concrete. Roller compacted concrete is a no-slump concrete. Its consistency is stiffer (almost dry, similar to asphaltic concrete) than conventional mass concrete. Gradation requirement for aggregates for RCC mixtures is much more flexible compared to that for conventional mass concrete. It can use aggregates that do not meet normal aggregate gradation requirements. ACI (1989) defines RCC as a concrete that has a consistency which allows it to be compacted with a vibratory roller. Generally, RCC is mixed in continuous process and can be transported with truck or conveyors. It is placed in layers by a bulldozer, and compacted with a vibratory roller (Schrader 1994). A freshly mixed RCC can have an appearance similar to that of gravel used for road base construction. However, wetter mixtures can resemble conventional no-slump concrete. After setting and hardening, the material looks like conventional mass concrete.

Generally, portland cement with and without fly ash or natural pozzolans is used as a binder. Due to low cement content of RCC mixtures, natural non-plastic fines or rock dust are used as a filler to increase paste content (Schrader 1994). Mixture proportions for RCC depends upon design stress, seepage control concepts, experience, available equipment, and schedule. RCC mixtures can be classified into three classes (Schrader 1994). Class One mixtures with high strengths (17 - 30 MPa) and clean aggregates are composed of 120 to 250 kg/m³ of cementitious materials (cement plus fly ash). Class Two includes mixtures with mid-strength range (10 - 20 MPa). The cementitious materials content for these mixtures range from 80 to 125 kg/m³. Class Three mixtures are proportioned with low strength (5 - 15 MPa) and natural fines
in the aggregates. These mixtures have 50 to 90 kg/m$^3$ of cementitious materials. The practical limits for RCC mixtures by Schrader (1994) are shown in Table 3.

Recently, RCC mixtures have been used in construction of dams in many parts of the world. Initially, the major dams that used RCC were Willow Creek Dam in the USA (Schrader 1982) and Shimajagawa Dam in Japan. However, these dams differed in regard to design, purpose, construction details, size, and cost (Schrader 1994).
Table 3  Practical RCC Mixtures (Schrader 1994)

<table>
<thead>
<tr>
<th></th>
<th>Dry Low Paste</th>
<th>Wet High Paste</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kg/m³</td>
<td>m³</td>
</tr>
<tr>
<td>Cement</td>
<td>60</td>
<td>0.019</td>
</tr>
<tr>
<td>Pozzolan (Ash)</td>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>Water</td>
<td>110</td>
<td>0.110</td>
</tr>
<tr>
<td>Air</td>
<td>0</td>
<td>0.005</td>
</tr>
<tr>
<td>Fine Aggregates</td>
<td>165</td>
<td>0.066</td>
</tr>
<tr>
<td>Total Paste</td>
<td>335</td>
<td>0.200</td>
</tr>
<tr>
<td>% Paste</td>
<td>14%</td>
<td>20%</td>
</tr>
</tbody>
</table>
5.4 High-Volume Fly Ash Concrete

High-volume fly ash concrete (HVFA) generally refers to concrete incorporating fly ash in excess of 40% of total cementitious materials. Recent investigations by Malhotra and his associates (Malhotra 1994) led to the development of high-volume fly ash concrete incorporating Class F fly ash ranging from 50 to 60% of total cementitious materials. These concrete mixtures have shown high strength levels when low water-to-cementitious materials (W/(C + F) = 0.30) were maintained with the use of a superplasticizer. Typically, high-volume fly ash concrete mixtures developed by Malhotra were composed of 150 kg/cm$^3$ cement, 210 kg/m$^3$ of Class F fly ash, 115 kg/m$^3$ water, 1275 kg/m$^3$ coarse aggregate (19 mm MSA), 620 kg/m$^3$ fine aggregate, 720 mL/m$^3$ air entraining admixtures, and 4 L/m$^3$ superplasticizer (Malhotra 1994). This mixture has shown good strength and durability-related properties, except good salt scaling resistance. Generally, HVFA concrete systems perform poorly in salt scaling tests. Several properties of the HVFA concrete, for example the time of set, slump, air-entrainment, elastic modulus, creep, and drying shrinkage, were comparable to or better than plain portland cement concrete. The fly ash in concrete exhibited better results with respect to workability, heat of hydration, and permeability. Naik and his associates (Naik and Singh 1995c) made contributions in the development of high-volume Class C fly ash concrete. Naik and Ramme (1989) developed high-volume Class C fly ash concrete systems for strength levels up to 35 MPa. Their results showed that beyond 7 days, concrete containing up to 60% fly ash showed higher compressive strength than no-fly ash concrete. Concrete containing up to 40% Class C fly ash has showed good resistance to salt scaling (Naik et al. 1995b, c). Investigations by Naik and his associates
revealed that superplasticized concrete incorporating Class C fly ash could be used in manufacture of HVFA concrete for cement replacements up to 70% (Naik et al. 1994; Naik et al. 1995d; Naik and Singh 1995). Low-early strength of high-volume fly ash concrete makes it suitable for many applications such as in deep foundations where early-age full loading is unlikely (Nehdi et al. 2003).

