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Considerations in producing high strength concrete

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Abstract

A review of literature regarding the requirements of ingredient-materials for producing high strength concrete (HSC) along with the results of an experimental study on achieving HSC has been reported in this paper. Use of quality materials, smaller water-binder ratio, larger ratio of coarse aggregate (CA) to fine aggregate (FA), smaller size of coarse aggregate, and suitable admixtures with their optimum dosages are found necessary to produce HSC. In the experimental study, the targeted strengths of concretes were from 60 MPa to 130 MPa. A larger ratio of CA to FA (1.81 except one mix of 1.60) was considered in the study. While the variables considered were the water-binder ratio (from 0.34 to as low as 0.20) and the superplasticizer-binder ratio (from 0.73% to 2.95%). Test results are found to support the reviewed information on HSC production. Also the water-binder ratio and the suitable admixtures with their optimum dosages are found to be the most important parameters for producing HSC.

Keywords: Admixture, aggregates, high strength concrete, mix proportion, water-cement ratio.

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1. Introduction

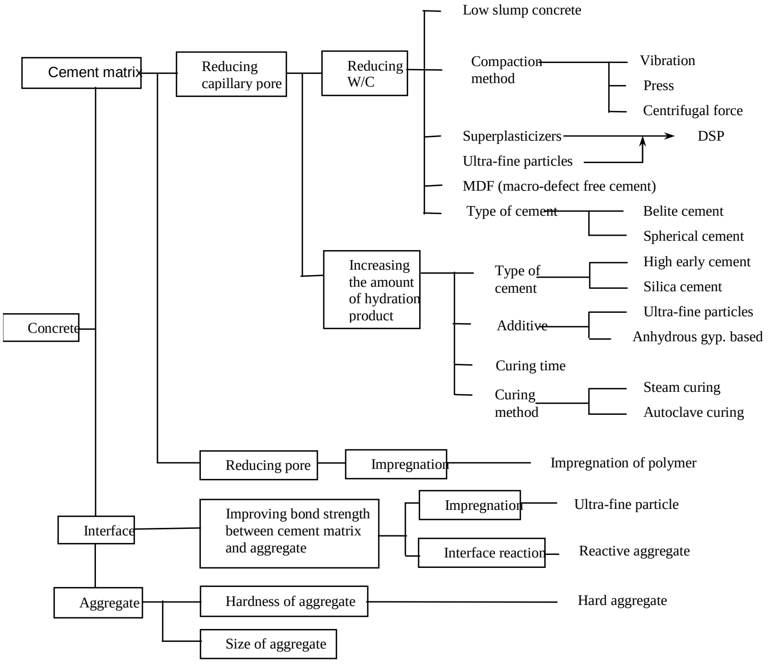
Concrete, a composite consisting of aggregates enclosed in a matrix of cement paste including possible pozzolans, has two major components – cement paste and aggregates. The strength of concrete depends upon the strength of these components, their deformation properties, and the adhesion between the paste and aggregate surface (Berntsson et al., 1990). With most natural aggregates, it is possible to make concretes up to 120 MPa compressive strength by improving the strength of the cement paste, which can be controlled through the choice of water-content ratio and type and dosage of admixtures (Mehta and Aitcin, 1990). However, with the recent advancement in concrete technology and the availability of various types of mineral and chemical admixtures, and special superplasticizer, concrete with a compressive strength of up to 100 MPa can now be produced commercially with an acceptable level of variability using ordinary aggregates (FIP/CEB, 1990). These developments have led to increased applications of high-strength concrete (HSC) all around the globe.

The bottom range of the strength of HSC varies with time and geographical location depending primarily on the availability of raw materials and technical know-how, and the demand from the industry. Concretes that were considered to be high strength 50 years ago are now regarded as low strength. For instance, concrete produced with compressive strength of 30 MPa was regarded as high strength in the 1950's. Gradually, concretes with compressive strength of 40-50 MPa in the 1960's, 60 MPa in the 1970's, and 100 MPa and beyond in the 1980's have evolved and used in practical structures. In spite of the rapid development in concrete technology in recent years, concrete with compressive strength higher than 40-60 MPa is still regarded as HSC. In the North American practice (ACI 318, 1999), high strength concretes are those that attain cylinder compressive strength of at least 41 MPa at 28 days. In the FIP/CIB (1990) state-of-the-art report on high strength concrete, it is defined as concrete having a 28-day cylinder compressive strength of 60 MPa.

