HIGH STRENGTH CONCRETE

(HSC)

THE RESEARCH

SUBMITTED BY

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Contents

١- Introduction

When considering high strength concrete (HSC) we must first define what we mean by ‘high strength’. The perception of what level of compressive strength constitutes ‘high strength’ which has been continually revised upwards over the past ٢٠ years and may well continue to rise in the near future. ‘The definition of high strength changes over the years as concrete strength used in the field. In this seminar I consider high-strength concrete (HSC) to have a strength significantly beyond what is used in normal practice. For example, today about ٩٠% of ready mixed concrete has a ٢٨-day specified compressive strength ranging from ٢٠ MPa (٣٠٠٠ psi) to ٤٠ MPa (٦٠٠٠ psi), with most of it between ٢٨ MPa (٤٠٠٠ psi) and ٣٥ MPa (٥٠٠٠ psi). Therefore for the purposes of this seminar, concrete with a characteristic concrete (cube) strength greater than ٨٠ MPa or at least ٧٠ MPa (١٠,٠٠٠ psi) will be considered as ‘high strength concrete’. We can also recognize that the definition of high-strength concrete varies on a geographical basis. In regions where concrete with a compressive strength of ٦٢ MPa (٩٠٠٠ psi)is already being produced commercially, high-strength concrete might be in the range of ٨٣ to ١٠٣ MPa (١٢,٠٠٠ to ١٥,٠٠٠ Psi)compressive strength. However, in regions where the upper limit on commercially available material is currently ٣٤ MPa (٥٠٠٠ Psi) concrete, ٦٢ MPa (٩٠٠٠ Psi) concrete is considered high strength. High-strength concrete is used for reduced weight, creep,or permeability; for improved durability; or where architectural considerations require smaller load carrying elements. The Two Union Square building in Seattle has the highest strength concrete used ina major building almost ١٤٠ MPa(٢٠,٠٠٠ psi) in the columns. In this case, high strengthwas needed to minimize creep. In other high-rise buildings, high-strength concrete helps achieve moreefficient floor plans through smaller vertical members. Furthermore we are concerned here with essentially conventional type concretes that can be used with currently accepted construction techniques and not more specialized cement-based materials such as reactive powder concretes (RPC) or heavily fibre reinforced concretes. It should be noted that there is an increasing tendency to consider the two terms ‘high strength’ and ‘high performance’ as being synonymous. In the my view, however, high strength concrete is only one of the extensive possible range of high performance concretes (which could include high workability concretes, lightweight concretes or even concretes with enhanced durability) and the two terms should be kept separate. The remainder of this seminar considers high strength concrete alone.

٢-Historical background

Although high-strength concrete is often considered a relatively new material, its development has been gradual over many years. As the development has continued, the definition of high-strength concrete has changed. In the ١٩٥٠s, concrete with a compressive strength of ٥٠٠٠ psi(٣٤ MPa) was considered high strength. In the ١٩٦٠s,concrete with ٦٠٠٠ and ٧٥٠٠ psi (٤١ and ٥٢ MPa) compressive strengths were used commercially. In the early١٩٧٠s, ٩٠٠٠ psi (٦٢ MPa) concrete was being produced.More recently, compressive strengths approaching ٢٠,٠٠٠psi (١٣٨ MPa) have been used in cast-in-place buildings.For many years, concrete with compressive strength inexcess of ٦٠٠٠ psi (٤١ MPa) was available at only a fewlocations. However, in recent years, the applications ofhigh-strength concrete have increased, and high-strengthconcrete has now been used in many parts of the world.The growth has been possible as a result of recent developments in material technology and a demand forhigher-strength concrete increase. The construction of Chicago'sWater Tower Place and ٣١١ South Wacker Drive concrete buildings would not have been possible without thedevelopment of high-strength concrete. The use of concrete superstructures in long span cable-stayed bridgessuch as East Huntington, W.V., and bridge over the OhioRiver would not have taken place without the availabilityof high-strength concrete.

٣-Objectives

١. To discuss the materials technology underlying the development of high strength concrete, examine the selection of optimum constituent materials and consider the concrete mix design.