5.5 Fiber-Reinforced Concrete

Plain portland cement concrete or other cement-based materials exhibit brittle behavior. Consequently, these materials possess low tensile strength as well as low tensile strain capability. Concrete is prone to have numerous micro- and macro-cracks during its setting and hardening process. These cracks tend to propagate rapidly even at low tensile loads. Fibers in moderate amounts (less than 2% by volume of concrete) have been used to improve tensile strength capability of cement-based materials.

Traditionally, reinforcing bars are used in concrete to improve tensile strength capacity of the reinforced concrete structural element. But these reinforcements do not improve properties of the concrete matrix. Consequently, reinforced concrete tends to exhibit stress-softening behavior (Balaguru and Shah 1992). Fibers are short and discontinuous. They are randomly distributed in the concrete matrix, leading to improved tensile properties of the matrix. ACI Committee 544 (1982) reported that total energy absorbed (toughness) is at least 10 to 40 times higher for a fiber-reinforced concrete than for plain concrete.
The magnitude of toughness depends upon factors such as fiber properties, concentration, aspect ratio (length to diameter ratio), shape, and surface texture of the fiber (ACI Committee 544, 1982). Various types of fiber that can be used in cement-based materials include acrylic, asbestos, cotton, glass, nylon, polyester, polyethylene, polypropylene, rayon, rock wool, and steel (ACI Committee 544 1982).

Influence of fiber parameters is summarized in Fig. 10. Coarse fiber (in the mm range) used in conventional fiber-reinforced concrete tends to improve tensile strain capacity but not tensile strength to a considerable extent (Fig. 10). This is primarily due to their ability to control only localized macrocracks, leaving microcracks free to propagate during loading. Fine fibers (in the nm range) can suppress growth of microcracks, thus improving tensile strength and the concrete matrix properties. These fibers with suitable length and amount can introduce tensile strain hardening behavior as opposed to strain softening behavior observed in conventional fiber-reinforced concrete (Shah 1994).

Recently, Shah and his associates from the Center for Advanced Cement-Based Materials at Northwestern University have developed an extrusion process to manufacture cement-based fiber-reinforced composites incorporating large amounts of fibers (2 to 8% by volume of concrete). This process extrudes cement-based composites through a die to manufacture different sizes and shapes of products. The process produces sheets, which exhibit strain-hardening behavior even at 2% fiber content. The resulting composites can exhibit tensile and bending strengths comparable to those observed with continuous fibers.
Fig. 10 Influence of Fiber Parameters on Tensile Behavior (Shah 1995).
5.6 Controlled Low Strength Materials (CLSM)

CLSM produced as flowable slurry is a highly fluid cementitious material that flows like a liquid, sets up and supports like a solid, and self levels without compacting. American Concrete Institute Committee 229 defines CLSM flowable slurry as, "cementitious material that is in a flowable state at placement and has specified compressive strengths of 1200 psi (8 MPa) or less at the age of 28 days." A number of names including flowable fill, unshrinkable fill, manufactured dirt, controlled density fill, flowable mortar, etc., are being used to describe this material.

There are several uses for CLSM. It can be used as backfill material for sewer trenches, utility trenches, bridge abutments, surrounding pipes and manholes, retaining walls, walls of navigation locks and other hydraulic structures, etc. CLSM can be used as a good-quality structural fill for foundations subbase, floor slab base, road bases. Additionally, it can be used as a fill material for abandoned tunnels, sewers, storage tanks, wells, abandoned utility vaults, voids under pavements, manholes.

