International Journal of Mechanical and Materials Engineering (IJMME), Vol. 4 (2009), No. 1, 9 - 18.

MATERIAL ASPECTS FOR HIGH-STRENGTH HIGH PERFORMANCE CONCRETE

Md. Safiuddin[1], M. N. Islam[2], M. F. M. Zain[2] and H. B. Mahmud[1]
[1]Department of Civil Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[2]Department of Architecture, Faculty of Engineering and Built Environment, National University of Malaysia,
43600 UKM Bangi, Selangor Darul Ehsan, Malaysia
E-mail: safiq@um.edu.my

ABSTRACT

The merits of high-strength high performance concrete (HSHPC) depend on the quality of constituent materials. The constituent materials play the vital roles to improve the performance of HSHPC. In particular, the use of supplementary cementing materials is essential when high strength and durability become the most critical issues to be considered for concretes. The addition of high-range water reducer and air-entraining admixtures are also inevitable to achieve good workability and freeze-thaw durability, respectively. This paper discusses various aspects of the major component materials of HSHPC. It briefly describes the property requirements of the component materials and emphasizes their contents or dosages needed for good performance. This paper also delineates the key roles of the constituent materials on the fresh and hardened properties, and durability of HSHPC.

Keywords: Aggregates; Air-entraining admixture; Cement; High-range water reducer; Supplementary cementing materials.

INTRODUCTION

The production of HSHPC needs more stringent control on materials selection than ordinary concrete to consistently meet the performance criteria for workability, strength, durability and other properties. Quality constituent materials should be selected in accordance with the standard specifications for the production of HSHPC. This is because the performance of high-strength high-performance concrete in both fresh and hardened states depends on the properties of the constituent materials and the roles they play when combined (Mehta and Aïtcin, 1990).

The selection criteria for the constituent materials of ordinary concrete may not be adequate in case of HSHPC. More control on the quality of constituent materials is needed and specifications require more enforcement to produce HSHPC (Kosmatka *et al*., 2002). The suitability of a material to produce HSHPC must be judged based on its effect on reaching maximum strength. Workability and durability are other very important issues that should also be considered carefully during material selection. Sometimes enough attention is not paid to material selection in ordinary concrete that originates many problems in production and quality control. However, it is not very critical in the case of ordinary concrete as in HSHPC. A key to the success in producing HSHPC is the proper selection of materials. A previous selection of materials can be critical for the optimum performance of concrete (Safiuddin, 1998). Therefore, a current and appropriate selection of constituent materials is necessary for the successful production and use of HSHPC.

HSHPC has been produced using a wide range of quality materials based on the results of trial mixtures (Safiuddin, 1998). This paper concisely describes some widely used constituent materials of HSHPC such as coarse and fine aggregates, cement and supplementary cementing materials, water, high-range water reducer and air-entraining admixture. In addition, this paper discusses various aspects of the constituent materials including their physical and chemical property requirements, and major roles in HSHPC.

COARSE AGGREGATES

Aggregates retained wholly on the 4.75-mm (No.4) sieve are defined as coarse aggregates (ASTM C 125-00a, 2002). They are granular materials usually used with fine aggregates to form the bulk of HSHPC. Coarse aggregates significantly influence the properties and durability of HSHPC. Therefore, the selection of coarse aggregates should be conducted carefully. In general, good quality coarse aggregates should be used to enhance the workability, strength, aggregate-matrix or interfacial bond and durability of HSHPC.

Physical Properties

Coarse aggregates should be strong, rough-textured, sound, non-porous, and non-reactive. Particularly, the soundness of coarse aggregate is vital to produce durable HSHPC. Coarse aggregates should be free from deleterious substances such as organic impurities, clay and silt, salts, and unsound fine particles to prohibit any adverse effects in hardened concrete. The physical property requirements for coarse aggregates given by the ASTM are shown in Table 1. Hard coarse aggregates should be used for HSHPC to contribute at least the strength of the cement gel. The aggregate size should also be decreased to achieve higher strength. This is because the size reduction process often eliminates internal defects in the aggregate such as large pores, micro-cracks and inclusions consisting of soft minerals.

In most cases, 10 mm or 12 mm is the preferable nominal maximum size of coarse aggregates for producing HSHPC. However, sufficiently strong coarse aggregates of 19 mm or 25 mm nominal maximum size can be used without adversely affecting the workability and strength of HSHPC (Mehta and Aïtcin, 1990).

Table 1 Physical property requirements of coarse aggregate (ASTM C 33-02a, 2002)

Property	Maximum allowable value (%)
Clay, lumps and friable particles content	3 – 10
Chert content	3 – 8
Coal and lignite	0.5 – 1
Material finer than 75-μm	1
Abrasion	50
Magnesium sulfate soundness	18

Coarse aggregates selected for HSHPC should have a low absorption value and a suitable shape coefficient. An absorption coefficient equal to or below 1% and a shape coefficient around or above 0.25 are good to improve the workability of concrete. Moreover, the coarse aggregates should comply with a Los Angeles coefficient equal to or below 15 and a crushing index equal to or below 15 to improve the strength of HSHPC (Gutiérrez and Cánovas, 1996).

Gradation

The gradation of coarse aggregate has significant effects on the workability of HSHPC. It is also important to obtain minimum voids and thus maximum density resulting in higher strength and greater durability of concrete. Furthermore, well-graded coarse aggregates require a minimum amount of mortar to fill in the voids. Consequently, the cement content becomes less and the shrinkage is reduced. Besides, the lower quantity of mortar reduces the extent of weak link for the ingress of deleterious agents into a mass of concrete, leading to enhanced durability. The ASTM gradation requirement for the coarse aggregates of most commonly used sizes is shown in Table 2.