٢. To discussthe properties of both fresh and hardened high strength concrete, high lighting any particular differences in behavior compared to more conventional concretes.

٣. To discuss, the production and use of high strength concrete on-site, illustrated by examples worldwide, will be examined.

٤. To understand both of the potential benefits and limitations of high strength concrete, together with the expertise required to produce and use the material in a practical and effective manner.

٤- Materials technology of HSC

In order to achieve high compressive strength, it is important to understand the factors that govern the strength of concrete, i.e.:-

- The properties of the cement paste.
- The properties of the transition zone between the paste and the aggregate.
- The properties of the aggregate.
- The relative proportions of the constituent materials.

All these factors must be optimized in order to make significant increases in compressive strength. Throughout this seminar the term ‘cement’ will be used to describe all the cementitious materials in the concrete and not just Portland cement alone.

٤.١- Paste properties

In conventional concrete technology, the strength of the paste is a function of its water/cement ratio. This is true also for high strength concrete but it is also the effect of the porosity within the paste, the particle size distribution of the crystalline phases and the presence of in homogeneities within the hydrated paste that must be considered in detail .A reduction in water/cement ratio will produce a paste in which the cementitious particles are initially closer together in the freshly mixed concrete .This results in less capillary porosity in the hardened paste and hence a greater strength. This reduced capillary porosity also favors the formation of fine-textured hydration products that have a higher strength than the coarser equivalents. The capillary porosity can also be reduced by optimizing the particle size distribution of the cementitious materials in order to increase the potential packing density. Special high strength cements are available and the inclusion of finely divided reactive materials such as silica fume will also contribute to an increase in packing density and reduced capillary porosity. It should be noted that even commercially available high strength concretes have free water/cement ratios as low as ٠.٢٢. This is well below the theoretical minimum for full cement hydration. However, the hydration of the cementitious particles within the paste is sufficient to ‘glue’ together the unhydrated cores of the particles and to reduce the interstitial porosity between these hydrated particles. The role of superplasticizers in enabling workable concretes to be produced at very low water/cement ratios (and without the need for excessively high cement contents) is critical. Furthermore the effect of superplasticizers in preventing the flocculation of Portland cement particles and distributing material such as silica fume homogeneously through the freshly mixed concrete leads to a reduction in inhomogeneities within the paste and hence improved paste strength. The strength of the paste will be limited by the flaws that form the weakest link, be they inhomogeneities or capillary pores. In order to improve the strength of the paste as a whole, all such flaws must be minimized.

٤.٢- Transition zone properties

When fracture surfaces of failed conventional concretes are examined, it is often observed that the failure has occurred, either with the paste itself or, more often, at the interface between the paste and the coarse aggregate particles. Whilst it is possible to increase the strength of the paste significantly as described above, if the transition zone to the aggregate is weak, the strength of the concrete will not increase commensurately. In conventional (say, ٤٠ MPa) concretes, this transition zone is quite large and is characterized by a high porosity and large crystalline hydration products (such as Portlandite($Ca(OH)_٢$). Reducing the water/paste ratio and the incorporation of silica fume into the concrete both contribute to reducing the width and improving the strength of the transition zone. The rapid conversion of $Ca(OH)_٢$ to CSH(Calcium silicate hydrate) by silica fume is thought to be of particular importance. Reduced bleeding within the paste also reduces the potential for accumulation of water around aggregate particles.

٤.٣- Aggregate properties

When the transition zone between the paste and the aggregate is improved the transfer of stresses from the paste to the aggregate particles becomes more effective. Consequently the mechanical properties of the aggregate particles themselves may be the ‘weakest link’ leading to limitation of achievable concrete strength. Fracture surfaces in HSC often pass through aggregate particles rather than around them. Crushed rock aggregates are generally preferred to smooth gravels as there is some evidence that the strength of the transition zone is weakened by smooth aggregates. The aggregate should have a high intrinsic strength and granites, basalts and limestone's have been used successfully, as have crushed glacial gravels. During the crushing process, aggregate particles may be severely microcracked .The number of microcracks will be greater in larger particles, consequently it is common practice to use smaller particles (١٠–١٤ mm nominal size) for high strength concrete (Mehta and Aitcin, ١٩٩٠a). It is assumed that small aggregate particles will contain less internal flaws and hence produce a higher concrete strength. It must be stressed that the selection of appropriate sources of aggregate is much more critical for high strength concrete than for conventional concretes.

