

Center for By-Products Utilization

NEW MATERIALS AND CONCRETE PRODUCTS FOR THE NEXT MILLENNIUM

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Report No. CBU-1999-08

Report No. 364

August 1999

For presentation and publication at the "Concreto - '99: The Myths, Challenges, and Opportunities for the Next Millennium," IMCYC, Mexico City, Mexico, September 1999.

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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 is proportioned to have both high-strength and high-durability related properties. This is accomplished through the use of mixture proportioning, high-quality constituent materials, 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 40 to 60 MPa at a low water-to-cementitious materials ratio using conventional materials and production technology, with chemical admixtures. HPC above 60 MPa requires the use of special aggregates (small size, closely graded, high-strength aggregates), high-performance low heat of hydration cement, special chemical admixtures, and special care in mixing, handling, and placing.

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. This is accomplished using low water to cementitious 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.

This paper 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), high-quality concrete (HQC), roller compacted concrete, high-volume fly ash concrete, fiber-reinforced 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).

Cement is a gluing agent that is used to glue together coarse aggregate and sand to produce concrete. The United States consumes approximately 90 million tons of Portland cement annually. The manufacture of cement is quite energy intensive. 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 , etc. 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, etc.

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 first 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 show 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: kaolinitic clay calcined at 750°C , blast furnace slag, and alkali disilicate powder $(\text{Na}_2\text{K}_2)\text{H}_2\text{SiO}_2$. 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 (Na_2O equivalent) varying from 1.5 to 2.5% and the Blaine fineness ranging between 2100 and 3100 cm^2/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.

Table 1: Material Cost Estimates

Material	Unit Price (\$ / Ton)
Type I Portland Cement	80
Additive 1	25
Additive 2	25
Additive 3	10
Additive 4	0
Additive 5	0
Additive 6	65
Additive 7	800
Admixture 1	280
Admixture 2	100

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.

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 more dense, 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 (NaSO_4),
- (4) Gypsum (CaSO_4),
- (5) Calcium Chloride (CaCl_2),
- (6) Sodium Carbonate (Na_2CO_3), and
- (7) Sodium Silicate ($\text{Na}_2\text{O-SiO}_2$).

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 product generated due to combustion of coal. It is removed from the combustion gases by particulate collecting devices such as cyclone separators, electrostatic precipitators, fabric filters, or wet scrubbers. Most fly ash particles are spherical in shape, with particle sizes ranging from 1 to 150 μm ($1 \mu\text{m} = 0.001 \text{ mm} = 1 \times 10^{-6} \text{ m}$), with a specific gravity varying between 2.1 and 2.8. Fly ash is composed primarily of SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , and MgO .

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

Class N: Raw or calcined natural pozzoloans that comply with the applicable requirements for the class as given herein, such as some diatomaceous earths; opaline cherts and shales, tuffs 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 hardened 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.

Aimin and Sarkar (1991) investigated the influence of gypsum (CaSO_4) 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 m^2/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 . 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 varies between 5 and 10% of total cementitious materials. 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.

Wu et al. (1990) studied the activation of slag cements using sodium sulfate (Na_2SO_4), potassium aluminum sulfate ($\text{KAl}(\text{SO}_4)_2 \cdot 2\text{H}_2\text{O}$), 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 a 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 (Ca(OH)_2) and sodium sulfate (Na_2SO_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 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_2O and Na_2O are also present in RHA as impurities. The K_2O content varies between 1 and 5%. Other minor impurities (less than 1%) such as CaO , MgO , and P_2O_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.

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 effecting compressive strength (Mehta 1994b). Even small amounts of cement replacement (10 to 20%) with RHA causes 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.

2.2.5 METAKAOLIN

Metakaolin can be manufactured using pure clays, calcined under controlled temperature of 700 - 900°C. This material is analogous to other pozzolans. It consumes Ca(OH)_2 produced during hydration of portland cement to create cementitious C-S-H glue.

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.

Metakaolin can be used in manufacture of high-alkali blended cements (Davidovits 1994). These cements consisted of Kaolonite clay calcinated at 750°C, blast furnace slag, and alkali disilicate powder $(\text{Na}_2, \text{K}_2)\text{H}_2\text{SiO}_4$. 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 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^2), 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. (1997, 1998) have attained compressive strengths in the range of 100 MPa and higher using 19 mm maximum size aggregates.

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 effect 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, corrosion inhibitors, etc.

2.4.1 WATER REDUCER

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. Whereas 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 have 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.

Colleparidi 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 (Colleparidi 1994). Several other superplasticizers, as described by Ramachandran (1994) and Colleparidi (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 are 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, etc. 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 mixture 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 needs 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

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 (Colleparidi 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

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, etc., cannot be made at the present time.