CLSM is used primarily for nonstructural applications. Its consistency is similar to that of pancake batter. CLSM fill is self-levelling and can be placed quickly and with minimum labor. It reaches the desired compaction and can harden within a few hours of placement. For excavatable slurry, compressive strength should be in the range of 50 to 100 psi (0.35 to 0.70 MPa) at the 28-day age. In many situations, this material can provide cost effective alternatives to conventional compacted granular backfill or structural fill materials (soil or other granular
materials). This is primarily due to lower cost of labor and time required for CLSM placement compared to the cost of placing and compacting conventional fill materials.

In cases where no future excavations or higher strengths are required, CLSM mixtures can be proportioned with higher amounts of cementitious materials. For uses as permanent fill material, CLSM mixtures can be proportioned to attain strengths up to 1200 psi (8 MPa) at the age of 28 days.

Flowable CLSM fill material can be delivered to a job site by conventional ready-mixed concrete trucks. CLSM can be placed either by chute, conveyor, or pump depending upon location and type of cavity to be filled. It can be placed in a dry (i.e., water free) excavation as well as under water. For small jobs, it can be delivered dry in a mobile mixer in which it can be mixed with water just before placement.

CLSM offers several advantages over conventional granular fill materials. The placement of conventional material requires testing after each lift of 12 to 24 inches (300 to 600 mm). CLSM mixture exhibits very low settlement. Thus, use of CLSM slurry will provide better support for overlying structures and will avoid their damages associated with the base/support settlement (and/or future maintenance costs associated with re-filling and levelling).

Recent investigations at the UWM Center for By-Products Utilization (CBU) have revealed that CLSM mixtures can be proportioned with large amounts of industrial by-products such as fly ash, bottom ash, foundry sand, scrap iron slag, post-consumer waste plastics and/or glass. Thus, use of CLSM made with industrial by-products will not only reduce disposal costs to producer of these by-products, but CLSM also reduces the lost revenue, resources, and energy
requirements for producing raw materials, as well as reducing landfill space requirements. CLSM mixture can be made using cement, water, sand, coarse aggregate, and various by-product materials as a replacement of cement, sand, and/or aggregates. More recently, research completed at CBU has established that many by-products containing CLSM are environmentally friendly materials as established by leachate tests. CLSM with by-products helps close the recycling loop (bypassing a landfill).

A number of studies by Naik and his coworkers (Naik et al. 1990; Ramme et al. 1993, 1994; Naik and Singh 1994b) and others (Krell 1989; Janard et al. 1992) have reported properties of flowable slurry materials using different mixture proportions. The properties of slurry materials measured include flow, strength, density, settlement, shrinkage, permeability, etc. A large number of studies (ACI 1994; Ramme et al. 1993; Naik and Singh 1994b) have been reported to develop excavatable CLSM mixtures for strength levels in the 0.35-0.70 MPa (50-100 psi) range at 28 days.

More recently, Naik and Singh (1997a,b) investigated properties of excavatable flowable slurry materials containing used foundry sand for strength levels in the range of 0.35 - 0.60 MPa. Various properties such as nail penetration, settlement, shrinkage, condition of permeability, set, compressive strength, were determined. Based on the results obtained, they reported that excavatable slurry could be manufactured using foundry sand as a replacement of fly ash up to 85%.
5.7 Self-Compacting Concrete (SCC)

Self-compacting concrete (SCC) is a highly workable concrete that easily flows through congested areas and does not require external or internal compaction but it gets fully compacted under its self-weight only (Okamura 1997). Self-compacting concrete (SCC) was originally developed at the University of Tokyo, Japan, in collaboration with leading concrete contractors during late 1980s (Campion and Jost 2000). The notion behind developing this concrete was the concerns regarding the homogeneity and compaction of cast-in-place concrete within intricate (i.e., highly reinforced) structures and to improve overall durability quality of concrete due to a lack of skilled labor. This concrete is highly flowable and cohesive enough to be handled without segregation. It is also referred as self-leveling concrete, self-consolidating concrete, super-workable concrete, highly-flowable concrete, non-vibrating concrete etc.

For concrete to flow smoothly through obstacles like highly reinforcement areas the shear stress should be small enough to allow the relative displacement of the aggregate. For this, a moderate viscosity of the paste is necessary (Hashimoto et al. 1989). The shear force required for relative displacement of aggregates largely depends on the water-to-cementitious materials ratio (W/Cm) of the paste. Increase of the water-to-cementitious materials ratio increases the flowability of the cement paste at the cost of decrease in its viscosity and deformability, the primary requirements for a self-compacting concrete. Therefore, in order to maintain deformability along with flowability in paste, a superplasticizer is indispensable in the concrete. With a superplasticizer, the paste can be made more flowable with little concomitant decrease in
viscosity (Okamura 1997). An optimum combination of W/Cm and superplasticizer for achievement of self-compatibility can be derived for fixed aggregate content concrete.