٥- Materials selection and mix design

It should be recognized that there is no single or unique composition for high strength concrete. HSC can be made with a range of materials and mix designs which will produce slightly differing properties.The production of high-strength concrete that consistently meets requirements for workability and strengthdevelopment places more stringent requirements onmaterial selection than for lower strength concretes.Quality materials are needed and specifications requireenforcement. High-strength concrete has been producedusing a wide range of quality materials based on the results of trial mixtures. This part from the seminar cites the state of knowledge regarding material selection and provides abaseline for the subsequent discussion of mix proportions.

٥.١-Materials selection

٥.١.١- Cements

HSC can be produced with most available Portland cements, but those cements that are particularly coarsely ground are usually unsuitable. Special cements have been developed for HSC in Norway which are more finely ground and with lower tricalciumaluminates (C٣A) content (***tricalcium aluminate (C٣A)***: liberates a large amount of heat duringthe first few days of hydration and hardening. It also contributes slightlyto early strength development. Cements with low percentages of C٣Aare more resistant to soils and waters containing sulfates) but elsewhere normal commercial products are generally employed.Silica fume is almost ubiquitous in HSC as it has approximately three times the cementing efficiency (on a weight for weight basis) as Portland cement. This facilitates the achievement of high strength without excessive cement contents. Silica fume is available in Europe (and elsewhere) both in the form of a water-based slurry and as a densified powder. To be effective it should always be used in conjunction with a superplasticizer. It is usually incorporated into concrete at ٥–١٥ per cent by weight of total binder. PFA and GGBS have also been used successfully together with Portland cement and silica fume, albeit at lower levels than in conventional structural concrete. The reasons for use include improvements in pumping performance and reducing in heat evolution. The use of metakaolin (a highly reactive pozzolan) has also been proposed for HSC although not yet used very extensively. As different sources of cementitious materials may interact with different efficiency, trials to establish the optimum combination and sources of materials may often be required. All cements should comply with appropriate national or international standards.

٥.١.١.١- Portland cements

Portland cement (Figure ٥.١) is indisputably the most widely used bindingmaterial in the manufacture of hydraulic-cement concrete. Selecting Portlandcements having the chemical and physical properties suitable for use in high-strength concrete is one of the most important, but frequently underestimatedconsiderations in the process of selecting appropriate materials for high-strength concrete. Cements should be selected based on careful consideration of all performance requirements, not just strength. To avoid interaction related problems, the compatibility of the cement with chemical admixturesand other cementing materials should be confirmed. Concrete producersexperienced in making high-strength concrete know firsthand how criticallyimportant cement selection can be, and those inexperienced can learn in very hard, expensive ways. In the end, the benefits of the time and resources devoted to material verification testing will considerably outweighthe cost.The performance of cement can vary widely when attempting to makehigh-strength concrete. Selecting appropriate cementing materials is themost important first step in the successful manufacture of high-strengthconcrete.