Table 2 Gradation requirements for coarse aggregates (ASTM C 33-02a, 2002)

Sieve size	Mass passing (%)
25.0 mm	100
19.0 mm	90 – 100
12.5 mm	---
9.5 mm	20 – 55
4.75 mm (No.4)	0 – 10
2.36 mm (No.8)	0 – 5

Content

The proportion of coarse aggregate in mixture composition of HSHPC depends on the characteristics of fine aggregate, particularly on its fineness modulus (Kosmatka *et al*., 2002). It also depends on the maximum size and shape of the coarse aggregate (Kosmatka *et al*., 2002; Aïtcin, 1997a). The oven-dry basis content of the coarse aggregate required for HSHPC can be found from Table 3.

Table 3 Bulk volume of coarse aggregate per unit volume of concrete (Kosmatka *et al*., 2002)

Nominal maximum size of coarse aggregate (mm)	Bulk volume of dry-rodded coarse aggregate per unit volume of concrete for different fineness moduli of fine aggregate			
	FM♣ 2.40	FM 2.60	FM 2.80	FM 3.00
9.5	0.50	0.48	0.46	0.44
12.5	0.59	0.57	0.55	0.53
19.0	0.66	0.64	0.62	0.60
25.0	0.71	0.69	0.67	0.65
37.5	0.75	0.73	0.71	0.69
50.0	0.78	0.76	0.74	0.72
75.0	0.82	0.80	0.78	0.76
150.0	0.87	0.85	0.83	0.81

♣ Fineness modulus

The coarse aggregate content required for HSHPC can also be estimated based on Figure 1 as a function of the typical particle shape (Aïtcin, 1997a).

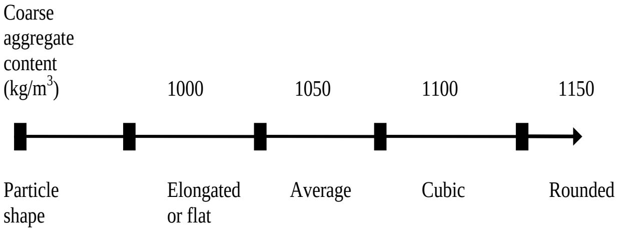

Figure 1 Coarse aggregate content on the basis of particle shape (Aïtcin, 1997a).

Key Roles

Coarse aggregates constitute a greater volume of the aggregate phase and form the skeleton for concrete. They disperse in mortar and provide surface area for bonding, and largely influence the strength of concrete. They reduce shrinkage and result in higher volume stability. Also, they significantly influence the workability of concrete. When well-graded, they also decrease porosity and increase density, and thus enhance the durability of concrete.

FINE AGGREGATES

Fine aggregates are defined as the aggregates passing the 9.5-mm sieve and almost entirely passing the 4.75-mm sieve and predominantly retained on the 75 μm sieve (ASTM C 125-00a, 2002). Sand is the most common form of fine aggregate that can be obtained naturally from pit, river, sea, and lake. Other materials such as quarry dust, rock fines, and surki can be used as fine aggregate.

Physical Properties

The physical properties of fine aggregates should be conducive to the performance of HSHPC. Fine aggregates should be sound, damp-free, low absorbent, and free from deleterious materials such as clay, silt, organic matter, shells, and salts to produce high-quality concrete. Their grains ought to be sharp and angular to enhance the strength and interfacial bond of concrete. However, the fine aggregates with a rounded particle shape and smooth surface texture require less mixing water, and therefore are conducive to improve the workability of concrete. The ASTM requirements for the key physical properties of fine aggregates are shown in Table 4.

Table 4 Physical property requirements for fine aggregates (ASTM C 33-02a, 2002)

Property	Maximum allowable value (%)
Clay, lumps and friable particles content	3
Coal and lignite content	0.5 – 1
Content of materials finer than 75-μm	3 – 5

Gradation

The gradation or size distribution of fine aggregates influences the performance of HSHPC. In general, the gradation has a significant effect on the workability and other properties such as porosity and shrinkage of concrete. Also, it influences the durability of concrete. The well-graded fine aggregates lessen the quantity of paste, which is the weak link in a mass of concrete. It also results in an increased economy as the quantity of cement is lowered for a given workability. Hence, the fine aggregates should be well-graded to produce HSHPC. The optimum gradation of fine aggregates is determined more by their effects on water requirement than on physical packing. The ASTM has set the requirements for fine aggregate grading, as shown in Table 5.

Table 5 Gradation requirements for fine aggregates (ASTM C 33-02a, 2002)

Sieve	Mass passing (%)
9.5 mm	100
4.74 mm (No.4)	95 – 100
2.36 mm (No.8)	80 – 100
1.18 mm (No.16)	50 – 85
600 μm (No.30)	25 – 60
300 μm (No.50)	5 – 30
150 μm (No.100)	0 – 10

Fine aggregate gradation is determined by sieve analysis. It introduces a parameter known as ‘fineness modulus’, which is a ready index of the coarseness or fineness of fine aggregates. The larger the index, the coarser is the fine aggregate. A fineness modulus between 2.5 and 3.2 is usually recommended for HSHPC to facilitate the workability of fresh mixture (Nawy, 1996). Lower values increase the water demand and thus decrease the workability of concrete. Fine aggregates with a fineness modulus of about 3.0 give the best workability and compressive strength (ACI 363R-92, 2005).

Content

Fine aggregate content is vital for HSHPC, as it influences the workability and strength of concrete. The fine aggregate content depends on the quantity of coarse aggregate present in concrete. It also depends upon the fineness modulus of fine aggregate. The fine aggregate content in HSHPC should be adequate to improve the cohesiveness of fresh concrete mixture with high workability (Safiuddin *et al.*, 2005). In general, the fine aggregate content of HSHPC ranges from 35 to 40% of the concrete volume (Safiuddin, 1998; Nawy, 1996).