HSC offers many advantages over conventional concrete. The high compressive strength can be advantageously used in compression members like columns and piles. Higher compressive strength of concrete results reduction in column size and increases available floor space. HSC can also be effectively used in structures such as domes, folded plates, shells and arches where large in-plane compressive stresses exist. The relatively higher compressive strength per unit volume, per unit weight will also reduce the overall dead load on foundation of a structure with HSC. Also, the inherent techniques of producing HSC generate a dense microstructure making ingress of deleterious chemicals from the environment into the concrete core difficult, thus enhancing the long-term durability and performance of the structure. Since the introduction of concrete with a compressive strength of 62 MPa in columns, shear walls and transfer girders of the Water Tower Place in Chicago in 1975, many applications of HSC in projects, ranging from transmission poles to the tallest building (KLCC Twin Tower in Kuala Lumpur, Malaysia) on earth, with concrete strength reaching up to 131 MPa in the Union Square building in Seattle, Washington have been reported. ACI 363 (1992), CEB-FIP (1994), FIP/CEB (1990) and Russell (1994) have summarized worldwide development and use of HSC to demonstrate its versatility and wide ranging application potentials.

Production of HSC may or may not require special materials, but it definitely requires materials of highest quality and their optimum proportions (Carrasquillo, 1985). The production of HSC that consistently meets requirements for workability and strength development places more stringent requirements on material selection than that for lower strength concrete (ACI 363R, 1992). However, many trial batches are often required to generate the data that enables the researchers and professionals to identify optimum mix proportions for HSC. Practical examples of mix proportions of HSC used in structures already built can also be the useful information in achieving HSC. The various techniques of producing HSC, as summarized by Nagataki and Sakai (1994), are presented in Fig. 1.

In this paper eight numbers of trial mixes have been considered, following the reviewed information, in order to achieve concretes with compressive strengths from 60 MPa to as high as 130 MPa. The information obtained from literature as well as the results of experimental work described herein will be beneficial to researchers and engineers dealing with HSC.



(Note: DSP = Densified Systems of homogeneously arranged ultra-fine Particles)

Fig. 1. Various techniques for achieving high strength concrete (Nagataki and Sakai, 1994)

2. Ingredient materials for high strength concrete

2.1 Cement

Strength development of concrete will depend on both cement characteristic and cement content. The choice of Portland cement for HSC is extremely important. Unless high initial strength is the objective, such as in prestressed concrete, there is no need to use a Type-III cement. When the temperature rise is expected to be a problem, a Type-II low-heat-of-hydration cement can be used, provided it meets the strength-producing requirements (ACI 363R, 1992).

For HSC containing no chemical admixture or fly ash, a high cement content of 8 to 10 sacks/cu. yd. must be used. The optimum cement content depends on cement type: 10 sacks/cu. yd. for Type-I cement and 9.25 sacks/cu. yd. for Type-II cement (Peterman and Carrasquillo, 1986).

2.2 Water and water-cement ratio

The single most important variable in achieving HSC is the water-cement ratio (Peterman and Carrasquillo, 1986). HSC produced by conventional mixing technologies are usually prepared with water-cement ratios in the range of 0.22 to 0.40, and their 28 days compressive strength is about 60 to 130 MPa when normal density aggregates are used (FIP/CEB, 1990). The requirements for water quality for HSC are no more stringent than those for conventional concrete. Usually, water for concrete is specified to be of potable quality (ACI 363R, 1992).

2.3 Aggregates

The properties of the aggregate are decisive for the compressive strength and modulus of elasticity of HSC. In normal strength concrete (NSC), the aggregate has a higher strength and stiffness than the cement paste. Failures in NSC are characterized by fractures in the cement paste and in the transition zone between paste and aggregate. Reduced water-cement ratio, therefore, causes a great improvement in compressive strength of cement paste and hence of concrete.

2.3.1 Coarse aggregate

In HSC the capacity of the aggregate can be the limiting factor. This may be either the result of the aggregate being weaker than the low water-cement matrix, or alternatively it is not sufficiently strong and rigid to provide the strengthening effect. This is mainly related to the coarse aggregate (CA). For optimum compressive strength with high cement content and low water-cement ratios the maximum size of CA should be kept to a minimum, at ½ in. or 3/8 in. The strength increases were caused by the reduction in average bond stress due to the increased surface area of the individual aggregate. Smaller aggregate sizes are also considered to produce higher concrete strengths because of less severe concentrations of stress around the particles, which are caused by differences between the elastic moduli of the paste and the aggregate. Many studies have shown that crushed stone produces higher strengths than rounded gravel. The most likely reason for this is the greater mechanical bond, which can develop with angular particles. However, accentuated angularity is to be avoided because of the attendant high water requirement and reduced workability. The ideal CA should be clean, cubical, angular, 100% crushed aggregate with a minimum of flat and elongated particles (ACI 363R, 1992).