SCC often incorporates several mineral and chemical admixtures, in particular a superplasticizer and a viscosity-modifying admixture (VMA). Superplasticizer is used to insure high fluidity and reduce the water-to-cementitious materials ratio. The VMA is incorporated to enhance the yield value and viscosity of the fluid mixture, hence reducing bleeding of the concrete. Use of mineral admixtures such as fly ash, blast furnace slag, limestone powder, etc., could increase the slump and cohesiveness of the concrete mixture. Use of mineral admixtures also reduces the cost of concrete. The incorporation of one or more mineral admixtures or powder materials having different morphology and grain-size distribution can improve particle-packing density and reduce inter-particle friction and viscosity. Hence, it improves deformability, self-compatibility, and stability of the self-compacting concrete (Sonebi et al. 2000). Use of fly ash and blast furnace slag in self-compacting concrete results in a reduction in the dosages of superplasticizer by needed to obtain similar slump/flow compared to concrete made with portland cement only (Yahia et al. 1999). The well known beneficial advantages of using fly ash in concrete such as improved rheological properties and reduced cracking of concrete due to the reduced heat of hydration of concrete can also be incorporated in SCC by utilization of this material as a filler. The use of self-compacting concrete can yield many advantages, such as:

- Promote the development of a more rational concrete production
- Industrialized production of concrete
Significant reduction in the cost of in-situ cast concrete, pre-cast construction by eliminating compaction needed during concreting, labor, and equipment wear and tear cost related to compaction.

- Reduction in the construction time by accelerating the construction process
- Improve the quality, durability, and reliability of concrete structures
- Improve working environment at construction sites by reducing noise pollution
- Easily placed in thin-walled elements or elements with limited access.
- Ease of placement results in cost savings through reduced equipment and labor requirement.

This can create can be used for a variety of applications varying from normal construction activities to pre-cast and pre stressed construction industry. Further, it can be used in the construction of special architectural structures that was very difficult with conventional concrete.

### 5.7 Ultra High Strength Concrete/Reactive Powder Concrete (RPC)

New generation of superplasticizer and advanced mineral admixtures like silica fume has made it possible to develop concrete having compressive strength beyond 800 MPa. Concrete with compressive strength greater than 200 MPa is generally referred as ultra-high strength concrete, compact reinforced composite, ultra-high performance concrete, reactive powder concrete (Feylessoufi et al. 2001; Reda et al. 1999; Loukili et al 1999; Dugat et al. 1996; Feylessoufi et al. 1996; Richard and Cheyrezy 1995). This concrete is highly specialized concrete in comparison of ordinary, high-strength and high performance concretes. This concrete
is characterized by a high silica fume content (20-25% of cement by weight), a very low water-to-cement ratio (0.15-0.20), and no coarse aggregate. Ductility of such concrete is ensured by incorporation of steel fibers in the range of 5-6% by volume (Loukili et al 1999; Dugat et al. 1996). Comparative mechanical properties of reactive powder concrete, ordinary concrete and high-strength concrete are given in Table 4. This concrete has very dense microstructure that gives superior durability compared to conventional high-strength concrete. The considerable ductility, and high compressive strength and flexural strength provide designers with new possibilities. Such concrete has applicability in unreinforced prestressed structures.
Table 4. Mechanical properties of RPC compared to those of ordinary concrete (OC), high-strength concrete (HSC), and reactive powder concrete (Dugat et al. 1996)

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th>Ordinary concrete</th>
<th>High-strength concrete</th>
<th>Reactive powder concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength (MPa)</td>
<td>20-50</td>
<td>60-80</td>
<td>200-680</td>
</tr>
<tr>
<td>Flexural strength (MPa)</td>
<td>4-8</td>
<td>6-10</td>
<td>15-140</td>
</tr>
<tr>
<td>Fracture energy (J/m²)</td>
<td>130</td>
<td>140</td>
<td>1000-40000</td>
</tr>
<tr>
<td>Ultimate tensile strain (10⁻⁶)</td>
<td>100-150</td>
<td>100-150</td>
<td>2000-8000</td>
</tr>
</tbody>
</table>
5.8 Conductive Concrete