Major Roles

Fine aggregates constitute a greater volume of concrete resulting in a reduction of cost. They subdivide the cement paste and thus offer more surface area for dispersion and adhesion of cementing materials. Moreover, they prevent excessive shrinkage and cracking in concrete during setting. They also help in the adjustment of strength of concrete by varying its proportion in mixture composition. If well-graded, the fine aggregates increase the density or unit weight of concrete. In addition, they contribute to improve the interfacial bond between coarse aggregates and mortar matrix.

CEMENT

Cement is an essential constituent of HSHPC. It hardens by interacting with water and forms hard water-resisting compound after final setting. Most widely used cement is portland cement. It is a hydraulic cement produced by pulverizing the clinker consisting essentially of hydraulic calcium silicates and usually containing one or more of the forms of calcium sulfate as an interground addition (ASTM C 150-02, 2002). There are mainly five types of portland cement. Among these, normal (ASTM Type I) portland cement is most common.

Physical Properties

The physical properties of cement affect the strength and durability of HSHPC. The specific gravity of normal portland cement ranges from 3.12 to 3.16 and it weighs about 1208 kg/m^3. Commercial cements meeting the ASTM standard specification for normal portland cement (ASTM C 150-02, 2002) differ considerably in fineness. The particle fineness of normal portland cement ranges from 10 microns to 50 microns (Nawy, 1996). The surface fineness of normal portland cement determined by the air permeability method usually varies from 250 to 400 m^2/kg (Neville, 1996). It influences the water requirement for a given workability. As the effect of cement fineness on water demand is more noticeable in HSHPC because of high cement content, the uniformity of cement should be maintained throughout the work. The Blaine fineness of normal portland cement should not vary by more than 375 cm^2/g (Safiuddin, 1998). The ASTM has also set forth the physical requirements for portland cement. The ASTM requirements for the physical properties of normal portland cement are shown in Table 6.

Table 6 Physical property requirements for normal portland cement (ASTM C 150-02, 2002)

Property	Requirement
Fineness (Specific surface)	≥ 160 m^2/kg if measured by turbidimeter test; ≥ 280 m^2/kg if measured by air permeability test
Autoclave expansion	Maximum 0.80%
Compressive strength	≥ 12 MPa at 3 days, ≥ 19 MPa at 7 days, ≥ 28 MPa at 28 days
Initial setting time	≥ 60 min if measured by Gillmore test; ≥ 45 min if measured by Vicat test
Final setting time	≤ 600 min if measured by Gillmore test; ≤ 375 min if measured by Vicat test

Chemical Composition

Portland cement is produced from calcareous materials such as limestone or chalk, and from argillaceous materials such as clay and shale. These raw materials are the sources of various oxide compounds. The major oxide components of normal portland cement are lime, silica and alumina. Lime and silica are the main oxide components that form calcium silicate hydrate (CSH) in presence of water, and thus contribute to strength development in concrete. The chemical composition of normal portland cement with typical ranges of mass content for various components is shown in Table 7. The ASTM has set forth the chemical requirements for various portland cements. The ASTM chemical requirements for normal portland cement are given in Table 8.

Table 7 Chemical composition of normal portland cement (Brandt, 1995)

Constituent	Mass content (%)
Lime (CaO)	58 – 66
Silica (SiO_2)	18 – 26
Alumina (Al_2O_3)	4 – 12
Iron (Fe_2O_3 and FeO)	1 – 6
Magnesia (MgO)	1 – 3
Sulfuric anhydrite (SO_3)	0.5 – 2.5
Alkalis (Na_2O and K_2O)	≤ 1.0

Content

The performance of concrete is a function of cement content. HSHPC generally contains more cement than ordinary concrete. Usually, the minimum cement content for ordinary concrete used in flatwork varies from 282 kg/m^3 to 366 kg/m^3 depending on the maximum size of aggregate (Kosmatka *et al.*, 2002). Conversely, the cement content more often ranges from 392 kg/m^3 to 557 kg/m^3 in HSHPC (ACI 363R-92, 2005; Taylor *et al.*, 1996). It is recommended that the cement content should be below 500 kg/m^3 in HSHPC (Gutiérrez and Cánovas, 1996). This will avoid excessive increase in brittleness and reduce the material cost of concrete. However, the cement content must be above the minimum value to ensure concrete durability.

Table 8 Chemical requirements for normal portland cement (ASTM C 150-02, 2002)

Property	Requirement
Magnesia content	≤ 6.0%
Sulfuric anhydrite content	≤ 3% when $C_3A^{\spadesuit}$ ≤ 8.0%, ≤ 3.5% when C_3A > 8.0%
Loss on ignition	≤ 3%
Insoluble residue	≤ 0.75%
Equivalent alkalis	≤ 0.6%

♠ Tricalcium aluminate

Key Roles

Cement reacts with water and forms binding products that bind the aggregates and offer strength and hardness to the concrete mass. It possesses good plasticity and assists to maintain good workability. In addition, cement contributes to produce a dense pore structure, and thus reduces the total porosity of concrete. The hydrated mass of cement also provides water tightness and makes the concrete impervious to deleterious agents.

SUPPLEMENTARY CEMENTING MATERIALS

Supplementary cementing materials are popular to produce HSHPC. They are finely divided materials, which contribute to the hardened properties of concrete through hydraulic or pozzolanic activity or both (CSA A23.5-98, 2001). Supplementary cementing materials can be obtained as industrial by-products such as silica fume, fly ash (Class C and Class F), and ground granulated blast-furnace slag or from agricultural wastes such as rice husk ash. In addition, some supplementary cementing materials can be obtained naturally such as volcanic tuff, pumicite, calcined clay and shale. Supplementary cementing materials can also be industrially manufactured such as high reactivity metakaolin. However, the most widely used supplementary cementing materials for HSHPC are obtained as industrial by-products. Silica fume is one of such elegant supplementary cementing materials. Fly ash and ground granulated blast-furnace slag have also been used successfully as a supplementary cementing material in the production of HSHPC (Sarkar, 1994; Poon *et al.*, 2000; Bakharev *et al.*, 2001). Moreover, metakaolin and rice husk ash have been used to produce HSHPC (Coldarone and Gruber, 1995; Mahmud *et al.*, 2005; Zhang and Malhotra, 1996).