Among the different crushed aggregates that have been studied – traprock, quartzite, limestone, greywacke, granite, and crushed gravel – traprock tends to produce the highest concrete strength. Limestone, however, produces concrete strengths nearly as high as those achieved using traprock. Gradation of CA within ASTM limits makes very little difference in strength of HSC. Optimum strength and workability of HSC are attained with a ratio of CA to FA above that usually recommended for NSC. Also, due to the already high fines content of HSC mixes, use of ordinary amounts of CA results in a sticky mix (Peterman and Carrasquillo, 1986).

2.3.2 Fine aggregate

Fine aggregates (FA) with a rounded particle shape and smooth texture have been found to require less mixing water in concrete and for this reason are preferable in HSC. HSC typically contain such high contents of fine cementitious materials that the grading of the FA used is relatively unimportant. However, it is sometimes helpful to increase the fineness modulus (FM) as the lower FM of FA can give the concrete a sticky consistency (i.e. making concrete difficult to compact) and less workable fresh concrete with a greater water demand. Therefore, sand with a FM of about 3.0 is usually preferred for HSC (ACI 363R, 1992).

2.4 Admixtures

Admixtures are widely used in the production of HSC. These materials include air-entraining agents and chemical and mineral admixtures. Significant increases in compressive strength, control of rate of hardening, accelerated strength gain, improved workability, and durability are contributions that can be expected from the admixture or admixtures chosen. Reliable performance on previous work should be considered during the selection process.

2.4.1 Chemical admixtures

Chemical admixtures such as superplasticizers (high–range water reducer) increase concrete strength by reducing the mixing water requirement for a constant slump, and by dispersing cement particles, with or without a change in mixing water content, permitting more efficient hydration. The main consideration when using superplasticizers in concrete are the high fines requirements for cohesiveness of the mix and rapid slump loss. Neither is harmful for the production of HSC. HSC mixes generally have more than sufficient fines due to high cement contents. The use of retarders, together with high doses and redoses of superplasticizers at the plant or at the job site can improve strength while restoring slump to its initial amount. Even a superplasticized mix that appears stiff and difficult to consolidate is very responsive to applied vibration (Peterman and Carrasquillo, 1986).

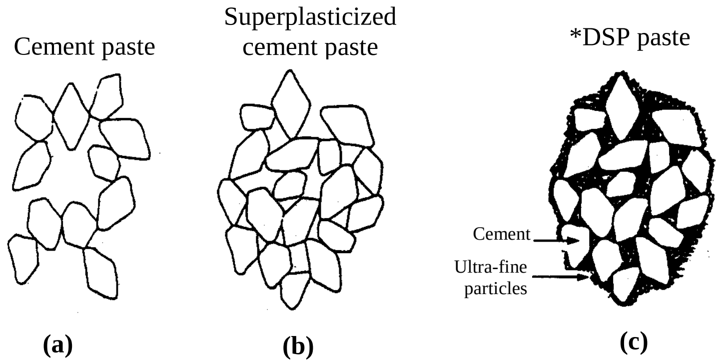
2.4.2 Mineral admixtures

Finely divided mineral admixtures, consisting mainly of fly ash and silica fume (SF), and slag cement has been widely used in HSC. Fly ash for HSC is classified into two classes. Class F fly ash is normally produced from burning anthracite or bituminous coal and has pozzolanic properties, but little or no cementitious properties. Class C fly ash is normally produced from burning lignite or sub-bituminous coal, and in addition to having pozzolanic properties, has some autogenous cementitious properties (ACI 363R, 1992). When adding fly ash during concrete production, the workability is normally improved due to the ‘lubricating’ effect of the spherical particles (FIP/CEB, 1990).

Silica fume (SF) is a by-product of the melting process used to produce silicon metal and ferrosilicon alloys. The main characteristics of SF are its high content of amorphous SiO_2 ranging from 85 to 98%, mean particle size of 0.1 – 0.2 micron (approximately 100 times smaller than the average cement particle) and its spherical shape. Because of its extreme fineness and high silica content, SF is a highly effective pozzolanic material. The SF reacts pozzolanically with the lime during the hydration of cement to form the stable cementitious compound calcium silicate hydrate (CSH). Normal SF content ranges from 5 to 15 percent of Portland cement (ACI 363R, 1992). The use of SF as replacement of a part of the cement gives considerable strength gain. For most binder combinations, the use of SF is the only way of producing concrete of normal workability with a strength level exceeding 80 MPa. To ensure a proper dispersion of the ultra-fine SF particles, plasticizers should be used in these mixtures (FIP/CEB, 1990).