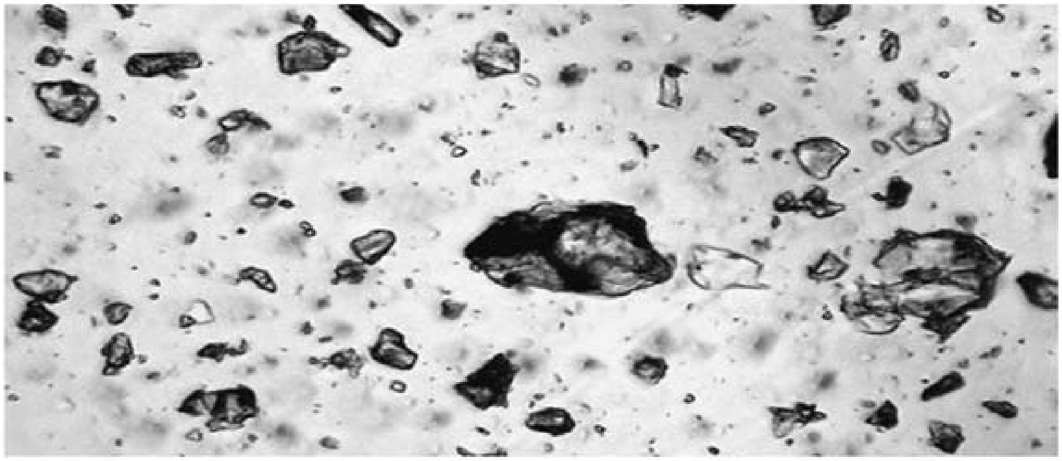


Figure 5.1 Micrograph of Type I Portland cement. Field of view is 400 μm wide. Courtesy of Portland Cement Association.

٥.١.٢- Admixtures

The role of admixtures is much more significant in HSC than for more conventional concretes .To produce workable concretes at very low levels of water/cement ratios (typically below ٠.٣٠), without needing unacceptably high cement content, requires the use of superplasticiszers.Melamine-based, naphthalene-based and polycarboxylate ether-based superplasticizers have been used successfully, either individually or in combination. The dosage rates of the superplasticizers can be very high (up to ٣ per cent by weight of cement) in order to achieve the required workability. It should be noted that there is generally a saturation dosage of superplasticizers above which no further increase in workability will occur.

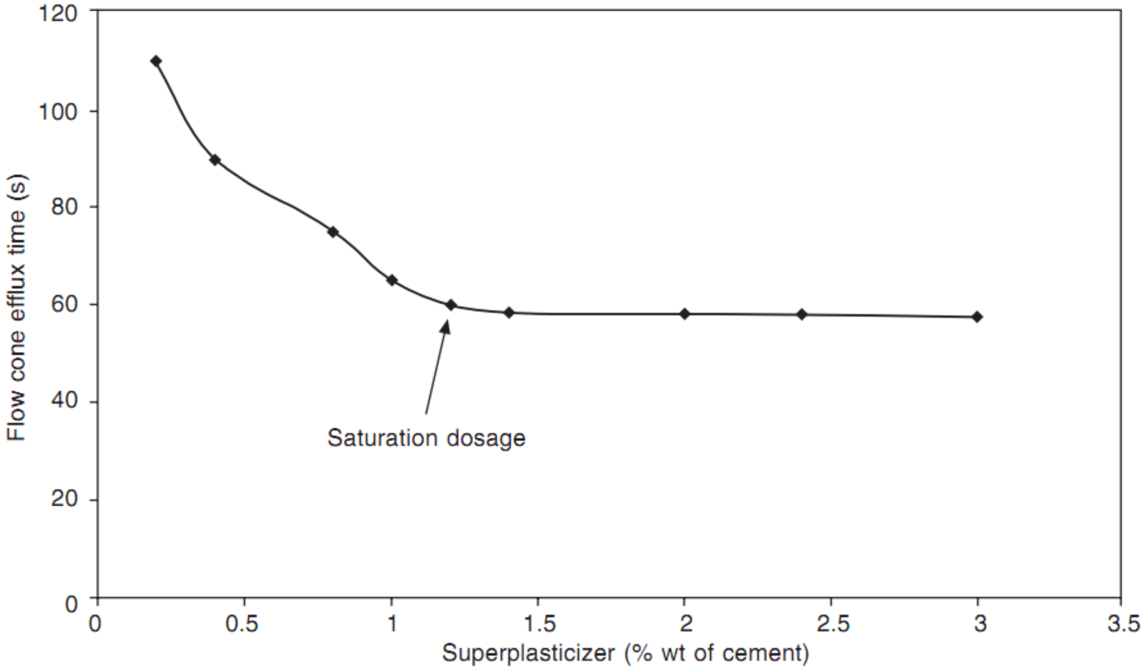


Figure ٥.٢.١Idealized effect of superplasticizer dosage on flow cone efflux time (at constant w/c ratio).

This can easily be determined by the use of a flow cone. The efflux time is measured at the same free water/cement ratio for a series of admixture dose rates. This will enable the maximum effective level of admixture addition (i.e. minimum efflux time) to be identified (see Figure ٥.٢).