Physical Properties

The ASTM and CSA have specified the physical requirements for natural and most common artificial supplementary cementing materials (CSA A23.5-98, 2001; ASTM C 618-03, 2003; ASTM C 989-99, 1999; ASTM C 1240-01, 2002). These requirements mainly provide the limits for the fineness, expansion or contraction, pozzolanic activity, uniformity, and reactivity of supplementary cementing material. Table 9 provides the key physical requirements for silica fume, which is commonly used in HSHPC.

Table 9 Physical requirements for silica fume (ASTM C 1240-01, 2002)

Property	Requirement
Percent retained on 45-μm sieve	≤ 10%
Accelerated pozzolanic activity index	≥ 85%
Specific surface	≥ 15 m^2/g

Chemical Properties

The ASTM and CSA have specified the chemical requirements for silica fume, fly ash (Class C and Class F), ground granulated blast-furnace slag, and most natural supplementary cementing materials (CSA A23.5-98, 2001; ASTM C 618-03, 2003; ASTM C 989-99, 1999; ASTM C 1240-01, 2002). These requirements mostly provide the limits for several chemical components and igneous loss. Table 10 lists the key chemical requirements for silica fume, which is used in many countries to produce HSHPC.

Table 10 Chemical requirements for silica fume (ASTM C 1240-01, 2002)

Property	Requirement
Silica content	≥ 85%
Moisture content	≤ 3%
Loss on ignition	≤ 6%
Alkalis as $Na_2O^{♥}$	≤ 1.5%

♥ Applicable when the aggregates are reactive

Content

The content of supplementary cementing materials in HSHPC varies depending on the type, purpose and benefits sought. For instance, the content of silica fume differs from 3% to 30% by weight of cement depending on the strength and durability requirements. However, the practical and economical optimum content of silica fume is chosen toward 10% to 15% due to high cost and workability problem encountered in fresh concrete (De Larrard and Malier, 1994). Similar contents are used in case of rice husk ash and high-reactivity metakaolin. In contrast, usually higher contents of fly ash and ground granulated blast-furnace slag are incorporated in HSHPC. Class C fly ash has been used with a content varying from 20 to 40% (Ellis, 1992) whereas the content of Class F fly ash is usually limited to 15% to 25% in HSHPC (Safiuddin and Zain, 2006). Furthermore, ground granulated blast-furnace slag has been incorporated in HSHPC mostly with a content in the range of 30% to 50% of cement by weight (Safiuddin and Zain, 2006).

Major Roles

Supplementary cementing materials influence the fresh and hardened properties and durability of HSHPC. They can produce positive or negative effects on the fresh properties. For example, fly ash reduces the water demand and thus improves the workability of concrete. In contrast, silica fume and rice husk ash increase the water demand due to lower particle size and excessive surface fineness, and thus decrease the concrete workability for a given water content (Safiuddin and Zain, 2006).

Most supplementary cementing materials contribute to increase the strength of HSHPC due to enhanced cementing efficiency resulting from secondary hydration or pozzolanic reaction (Safiuddin, 1998; Safiuddin and Zain, 2006). The pozzolanic reaction takes place between fine grains of supplementary cementing material and calcium hydroxide liberated during cement hydration, and thus results in more CSH gel that increases the strength of concrete. In addition, supplementary cementing materials physically act as a filler to decrease the average size of the pores in the matrix of HSHPC (Safiuddin and Zain, 2006). This is known as micro-filling, which also contributes to increase the strength of concrete due to dense microstructure.

Improvement of concrete durability is one of the major benefits offered by the supplementary cementing materials. They can produce HSHPC strongly resistant to aggressive environments. They minimize or eliminate the risk of corrosion, sulphate attack and alkali-silica reaction (Safiuddin and Zain, 2006; Hassan *et al.*, 2000; Malhotra, 1993). Supplementary cementing materials also result in similar or better freezing and thawing resistance in HSHPC as compared to ordinary concrete (Hassan *et al.*, 2000). Moreover, supplementary cementing materials impart higher acid resistance (Roy *et al.*, 2001). In fact, the micro-filling (physical) and pozzolanic (chemical) effects of supplementary cementing materials contribute to the densification of microstructure, particularly in the interfacial transition zone (ITZ) of HSHPC. Therefore, the porosity and transport properties of HSHPC greatly decrease that result in enhanced durability.

WATER

Water is the least expensive but most important component of HSHPC. The water to be used in mixing should be free of harmful impurities to produce good concrete. Mixing water having harmful ingredients, contaminants, silt, oil, sugar or chemicals is destructive to the strength and setting properties of cement. It can disrupt the affinity between aggregates and cement paste and may adversely affect the workability of concrete

(Nawy, 1996). The impurities of water may also cause staining on the surface of hardened concrete and lead to the corrosion of reinforcement. Therefore, the suitability of mixing water must be examined before use in HSHPC.

Quality

Mixing water should preferably be potable or clean, fresh and free of obvious contaminants. If water contains the substances, which cause unusual color and objectionable smell or taste, it should not be used unless service records indicate that it is not injurious to the quality of concrete. In general, any drinkable water having no test and odour is suitable to be used as mixing water for HSHPC. Water not fit for drinking may also be used satisfactorily. As a rule, any water with a pH of 6.0 to 8.0 and silt content below 2000 parts per million (ppm) is suitable for use in concretes (Neville and Brooks, 1999; Shetty, 2001). When the suitability of water is questionable, the mixing water should be tested to verify the acceptance criteria given in Table 11 prior to use in preparing concretes.