2.4.6 CORROSION INHIBITORS

Corrosion inhibitors are chemical admixtures that can be added to concrete mixtures to prevent a rust forming reaction in the steel reinforcement. 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 $\text{Ca}(\text{NO}_2)_2$ and NA-molybdate have exhibited better results than $\text{Ca}(\text{NO}_2)_2$ alone. Research is in progress to develop admixtures that can act as accelerators as well as corrosion inhibitors.

2.4.7 ANTIWASH ADMIXTURES (AWA'S)

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 water soluble 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 dump sites 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

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. 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.

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

The hydrated cement paste 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 $\text{Ca}(\text{OH})_2$ 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 $\text{Ca}(\text{OH})_2$ 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 $\text{Ca}(\text{OH})_2$ 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 $\text{Ca}(\text{OH})_2$ 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).

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.

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).

Fig. 4 Various Models of the Interface Zone (Breton et al. 1993)

Recent investigations by Naik and his co-workers (Naik et al. 1995; Gilot 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 (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.

4.0 TESTING OF CONCRETE

Conventional practice of destructive and nondestructive testing is not discussed. 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).

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 condensation 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).

4.1 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 m 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 characteristics 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 are 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 surface waves. A relatively recent reference book by Malhotra and Carino (1991) provides detailed information about many nondestructive testing methods.

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 wave forms 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, Δt = round-trip travel time, and C_p is the speed of the P-wave (dilatational waves, commonly known 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,

Fig. 7 Schematic of pulse echo test technique (Malhotra and Carino 1991)

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 placed 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 Salsaloni and Carino (1986) led to the successful use of impact-echo method for flaw detection for thin concrete structures.

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:

$$D = C_p/2f$$

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.

5.0 CEMENT-BASED MATERIALS, THEIR PROPERTIES, AND APPLICATIONS

5.1 HIGH-STRENGTH CONCRETE (HSC)

Currently, concrete having compressive strength excess of 42 MPa is called high-strength concrete. 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 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

Fig. 9 Experimental arrangement for analysis of surface waves method (Malhotra and Carino 1991).

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)

High-performance concrete mixture proportions depends heavily upon individual applications. The general potential attributes of high-quality concrete (HQC) are given in Table1.

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

**Table 1: 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**

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.

5.3 ROLLER COMPACTED CONCRETES

Roller compacted concrete (RCC) is substantially different from that of conventional mass concrete placement for a dam. 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. These mixtures 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/m³ of cementitious materials. The practical limits for RCC mixtures by Schrader (1994) are shown in Table 2.

Table 2. Practical RCC Mixtures (Schrader 1994)

	Dry Low Paste		Wet High Paste	
	Kg/m ³	m ³	Kg/m ³	m ³
Cement	60	0.019	90	0.029
Pozzolan (Ash)	0	0.000	150	0.059
Water	110	0.110	105	0.105
Air	0	0.005	0	0.005
Fine Aggregates	165	0.066	0	0.000

Total Paste	335	0.200	345	0.198
% Paste	14%	20%	14%	20%

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).

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 at CANMET were composed of 150 kg/cm³ cement, 210 kg/m³ of Class F fly ash, 115 kg/m³ water, 1275 kg/m³ coarse aggregate (19 mm MSA), 620 kg/m³ fine aggregate, 720 mL/m³ air entraining admixtures, and 4 L/m³ 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 can 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).

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 compared to a 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 are 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.

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. The 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)

Fig. 10 Influence of Fiber Parameters on Tensile Behavior (Shah 1995).

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, etc. Additionally, it can be used as a fill material for abandoned tunnels, sewers, storage tanks, wells, abandoned utility vaults, voids under pavements, manholes, etc.

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, etc. 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 have 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, etc. were determined. Based on the results obtained, they reported that excavatable slurry can be manufactured using foundry sand as a replacement of fly ash up to 85%.

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 needs to be scientifically established. The constituent materials include cementitious materials, aggregates, mineral admixtures, chemical admixtures, etc.

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 effecting concrete properties. The effects 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 lingsulfate-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.

7.0 SUMMARY AND CONCLUSIONS

Numerous structures made in the past 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 have high-quality,

high-strength and high-durability.

This paper 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 and foundry-crete. 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 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 water to cementitious 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. 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 convention concrete. High-volume fly ash concrete with fly ash content in excess of 40%

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, 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, etc. These materials are being used as backfill materials for utility trenches, surrounding pipes and manholes, etc. It can be used as a fill material for abandoned tunnels, sewers, underground cavities, etc.

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