Conventional moist and oven-dried concrete can be classified as semiconductor and insulator respectively (Monfore 1968). Air-dried concrete has a resistivity of the order of $10^6$ ohm-cm (Neville 1995). Conductivity of moist concrete is influenced by the presence of salts in the electrolytic solution and the ambient temperature (Farrar 1978; Monfore 1968). However, conductive concrete is a new type of concrete that possesses high electrical conductivity along with structural mechanical properties. Concrete is a poor electrical conductor especially under dry conditions. Therefore, conductive particles and fibers are added to conventional aggregate and cement paste compositions to manufacture conductive concrete (Farrar 1978; http://irc.nrc-cnrc.gc/newsletter/v1no1/conductive_e.html 2003). The design formulation is based on the ‘electrical percolation’ principle by which the composite conductivity increases-dramatically, by several orders of magnitude when the content of conductive phase reaches a critical ‘threshold’ value. Further, increase in the conductive phase content boost composite conductivity only slightly. The design specifies an amount just over the threshold content, assuring high conductivity and mechanical strength as well as good mixing conditions. Additives for making conductive concrete includes carbon fibres, steel fibers, carbon black, coke breeze, ferrous compound etc. In order to increase the conductivity, it is essential to provide fiber-to-fiber and/or fiber-to-particle continuity throughout the concrete so that a conductive fiber and/or particle network might be formed in the concrete (Farrar 1978; Yehia and Tuan 1999; Banthia et al 1992). It is reported that when steel fibers and coke breeze and steel shavings were used as conductive additives, the material cost of conductive concrete was about five times that of
conventional concrete (Yehia and Tuan 1999). This was mainly due to the cost of the electrically conductive additives. The cost of steel fibers was about four times the cost of coke breeze and steel shavings of the same weight.

In the mono-fiber systems, carbon fibers are far more effective in improving the conductivity than steel fibers, although the carbon fibers themselves are much less conductive than steel fibers. This is attributed to the extremely fine size of carbon fibers, which contributes to the effectiveness of the inter-fiber continuity. At 28 days, the resistivities of plain concrete, concrete containing carbon fiber (5% by volume), and concrete containing steel fiber (5% by volume) were 66,000, 78, and 7,400 ohm-cm, respectively. In the hybrid-fiber system where carbon fiber and steel fiber were used together, it was possible to mobilize the high conductivity of steel fibers by optimum proportioning of steel and carbon fibers. The 28-day resistivity of concrete containing carbon fiber (2% by volume) and steel fiber (1% by volume) was 190 ohm-cm (Banthia et al 1992).

Concrete with electrical conductivity properties may have important applications in the military and construction industry, especially for de-icing road from snow. Along with specially configured electrodes and an electrical power supply, it can be used to de-icing on roads, sidewalk, bridges, and runways. When placed as an overlay, conductive concrete with very low resistively can be used as a secondary anode in existing cathodic protection systems. This concrete attenuates electromagnetic and radio waves, hence, can be used to shield computer equipment from eavesdropping efforts and to protect electrical installations and electronic equipment from interference (Farrar 1978; Yehia and Tuan 1999; Xie and Beaudoin 1995).
5.9 Self-Curing Concrete

Curing is one of the most important parameters for concrete durability and strength development. However, adequate curing as specified by codes of practice and specifications, is in practice seldom met to the desirable degree (Cather 1994). In practice, it is not possible to apply the same curing method to all concrete surfaces of the same structure. In recent years, attempts have been made to develop a curing system whereby a chemical agent is introduced in the concrete during mixing so as to make it self-cure (Dhir et al. 1994, 1996, 1998).

Self-curing of concrete is a process concerned with achieving optimum curing of concrete without the need for applying external curing methods. Self-curing of concrete can be achieved by adding appropriate polymer i.e., water-soluble chemical during mixing operation of the concrete mixture (Dhir et al. 1994). The addition of chemical reduces water evaporation from set concrete specimens. Dhir et al. 1998, attributed the improvement in water retention to three mechanisms namely:

- Lowering of vapor pressure
- Reduction of bleeding
- Reduction of permeability

They reported improvement not only in water retention, but also in the degree of hydration of the cement. Possibility for using certain type of hydrophilic polymers for making self-curing concrete is also reported (Dhir et al. 1994; Kolias et al 1999). The addition of hydrophilic polymer such as glycol (with an average molecular weight of 200) leads a reduction in the vapor pressure of water above concrete. The formation of hydrogen bond between polymer molecules
and water molecules further reduces the vapor pressure. Hence, this chemical acts as a barrier to evaporation of water from concrete thereby increases the degree of cement hydration. The internal curing system like self-curing leads several advantages such as a better quality concrete surface, greater turnover, and a reduction in cost of operation. Published research data advocate the use of appropriate self-curing polymers for the production of concrete with improved mechanical and durability properties. Further, the use of self-curing compound overcomes several shortcomings arising due to improper curing of normal as well as high-strength concrete at site.