Table 11 Acceptance criteria for questionable mixing water (ASTM C 94/C 94M-00, 2002)

Property	Limit
7 days compressive strength	At least 90% of control
Setting time, maximum deviation from control	Initial: 1 h; Final: 1.5 h

Mixing water should not contain excessive solids, chlorides, alkalis, carbonates, bicarbonates, sulfates, and other salts, which are inferior to the quality of concrete. Water containing dissolved solids below 2000 ppm can generally be used satisfactorily for making concretes. Although dissolved solids exceeding 2000 ppm are not always harmful, they can adversely affect the hydration of certain cement (White, 1977). Therefore, water having more than 2000 ppm dissolved solids should be tested for its effect on strength and setting time. Water containing organic acids may also adversely affect the hydration of cement. Therefore, further testing is necessary in case of such water. In general, before use, the questionable mixing water is required to comply with the chemical requirements listed in Table 12.

Content

The quantity of mixing water should be sufficient to complete the chemical reactions with cement or binder and to fill up the gel-pores. It has been estimated that 23% water by weight of cement is required for chemical reactions and 15% water is necessary to occupy the space within gel-pores. Therefore, at least 38% water by weight of cement is essential for full hydration in concrete (Shetty, 2001). However, this amount can be reduced to 20% and even to 16% using high-range water reducers (Pliskin, 1994). In general, 20% to 40% water by weight of binder is used for HSHPC (Aïtcin, 1997b). A simplified approach based on the concept of saturation point, as shown in Figure 2, can be used to estimate the mixing water content for HSHPC. If the saturation point is not known, it is suggested to decide the water content through a number of trial mixtures starting with a water content of 145 l/m^3 (Aïtcin, 1997a). The minimum water content for HSHPC usually varies in the range of 120 to 165 l/m^3 (Aïtcin, 1997a; Aïtcin, 1998).

Table 12 Chemical requirements for questionable mixing water (Shetty, 2001; ASTM C 94/C 94M-00, 2002)

Chemical	Tolerable concentration (ppm)
Chloride as Cl^-	Prestressed concrete: 500; Other reinforced concrete: 1000
Sulfate as SO_4^{-2}	3000
Alkalis as Na_2O and K_2O	600
Sodium and potassium carbonates and bicarbonates	1000
Sodium sulfide	100
Total solids	50000
Organic acids	3000

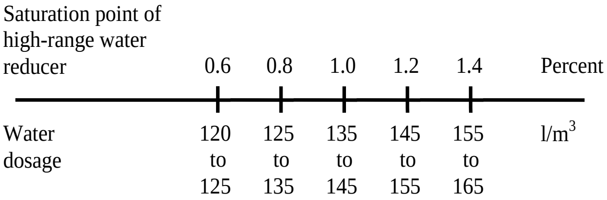

Figure 2 Determination of minimum water dosage (Aïtcin, 1997a)

Key Roles

Water performs physical and chemical functions in HSHPC. In physical function, water wets and lubricates the aggregates to achieve a good workability, whereas in chemical function it reacts with cement to produce hydration products. Sufficient water is required for the optimum hydration of cement and to maintain the required workability for easy placement (Owens, 1992). The hydration of cement can take place only in the presence of water. Reacting with water, the cement paste hardens and binds the aggregates, and thus provides sufficient strength and hardness to the concrete. Water also participates in pozzolanic reactions to produce secondary hydration products.

HIGH-RANGE WATER REDUCER

High-range water reducer (superplasticizer) has made a breakthrough in concrete industry. This is an essential component material for HSHPC. High-range water reducer provides a high degree of water reduction, and thus increases the workability of concrete. Depending on the type of admixture and the composition of concrete mixture, high-range water reducer can reduce the quantity of mixing water in the range of 12 to 45% (Safiuddin, 2008; ASTM C 494/C 494M-99a, 2002). It can easily change a zero-slump concrete to a highly flowing HSHPC with a slump greater than 200 mm (Zain *et al*., 1999).

There are four main categories of high-range water reducers or superplasticizers for HSHPC, as listed below (Neville, 1996; Mindess *et al*., 2003):

a. Melamine-based high-range water reducers
b. Naphthalene-based high-range water reducers
c. Modified lignosulfonates
d. Polycarboxylate-based high-range water reducer

Physical Properties

High-range water reducers are formulated to produce high plasticity, normal setting characteristic, and accelerated strength in concretes. They usually possess a viscosity in the range of 60 to 80 centipoise, but differ in solid content depending on the types (Aïtcin, 1998). The solid content can vary from 22 to 42% by weight. High-range water reducer is clear to dark brown in color when available in liquid form. The color of powder high-range water reducer is brownish. The specific gravity of high-range water reducer is near to that of water and therefore it can be easily dispersed with water. The ASTM has set forth the specific physical requirements for high-range water reducer, as given in Table 13. A high-range water reducer to be used in HSHPC should conform to these physical requirements for optimum performance.

Table 13 Physical requirements for high-range water reducers (ASTM C 494/C 494M-99a, 2002)

Property	Requirement
Water content	≤ 88% of control
Setting time, allowable deviation from control (h:min)	Initial: Not more than 1:00 earlier nor 1:30 later, Final: Not more than 1:00 earlier nor 1:30 later
28 days compressive strength	≥ 110% of control
28 days flexural strength	≥ 100% of control
Shrinkage	≤ 135% of control
Relative durability factor	≥ 80%

Chemical Structure

Naphthalene and melamine-based high-range water reducers are mostly used in the production of HSHPC. Naphthalene high-range water reducers are the sulfonated salts of polycondensate of naphthalene and formaldehyde. The raw materials for the naphthalene-based high-range water reducers are naphthalene, sulfuric acid and formaldehyde. On the other hand, melamine high-range water reducers are the sulfonated salts of polycondensate of melamine and formaldehyde. They are produced from the raw materials of melamine, sulfuric acid and formaldehyde. In both cases, the raw materials are chemically combined through the processes of sulfonation and polymerization to produce naphthalene and melamine high-range water reducers. The chemical structures of naphthalene and melamine high-range water reducers are shown in Figures 3 and 4, respectively.