3. Basic considerations for the mix design of high strength concrete

The mechanical properties of the concrete can be improved by obtaining a denser packing of the solids. The paste-aggregate bond can also be improved. The first effect might be explained by so-called ‘DSP-concrete’ (Densified Systems containing homogeneously arranged ultra-fine Particles) (Fig. 2). Larger amounts of silica fume (SF) (more than 10% of the cement weight) are used to ‘refine’ the particle structure and thereby reduce the total pore volume and the average pore size. The size and spherical geometry of SF particles allow them to fill effectively the voids between the larger and angular cement grains. Extreme dosages of dispersing agents are used to overcome the surface tensions, permitting dense particle packing. Very low water demand is obtained and, thus, pastes of very low water-cement ratios can be produced. The SF eventually also contributes to the formation of CSH-gel through pozzolanic reactions, causing a denser and more homogeneous gel structure.



(*DSP – Densified Systems containing homogeneously arranged ultra-fine Particles)

Fig. 2. The structure of the cement paste in fresh concrete (FIP/CEB, 1990)

A dense cementitious matrix is not sufficient by itself to obtain HSC since the aggregate-matrix bond may not be strong enough. In NSC the interfacial zone is often a weak link, since it tends to be more porous and heterogeneous than the bulk paste matrix. The addition of SF can drastically change the microstructure of the paste at the interface, causing it to be as dense as that of the matrix. This provides a much more efficient bond between the aggregate and the matrix. This effect of SF is associated with its ability to pack densely at the aggregate surface, as well as to reduce the internal bleeding of the concrete. Due to these interfacial effects, the aggregates in high strength silica fume concrete are becoming active load-bearing components in the concrete, contributing to the overall strength, and not just inert mechanical fillers as in NSC. Therefore, the pillars of practical mix design for HSC are:

(i) Reduced water-cement ratio.
(ii) Extensive use of plasticizers.
(iii) Application of cement with a high strength potential.
(iv) Application of pozzolans and in particular SF.

4. Requirements of ingredients for high strength concrete

From the preceding discussions on information found from literature, the necessary requirement of different ingredient materials required for producing HSC can be summarized as stated in Table 1.

5. Practical examples of selected HSC mixes

Mixture proportioning is more critical for high strength concrete than for normal strength concrete. Usually, specially selected pozzolanic and chemical admixtures are employed, and attainment of a low water to cementitious materials ratio is considered essential (ACI Committee 211, 1993). Table 2 shows the amount of different ingredients of concretes used for few structures already built along with few laboratory tests as reported by Mehta and Aitcin (1990).

As a supporting part of author’s research work (Rashid, 2002), efforts were made to achieve HSCs in the lab, by trial mix proportioning, for the strength range starting from 60 MPa to as high as 130 MPa. Following the requirements of HSC as described in Table 1, the guidelines of ACI Committee 211 (1993) and the suggestions of Mehta and Aitcin (1990), a total of eight numbers of mix proportions were selected (Table 3). Common materials used were ASTM Type-I cement, locally available sand with fineness modulus of 2.80, crushed granite of 10 mm maximum size, and potable water. The admixtures used were condensed silica fume and DARACEM-100 (superplasticizer). Coarse aggregates of all mixes except those of Mix-6 were washed with water before 24 hour of their use in concrete casting. For each mix a numbers of cylinders were cast in steel molds and were compacted using table vibrator. The cylinders were demolded on the following day and were moist-cured (using water fog) for 21 days. Then the concrete cylinders were kept in air-dry condition in the laboratory prior to testing. Table 3 describes the quantities of different ingredients, their ratios either by weight or by volume, and the 28-day compressive strengths as obtained by testing 100×200 mm cylinders. Test results are seen to be in agreement with the reviewed information from literature.

Table 1
Requirements of ingredient-materials for high strength concrete

Material / issue	Requirements
Cement	- Portland cement - Higher content (8 to 10 sacks per cu. yd. of concrete)
Water	- Potable quality - w/b ratio 0.22 to 0.40
Fine aggregate	- Sand with rounded particle shape - Higher FM (around 3.0) - Smaller sand content or coarser sand - Grading is not critical for concrete strength
Coarse aggregate	- Smaller maximum size (10 – 12 mm) is preferred - Angular and crushed with a minimum flat and elongated particles - Type of aggregate depending on the concrete strength targeted - Gradation within ASTM limits has little effect on concrete strength - Higher CA/FA ratio than that for normal strength concrete
Admixtures (chemical & mineral)	- Type of admixture depends on the property of the concrete to be improved - Reliable performance on previous work can be considered during selection - Optimum dosage
Overall basic considerations	- Quality materials - Improved quality of cement paste as well as aggregates - Denser packing of aggregates and cement paste - Improved bond between aggregate surface and cement paste - Minimum numbers as well as smaller sizes of voids in the paste