6.0 FUTURE RESEARCH NEEDS

In order to produce durable advanced cement-based materials, optimization of various aspects of material technology should be carried out. This includes optimum selection of constituent materials, optimization of mixture proportion technology, mixing for HSC, HPC, HQC, special care in handling and placing, curing for optimum performance, etc.

The effects of constituent materials on properties of concrete need to be scientifically established. The constituent materials include cementitious materials, aggregates, mineral admixtures, and chemical admixtures.

In order to manufacture low-cost durable cement-based composites, low-cost, high-performance blended cementitious materials using large amounts of low-cost/no-cost by-products are needed. Further research is required to establish blended cements incorporating more than 50% of non-portland cement materials. Both shape and size of aggregates, besides their other physical and mechanical properties, are important in affecting concrete properties. The effect of
these parameters needs to be established for optimum performance of cement-based composites.

There is a need to develop optimum mixture proportioning technology for advanced cement-based materials for many varied applications.

Mixing plays a very important role in producing a homogeneous mixture of concrete, especially concrete incorporating low water to cementitious materials ratio, and discontinuous fibers. Therefore, an effective method of concrete mixing and manufacturing technology involving the use of shear actions needs to be developed for materials having high cementitious content, finer constituents, fibers, etc. In particular, a mixing technology for fiber-reinforced concrete needs to be developed for incorporating higher amounts of fiber (more than 2% by volume of concrete) in order to modify matrix favorably for large concrete construction.

More research is needed to establish high-strength and durability performance of lightweight aggregate made with industrial by-products.

There is an urgent need to establish cost-effective HRWR agents such as lingosulfate-based superplasticizers, which can perform comparable to or better than melamine-based or naphthalene-based superplasticizers. Further investigations are needed to establish performance of set-extending admixtures on cement-based materials. More research is needed to establish the effects of non-chloride admixtures on concrete strength, especially long-term. Further research is also needed to establish the effects of set extending as well as antifreezing admixtures on properties of cement-based materials.
More research is needed to establish optimum mixture proportion and production technology for HPC. Additionally, detailed strength and durability-related properties need to be determined for establishing material specifications for this class of material.

Long-term performance of high-volume fly ash concrete needs to be established for developing material specification, especially performance under deicing salt environment.

Self-compacting concrete is being regarded as one of the most wanted development in the field of concrete technology to overcome the shortcomings associated with durability quality of convention concrete. In the past couple years this technology has been adopted globly for the wide range of applications. However, much more including development of specifications and standard codes etc., are yet to be done in this field.

Extensive research is needed to be carried out for self-curing, conductive concrete, ultra-high strength concrete/reactive powder concrete to bring these innovations technologies in practice.

7.0 SUMMARY AND CONCLUSIONS

Numerous existing structures are experiencing deterioration at an alarming rate. This might be due to their exposure to hostile environments and/or excessive loads above their anticipated design loads. Consequently, huge sums of money are spent for repair and maintenance, resulting in the draining of the nation's economy. Therefore, it is essential to design concrete structures for long service life. This requires the development of low-cost, advanced cement-based materials. To address this problem, a new breed of concrete called high-
performance concretes can be designed which may have high-quality, high-strength and high-durability.

This chapter briefly presented current innovations in the manufacture of constituent materials, microstructure of hydrated cement paste and concrete, testing of concrete, and advances in cement-based composite materials such as high-strength concrete, high-performance concrete, roller compacted concrete, high-volume fly ash concrete, fiber-reinforced concrete, controlled low strength material, self-compacting concrete, ultra-high strength concrete, conductive concrete, and self curing concrete. In order to produce durable concrete, various aspects of material production technologies for cement-based materials need to be optimized. These include constituent materials, mixture proportioning, mixing, handling, placing, compacting, curing, etc. All selected constituent materials such as cement, aggregate, mineral admixtures, and chemical admixtures should provide high-performance for individual applications.