Dosage

There is no straight forward way to determine the proper dosage of high-range water reducer for HSHPC. It greatly depends upon the materials characteristics and mixture composition of concrete, and on the compatibility of high-range water reducer with cement (binder). The dosage of liquid high-range water reducer for HSHPC generally varies from 5 to 20 l/m^3 (Aïtcin *et al*., 1994). Also, HSHPC of 200-mm slump can be obtained using high-range water reducer with a solid content dosage between 0.75 % and 1.50 % by weight of total binder (Aïtcin, 1994). A very high dosage of high-range water reducer might cause segregation and bleeding in fresh HSHPC, and may delay cement hydration. Therefore, the dosage of high-range water reducer should be chosen carefully.

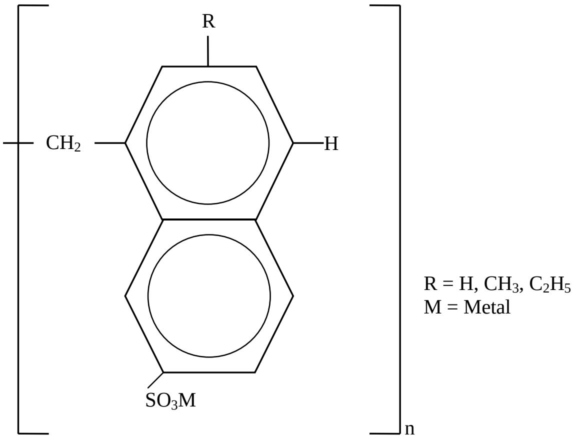

Figure 3 Chemical structure of naphthalene-based high-range water reducer (Rixom and Mailvaganam, 1999)

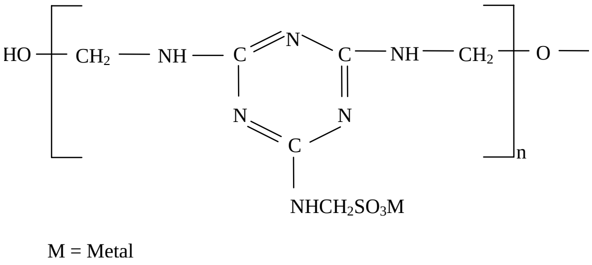

Figure 4 Chemical structure of melamine-based high-range water reducer (Rixom and Mailvaganam, 1999)

Major Roles

A high-range water reducer is generally added in HSHPC to improve its workability by liquefying and dispersing actions. High-range water reducers improve the workability of concrete by lowering the shear and flow resistance (liquefying action) (Faroug *et al*., 1999). Moreover, they hinder the coagulation of cement particles and disperse them more evenly, hence enhance the workability of concrete (dispersing action) (Aïtcin *et al*., 1994). Due to liquefying and dispersing actions, high-range water reducers can either increase the strength by lowering the quantity of mixing water for a given workability, or reduce both cement and water contents to achieve a given strength and workability. In addition, they contribute to denser packing and lower porosity in concrete by increasing the workability and by improving the hydration through greater dispersion of the cement particles. Consequently, the transport properties are reduced leading to a good durability.

AIR-ENTRAINING ADMIXTURE

Air-entraining admixture is a chemical agent, which serves the purpose of air entrainment in cement paste, mortar or concrete (Dodson, 1990). It is generally formulated from neutralized wood resins, fatty-acid salts, alkyl-aryl sulfonates, alkyl sulfates and phenol ethoxylates (Rixom and Mailvaganam, 1999). Air-entraining admixtures can be anionic, cationic and non-ionic. However, most of the modern air-entraining admixtures are anionic. The anionic air-entraining admixture imparts much better stability to the entrained air-voids.

Physical Properties

Air-entraining admixture is generally formulated in liquid form. The relative density of air-entraining admixture is closer to that of water. It is also soluble in water. Hence, the dispersion of air-entraining admixture in concrete is enhanced when used with the mixing water. Also, most air-entraining admixtures are not totally evaporable. They contain some solids. The solid content depends on the type of air-entraining admixture. It usually varies in the range of 5% to 20% by weight (Rixom and Mailvaganam, 1999). The air-entraining admixture intended for use in HSHPC must be compatible with other admixtures such as high-range water reducer. The ASTM has specified several physical requirements for air-entraining admixture, as given in Table 14, to ensure its good performance in concrete.

Chemical Properties

The chemical properties of air-entraining admixtures depend upon the raw materials from which they are made up. The commercially available air-entraining admixtures generally contain no chloride and possess a higher pH, thus do not promote corrosion of reinforcing steel in concrete. Also, they usually do not have any volatile organic compounds. Nevertheless, currently there is no ASTM standard specification for the chemical requirements of air-entraining admixture.

Dosage

A certain dosage of air-entraining admixture should be used to maintain an air content in the range of 4 to 7% for HSHPC, which will be exposed to freezing and thawing environment. HSHPC may require a higher dosage of air-entraining admixture than ordinary concrete to maintain a specified air content due to the presence of supplementary cementing material and high-range water reducer. However, very high dosage of air-entraining admixture is not beneficial for the strength and freeze-thaw durability of concrete. In general, the dosage of air-entraining admixture should not exceed 1 to 2% by weight of total cementing materials (Nawy, 1996). Excessive dosage will generate a large amount of air bubbles, which would make the concrete porous and reduce its strength and durability. Therefore, an optimum dosage of air-entraining admixture is desirable in HSHPC.