Lignosulphonate-based plasticizers may also be combined with melamine superplasticizers in order to extend their workability retention. Compatibility between different admixtures used in combination as well as compatibility between admixturesand different cement types, must be considered when materials are selected (again flowcone tests may be useful).

We have two type of admixture:-

١) Chemical admixtures
   a) Air-entraining admixtures.
   b) Retarders.
   c) Normal-setting water reducers (plasticizer).
   d) High-range water reducers (superplasticizer).
   e) Accelerators
٢) Mineral admixtures and slag cement
   a) Fly ash.
   b) Silica fume.
   c) Slag cement.
   d) Metalaolin

The specification of various type of admixture according to (ASTM ٤٩٤-B٢) see table ٥.٢.١ and the list of commercial plasticizer and superplasticizer manufactured in India see table ٥.٢.٢.

٥.١.٢.١ Chemical admixtures

٥.١.٢.١.١ General

Admixtures are widely used in the production of high-strength concretes. These materials include air-entraining agents and chemical and mineraladmixtures. Air-entraining agents are generally surfactants that will develop an air-void system appropriate fordurability enhancement. Chemical admixtures are generally produced using lignosulfonates, hydroxylated carboxylic acids, carbohydrates, melamine and naphthalenecondensates, and organic and inorganic accelerators invarious formulations. Selection of type, brand, and dosage rate of all admixtures should be based on performance with the other materials being considered orselected for use on the project. Significant increases incompressive strength, control of rate of hardening, accelerated strength gain, improved workability, and durability are contributions that can be expected from theadmixture or admixtures chosen. Reliable performanceon previous work should be considered during the selection process.

٥.١.٢.١.٢ Air-entraining admixtures

(ASTM C ٢٦٠)theuse of air entrainment is recommended to enhance durability when concrete will be subjected to freezing and thawing while wet. As compressive strengths increase anwater-cement ratios decrease, air-void parameters improve and entrained air percentages can be set at the lower limits of the acceptable range as given in **ACI ٢٠١**Entrained air has the effect of reducing strength, particularly in high-strength mixtures, and for that reason has been used only where there is a concern for durability.

٥.١.٢.١.٣ Retarders

(ASTM C ٤٩٤, Types B and D) high-strength concrete mix designs incorporate high cement factors that are not common to normal commercial concrete. A retarder is an admixture that slows down the chemical process of hydration so that concrete remains plastic and workable for a longer time than concrete without retarder. The addition of water to retemper the mixture will result in marked strength reduction. Further, structural design frequently requires heavy reinforcing steel and complicated forming with attendant difficult placement of the concrete. A retarder can control the rate of hardening in the forms to eliminate cold joints and provide more flexibility in placement schedules. Projects have used retarders successfully by initially designing mixtures with sufficient retarder dosage to give the desirable rate of hardening under the anticipated temperature conditions. Since retarders frequently provide an increase in strength that will be proportional to the dosage rate, mixtures can be designed at different doses if it is expected that significantly different rates will be used. However, there is usually an offsetting effect that minimizes the variations in strengths due to temperature. As temperature increases, later age strengths will decline; however, an increase in retarder dosage to control the rate of hardening will provide some mitigation of the temperature-induced reduction. Conversely, dosages should be decreased as temperatures decline. While providing initial retardation, strengths at ٢٤ hours and later are usually increased by normal dosages. Extended retardation or cool temperatures may affect early (٢٤-hour) strengths adversely.

٥.١.٢.١.٤Normal-setting water reducers (plasticizers)

(ASTM C ٤٩٤, Type A) conventional water-reducing admixtures will provide strengthincreases without altering rates of hardening. Theirselection should be based on strength performance. Increases in dosage above the normal amounts will generally increase strengths, but may extend setting times.When admixtures are used in this fashion to provide retardation, a benefit in strength performance sometimesresults.