In order to obtain better results, blended cementitious materials should be used instead of portland cements only. For obtaining performance in a wide range of conditions, blended cements should be composed of portland cement and other materials (fly ash, blast furnace slag, rice husk ash, silica fume, etc.). Due to environmental concerns, attempts are underway to manufacture blended cements without portland cement.

Several pozzolanic materials such as fly ash, ground granulated blast furnace slag, rice husk ash, silica fume, metakaolin, etc. have been used as a replacement of portland cement in cement-based materials. Use of these materials activates pozzolanic reaction in concrete.
Lightweight aggregates can be manufactured using fly ash, paper mill sludge, and sewage sludge individually or a combination of these products using either sintering or fusion processes.

Various chemical admixtures such as water reducing agents, accelerators, antifreezing agents, air-entraining, alkali-aggregate reaction inhibitors, corrosion inhibitors, and antiwashing agents are used to either allow placement of concrete under different and/or difficult conditions and/or to improve performance. Performance of hydrated cement paste can be used to assess concrete performance.

Recent developments in destructive testing of concrete include flexural fatigue testing, freezing and thawing durability, and fresh and hardened concrete properties determination of CLSM. Various non-destructive testing methods such as infrared thermography, ground penetrating radar, pulse-echo, impact-echo, etc. can be used in determining hidden flaws/anomalies in existing concrete structures.

High-strength concrete up to 70 MPa can be manufactured using conventional materials and manufacturing techniques. However, HSC is produced at low watertocementitious materials ratio. HSC (above 70 MPa) requires the use of special aggregates (small size, closely graded, high-strength), high-performance blended cements, special chemical admixture, and special care in mixing, handling, and placing. Extensive research is in progress to develop HPCs for use under a wide range of conditions. High-performance concrete offers several benefits over conventional concrete. In recent years, HPC has been used for the structures varying from pavements to skyscrapers where reliability of performance and long-service life are sought. Currently, roller compacted concrete is rapidly being used in the manufacture of dams and
roadways throughout the world, irrespective of design, purpose, construction details, size, etc. This is primarily due to favorable economics and faster placement of the material compared to conventional concrete. High-volume fly ash concrete with fly ash content in excess of 40% and up to 70% total cementitious materials can be manufactured for numerous applications.

Fiber-reinforced concrete can be proportioned and manufactured to improve both tensile strength and tensile strain capacity. To accomplish this, a large amounts of discontinuous fiber needs to be added. However, current technology for bulk concrete construction allows inclusion of fibers less than 2% by volume of concrete. More recent investigations have shown use of large amounts of fiber in cement-based composite is possible through the use of extrusion technology. But this technology cannot be used for bulk concrete construction.

Controlled low-strength materials are produced as a flowable slurry material. This material is primarily utilized for non-structural materials. Flowable slurry can be manufactured using fly ash, bottom ash, foundry sand, coarse aggregates. These materials are being used as backfill materials for utility trenches, surrounding pipes and manholes. It can be used as a fill material for abandoned tunnels, sewers, and underground cavities.

Self-compacting concrete overcomes the shortcomings relating durability and constructability etc., associated with conventional concrete. The acceptability of this concrete is increasing in all fields of application varying from precast to routine construction works. This concrete also provide better construction environment at site.

Ultra-high strength concrete/reactive powder concrete has very dense microstructure that gives superior durability compared to conventional high-strength concrete. The considerable
ductility, and high compressive strength and flexural strength provide designers with new possibilities. Such concrete has applicability in unreinforced prestressed structures.

Concrete with electrical conductivity properties may have important applications in the military and construction industry, especially for de-icing road from snow. Along with specially configured electrodes and an electrical power supply, it can be used to de-icing on roads, sidewalk, bridges, and runways.

Curing is one of the most important parameters for concrete durability and strength development. In practice, it is not possible to apply the same curing method to all concrete surfaces of the same structure. The development of self-curing concrete leads several advantages such as a better durable quality concrete surface, greater turnover, and a reduction in cost of operation etc.
REFERENCES


ACI Committee 229 (1994). "Controlled low-strength materials (CLSM)." *ACI Concrete International*, 16(5), 55-64.


International Conference on High-Performance Concrete, and Performance and Quality of Concrete Structures. Recife, Brazil, October, 1-4.