Table 14 Physical requirements for air-entraining admixtures (ASTM C 260-01, 2002)

Property	Requirement
Bleeding of the net amount of mixing water	≤ 2% of control
Setting time, allowable deviation from control (h:min)	Initial: Not more than 1:15 earlier nor 1:15 later, Final: Not more than 1:15 earlier nor 1:15 later
28 days compressive strength	≥ 90% of control
28 days flexural strength	≥ 90% of control
Shrinkage	≤ 120% of control
Relative durability factor	≥ 80%

Key Roles

The main function of air-entraining admixture is to protect hardened concrete from frost attack and repeated freezing and thawing (Neville, 1996). It incorporates millions of non-coalescing air-voids, which act like pressure-releasing valves to counteract freezing water, and thereby protect the hardened concrete from the damaging action of frost and freeze-thaw. The microscopic air-voids also act as ball-bearings, and thereby enhance the workability of concrete (Mindess *et al.*, 2003). Moreover, the air-voids induced by an air-entraining admixture assist to minimize segregation and subsequent bleeding in concrete by reducing the sedimentation rate of cement and aggregates, and thus decreasing the differential movement of water (Shetty, 2001).

CONCLUSIONS

The fresh and hardened properties and durability of HSHPC are greatly influenced by the constituent materials. Therefore, the component materials selected for producing HSHPC should conform to the specified physical and chemical requirements for optimum performance. Based on the technical review made in the present study, the following conclusions can be drawn:

(a) The physical characteristics and gradation of coarse and fine aggregates significantly influence the workability, strength, and durability of HSHPC.
(b) Cement assists to maintain a good workability in HSHPC. Also, it offers strength, hardness, and water tightness.
(c) Supplementary cementing materials may increase or decrease the workability of HSHPC depending on their physical characteristics such as particle size and surface fineness.

(d) Most supplementary cementing materials improve the hardened properties and durability of HSHPC due to their micro-filling and pozzolanic effects.
(e) Water lubricates the aggregates to achieve a good workability in HSHPC. In addition, water reacts with cement and participates in pozzolanic reactions to produce hydration products, which play a key role to improve the strength and durability.
(f) High-range water reducer significantly improves the workability of HSHPC due to its liquefying and dispersing actions. Moreover, it can enhance the strength and durability due to increased workability and improved hydration, and also because of reduced amount of mixing water.
(g) Air-entraining admixture improves the freeze-thaw durability and workability of HSHPC by inducing numerous microscopic air-voids.
(h) The contents or dosages of constituent materials for a mixture composition of HSHPC largely depend on their types and physical/chemical characteristics.

REFERENCES

ACI 363R-92, 2005. State-of-the-art report on high-strength concrete, ACI Manual of Concrete Practice, Part 5, American Concrete Institute, Michigan, USA.

Aïtcin, P.-C., 1994. The use of superplasticizer in high performance concrete, High Performance Concrete: From Material to Structure, E & FN Spon, London, UK, pp.14-33.

Aïtcin, P.-C., 1997a. Sherbrooke mix design method, In: Proceedings of the One-day Short Course on Concrete Technology/High Performance Concrete: Properties and Durability, Kuala Lumpur, Malaysia, 33pp.

Aïtcin, P.-C., 1997b. High strength concrete: current trends and applications, In: Proceedings of the Fifth International Conference on Concrete Engineering and Technology, Kuala Lumpur, Malaysia, pp. 37-46.

Aïtcin, P.-C., 1998. High Performance Concrete, 1st Edition, E & FN Spon, London, UK.

Aïtcin, P.-C., Jolicoeur, C., and MacGregor, J.G., 1994. Superplasticizers: how they work and why they occasionally don’t. Concrete International, Vol. 16, No. 5, pp. 45-52.

ASTM C 33-02a, 2002. Standard specification for concrete aggregates, Annual Book of ASTM Standards, Vol. 04.02, American Society for Testing and Materials, Philadelphia, USA.

ASTM C 94/C 94M-00, 2002. Standard specification for ready-mixed concrete, Annual Book of ASTM Standards, Vol. 04.02, Philadelphia, USA.

ASTM C 125-00a, 2002. Standard terminology relating to concrete and concrete aggregates, Annual Book of ASTM Standards, Vol. 04.02, American Society for Testing and Materials, Philadelphia, USA.

ASTM C 150-02, 2002. Standard specification for portland cement, Annual Book of ASTM Standards, Vol. 04.02, American Society for Testing and Materials, Philadelphia, USA.

ASTM C 260-01, 2002. Standard specification for air-entraining admixtures for concrete, Annual Book of ASTM Standards, Vol. 04.02, American Society for Testing and Materials, Philadelphia, USA.

ASTM C 494/C 494M-99a, 2002. Standard specification for chemical admixtures for concrete, Annual Book of ASTM Standards, Vol. 04.02, American Society for Testing and Materials, Philadelphia, USA.

ASTM C 618-03, 2003. Standard specification for coal fly ash and raw or calcined natural pozzolan for use as a mineral admixture in concrete, Annual Book of ASTM Standards, Vol. 04.02, Philadelphia, USA.

ASTM C 989-99, 1999. Standard specification for ground granulated blast-furnace slag for use in concrete and mortars, Annual Book of ASTM Standards, Vol. 04.02, Philadelphia, USA.

ASTM C 1240-01, 2002. Standard specification for use of silica fume as a mineral admixture in hydraulic-cement concrete, mortar and grout, Annual Book of ASTM Standards, Vol. 04.02, Philadelphia, USA.

Bakharev, T., Sanjayan, J.G., and Cheng,Y.-B., 2001. Resistance of alkali-activated slag concrete to alkali-aggregate reaction. Cement and Concrete Research, Vol. 31, No. 2, pp. 331-334.

Brandt, A.M., 1995. Cement-based Composites: Materials, Mechanical Properties, and Performance, E & FN Spon, London, UK.