٥.١.٢.١.٥ High-range water reducers (super plasticizers)

(ASTM C ٤٩٤, Types F and G) High-range water reduction provideshigh-strength performance, particularly at early (٢٤-hour)ages. They are chemically different from normal plasticizer. Use of super plasticizers permit the reduction of the water to the extent upto ٣٠ per cent without reducing workability in contrast to the possible reduction up to ١٥ per cent in case of plasticizers. The use of super plasticizer is practiced for production of flowing, self leveling, self compacting and for production of high strength concrete and high performance concrete. It is the use of super plasticizer which has made it possible to use w/c as low as ٠.٢٥ or even lower and yet to make flowing concrete to obtain strength of order ١٢٠ Mpa or more. it is the use of super plasticizer which has made it possible to use fly-ash, slag and particularly silica fume to make high performance concrete. The slump loss characteristics of a high-range water reducer (HRWR) will determine whether it should be added at the plant (factory), the site,or a combination of each.Use of a HRWR in high-strength concrete may servethe purpose of increasing strength at the slump or increasing slump. The method of addition should distributethe admixture throughout the concrete. Adequate mixingis critical to uniform performance. Supervision is important to the successful use of a HRWR. The use ofsuper plasticizers is discussed further in **ACI SP-٦٨**.

٥.١.٢.١.٦ Accelerators

(ASTM C ٤٩٤, Types C and E) accelerating admixture are add to concrete to increase the rate of early strength development in concrete to

- Permit earlier removal of frame work.
- Reduce the required period of curing.
- Advance the time that a structure can be placed in service.
- Partially compensate for the retarding effect of low temperature during cold weather concreting.
- In the emergency repair work.

Accelerators are not normally used in high-strength concrete unless early form removal is critical. High-strengthconcrete mixtures can provide strengths adequate for vertical form removal on walls and columns at an early age.Accelerators used to increase the rate of hardening willnormally be counterproductive in long term strength development.

٥.١.٢.١.٧ Admixture combinations

Combinations of high-range water reducers with normal-setting water reducersor retarders have become common to achieve optimumperformance at lowest cost. Improvements in strengthgain and control of setting times and workability arepossible with optimized combinations. In certain circumstances, combinations of normal-setting or retardingwater-reducing admixtures plus an accelerating admixturehave also been found to be useful.When using a combination of admixtures, they shouldbe dispensed individually in a manner approved by themanufacturer(s). Air-entraining admixtures should, ifused, be dispensed separately from water-reducing admixtures.