Table 2
Mix proportions for selected HSC mixtures (Mehta and Aitcin, 1990)

Sl. No.	Description of concrete	*Strength, MPa	Component materials in 1-m^3 concrete batch, kg/m^3								#SP, L/m^3	w/b ratio by wt.
			Cementitious material					Water	Fine agg.	Coarse agg.		
			Cement	Fly ash	BFS	CSF	Total					
1	Water Tower Place, Chicago	65	500	60	---	---	560	178	608	1068	--$^{@}$	0.32
2	Commerce Tower, Houston	65	390	100	---	---	490	161	575	1141	--$^{@}$	0.33
3	Int. First Plaza, Dallas	80	360	150	---	---	510	148	603	1157	3$^{@}$	0.29
4	Nova Scotia Plaza, Toronto	82	315	---	135	36	486	145	745	1130	6	0.30
5	Expt. column, Montreal	90	500	---	---	30	530	135	700	1100	15	0.25
6		70	485	---	---	---	485	130	762	1143	3.4	0.27
7		72	317	---	167	---	484	133	749	1145	7.0	0.28
8		80	315	---	155	35	505	143	744	1142	7.5	0.29
9	Laboratory mixture	82	449	---	---	39	488	130	758	1149	11.0	0.27
10		91	427	---	---	59	486	132	754	1139	14.9	0.27
11		100	486	---	---	54	540	135	661	1112	20	0.25
12		107	517	---	---	58	575	126	641	1126	25	0.22

*Average compressive strength at 28-day.

#Superplasticizer

@Concrete Nos. 1 and 2 contained only a normal water-reducing admixture; Concrete No. 3 also contained a normal water-reducing admixture in addition to a superplasticizer.

Table 3
Trial quantities/mix proportions of ingredients for HSC (Rashid, 2002)

Sl. No.	Mix number	*Comp. strength, MPa	Component materials in 1-m^3 concrete batch, kg/m^3						**Super-plasticizer liter/m^3	W/B ratio (by wt.)	SP/B ratio (by wt.) %	CA/FA ratio (by vol.)	FA/TA ratio (by vol.)
			Cementitious material (Binder)			FA	CA	Water					
			OPC	CSF	Total								
1	Mix – 1	53.9	467	---	467	667	1067	160	---	0.34	---	1.60	0.39
2	Mix – 2	63.9	550	---	550	620	1120	181	3.33	0.33	0.73	1.81	0.36
3	Mix – 3	78.5		---				171	4.17	0.31	0.91		
4	Mix – 4	88.8		60	610			152	15.00	0.25	2.95		
5	Mix – 5	110.7						134	14.58	0.22	2.87		
6	Mix – 6	111.0						122	15.00	0.20	2.95		
7	Mix – 7	125.0						122	13.33	0.20	2.62		
8	Mix – 8	127.1						122	10.00	0.20	1.97		

*Average compressive strength (f'_c) at 28-day obtained by testing 100×200 mm cylinder.
** “Daracem 100” has been used as superplasticizer

6. Conclusions

HSC that consistently meets requirements for workability and strength development places more stringent requirements on material selection than that for lower strength concrete. Therefore, the production of HSC may or may not require the special materials, but it definitely requires materials of highest quality and their optimum proportions. In the production of HSC, use of strong, sound and clean aggregates is essential. The basic trick then lies in reducing the capillary pores in the matrix and improving the bond strength between cement matrix and aggregate. These can be accomplished by using low water-cement ratio and incorporating ultra-fine particles (particles much smaller than the grains of cement, such as silica fume) in the concrete mix, but not at the expense of workability necessary to achieve adequate compaction. The requirements of ingredient materials and the basic considerations in producing HSC are described in Table 1.

High strength concrete with compressive strength as high as 127 MPa can be obtained using OPC and the naturally available coarse aggregate. However, use of lower water-cement ratio along with superplasticizer is the most vital factor to be considered in HSC productions.

7. Acknowledgment

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Abbreviations

BFS = Blast furnance slag
CA = Coarse aggregate
CSF = Condensed silica fume
CSH = Calcium silicate hydrate
FA = Fine aggregate
FM = Fineness modulus
HSC = High strength concrete
NSC = Normal strength concrete
OPC = Ordinary portland cement
SP = Superplasticizer
TA = Total aggregate
W/B = Water to binder (cement+silica fume)