Coldarone, M.A., and Gruber, K.A., 1995. High reactivity metakaolin – a mineral admixture for high performance concrete, In: Proceedings of the International Conference on Concrete under Severe Conditions, Sapporo, Japan, pp. 1015-1024.

CSA A23.5-98, 2001. Supplementary cementing materials, Canadian Standards Association, Etobicoke, Ontario, Canada.

De Larrard, F., and Malier, Y., 1994. Engineering properties of very high performance concretes, High Performance Concrete: From Material to Structure, 1st English Language Edition, E & FN Spon, London, UK, pp. 85-114.

Dodson, V.H., 1990. Concrete Admixtures, Van Nostrand Reinhold, New York, USA.

Ellis, W.E. 1992. For durable concrete, fly ash does not replace cement, Durable Concrete, ACI Compilation 24, American Concrete Institute, Michigan, USA, pp. 28-38.

Faroug, F., Szwabowski, J., and Wild, S., 1999. Influence of superplasticizers on workability of concrete. Journal of Materials in Civil Engineering, Vol. 11, No. 2, pp. 151-157.

Gutiérrez, P.A., and Cánovas, M.F., 1996. High-performance concrete: requirements for constituent materials and mix proportioning. ACI Materials Journal, Vol. 93, No. 3, pp. 233-241.

Hassan, K.E., Cabrera, J.G., and Maliehe, R.S., 2000. The effect of mineral admixtures on the properties of high-performance concrete. Cement and Concrete Composites, Vol. 22, No. 4, pp. 267-271.

Kosmatka, S.H., Kerkhoff, S.H.B., Panarese, W.C., MacLeod, N.F., and McGrath, R.J., 2002. Design and Control of Concrete Mixtures, 7th Canadian

Edition, Cement Association of Canada, Ottawa, Canada.

Mahmud, H.B., Majuar, E., Zain, M.F.M., and Hamid, N.B.A.A., 2005. Strength, durability, and shrinkage of high strength rice husk ash concrete, In: Proceedings of the 7th International Conference on Utilization of High Strength/High Performance Concrete, ACI SP-228, Vol. I, American Concrete Institute, Michigan, USA, pp.189-201.

Malhotra, V.M., 1993. Fly ash, slag, silica fume, and rice-husk ash in concrete: a review. Concrete International, Vol. 15, No. 4, pp. 23-28.

Mehta, P.K., and Aïtcin, P.-C. 1990. Microstructural basis of selection of materials and mix proportions for high strength concrete, In: Proceedings of the Second International Symposium on High Strength Concrete, Michigan, USA, pp. 265-282.

Mindess, S., Young, J.F., and Darwin, D. 2003. Concrete, Second Edition, Prentice Hall, New Jersey, USA.

Nawy, E.G., 1996. Fundamentals of High Strength High Performance Concrete, Longman Group Limited, London.

Neville, A.M., 1996. Properties of Concrete, Fourth Edition, John Wiley & Sons, Inc., New York, USA.

Neville, A.M., and Brooks, J.J., 1999. Concrete Technology, Addison-Wesley Longman, Inc., Essex, England, UK.

Owens, P.L., 1992. Water and its role in concrete, Durable Concrete, ACI Compilation 24, American Concrete Institute, Michigan, USA, pp. 28-38.

Pliskin, L., 1994. High performance concretes – engineering properties and code aspects, High Performance Concrete: From Material to Structure, E & FN Spon, London, pp. 186-195.

Poon, C.S., Lam, L., and Wong, Y.L., 2000. A study on high strength concrete prepared with large volumes of low calcium fly ash. Cement and Concrete Research, Vol. 30, No. 3, pp. 447-455.

Rixom, R., and Mailvaganam, N., 1999. Chemical Admixtures for Concrete, Third Edition, E & FN Spon, London, UK.

Roy, D.M., Arjunan, P., and Silsbee, M.R., 2001. Effect of silica fume, metakaolin, and low-calcium fly ash on chemical resistance of concrete. Cement and Concrete Research, Vol. 31, No. 12, pp. 1809-1813.

Safiuddin, M., 1998. Influence of Different Curing Methods on the Mechanical Properties and Durability of High Performance Concrete Exposed to Medium Temperature, M.Sc. Thesis, The National University of Malaysia, Bangi, Malaysia.

Safiuddin, M., 2008. Development of Self-consolidating High Performance Concrete Incorporating Rice Husk Ash, Ph.D. Thesis, University of Waterloo, Ontario, Canada.

Safiuddin, M., West, J.S., and Soudki, K.A., 2005. Self-consolidating high performance concrete incorporating rice husk ash, In: Proceedings of the 33rd Annual General Conference of the Canadian Society for Civil Engineering, Toronto, Canada, June, 10pp.

Safiuddin, M., and Zain, M.F.M., 2006. Supplementary cementing materials for high performance concrete. BRAC University Journal, Vol. 3, No. 2, pp. 47-57.

Sarkar, S.L., 1994. Roles of silica fume, slag, and fly ash in the development of high-performance concrete microstructure, In: Proceedings of the ACI International Conference on High Performance Concrete, Singapore, November, pp. 449-460.

Shetty, M.S., 2001. Concrete Technology: Theory and Practices, S. Chand and Company Ltd., New Delhi, India.

Taylor, M.R., Lydon, F.D., and Barr, B.I.G., 1996. Mix proportions for high strength concrete. Construction and Building Materials, Vol. 10, No. 6, pp. 445-450.

White, G.R., 1977. Concrete Technology, Delmar Publishers Inc., New York, USA.

Zain, M.F.M., Safiuddin, M., and Yusof, K.M., 1999. A study on the properties of freshly mixed high performance concrete. Cement and Concrete Research, Vol. 29, No. 9, pp. 1427-1432.

Zhang, M.-H., and Malhotra, V.M., 1996. High-performance concrete incorporating rice husk ash as a supplementary cementing material. ACI Materials Journal, Vol. 93, No. 6, pp. 629-636.