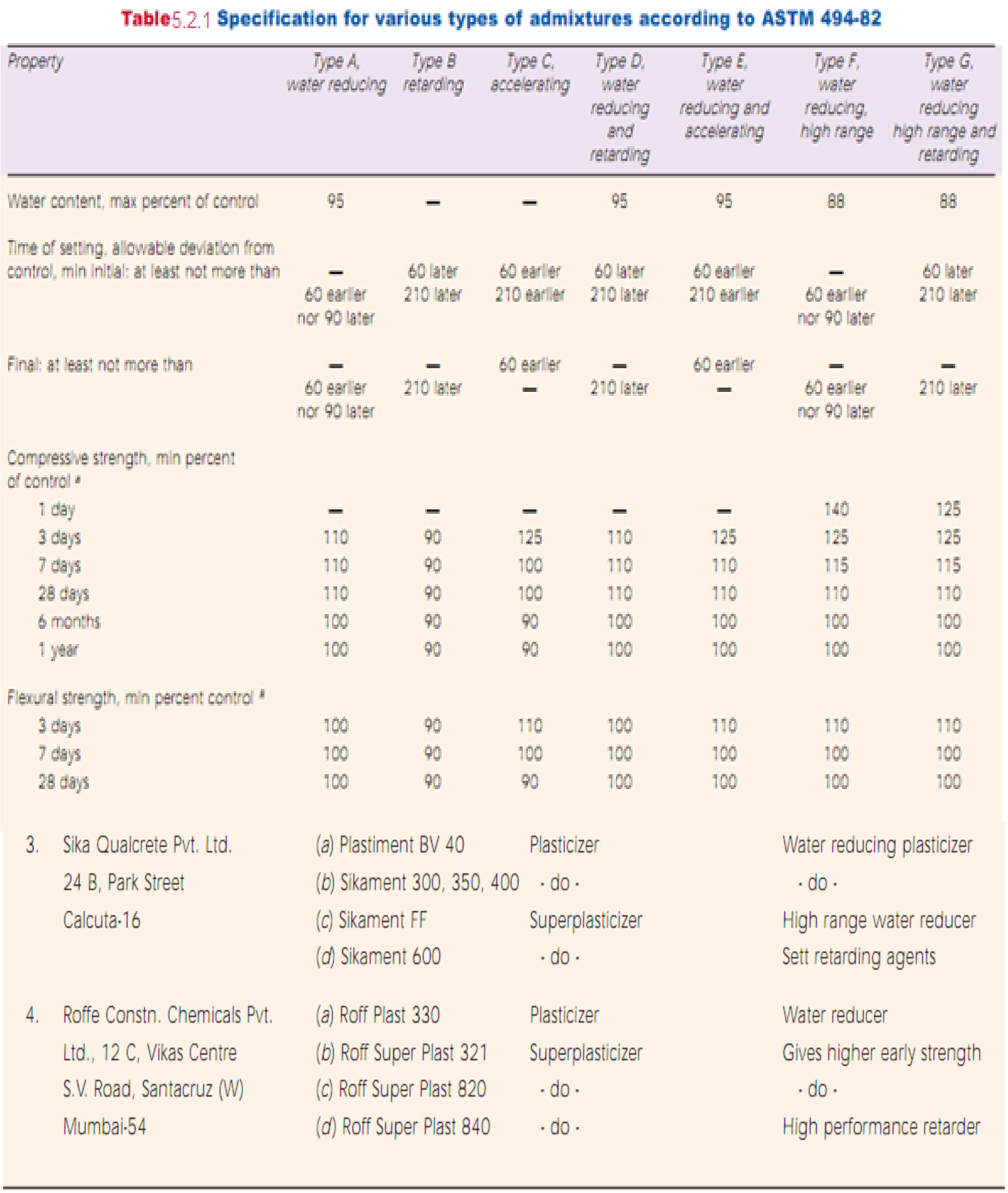


Table5.2.1 Specification for various types of admixtures according to ASTM 494-82

Property	*Type A, water reducing*	*Type B retarding*	*Type C, accelerating*	*Type D, water reducing and retarding*	*Type E, water reducing and accelerating*	*Type F, water reducing, high range*	*Type G, water reducing high range and retarding*
Water content, max percent of control	95	—	—	95	95	88	88
Time of setting, allowable deviation from control, min Initial: at least not more than	— 60 earlier nor 90 later	60 later 210 later	60 earlier 210 earlier	60 later 210 later	60 earlier 210 earlier	— 60 earlier nor 90 later	60 later 210 later
Final: at least not more than	— 60 earlier nor 90 later	— 210 later	60 earlier —	— 210 later	60 earlier —	— 60 earlier nor 90 later	— 210 later
Compressive strength, min percent of control *							
1 day	—	—	—	—	—	140	125
3 days	110	90	125	110	125	125	125
7 days	110	90	100	110	110	115	115
28 days	110	90	100	110	110	110	110
6 months	100	90	90	100	100	100	100
1 year	100	90	90	100	100	100	100
Flexural strength, min percent control *							
3 days	100	90	110	100	110	110	110
7 days	100	90	100	100	100	100	100
28 days	100	90	90	100	100	100	100

3.	Sika Qualcrete Pvt. Ltd.	(*a*) Plastiment BV 40	Plasticizer	Water reducing plasticizer
	24 B, Park Street	(*b*) Sikament 300, 350, 400	- do -	- do -
	Calcuta-16	(*c*) Sikament FF	Superplasticizer	High range water reducer
		(*d*) Sikament 600	- do -	Sett retarding agents
4.	Roffe Constn. Chemicals Pvt.	(*a*) Roff Plast 330	Plasticizer	Water reducer
	Ltd., 12 C, Vikas Centre	(*b*) Roff Super Plast 321	Superplasticizer	Gives higher early strength
	S.V. Road, Santacruz (W)	(*c*) Roff Super Plast 820	- do -	- do -
	Mumbai-54	(*d*) Roff Super Plast 840	- do -	High performance retarder

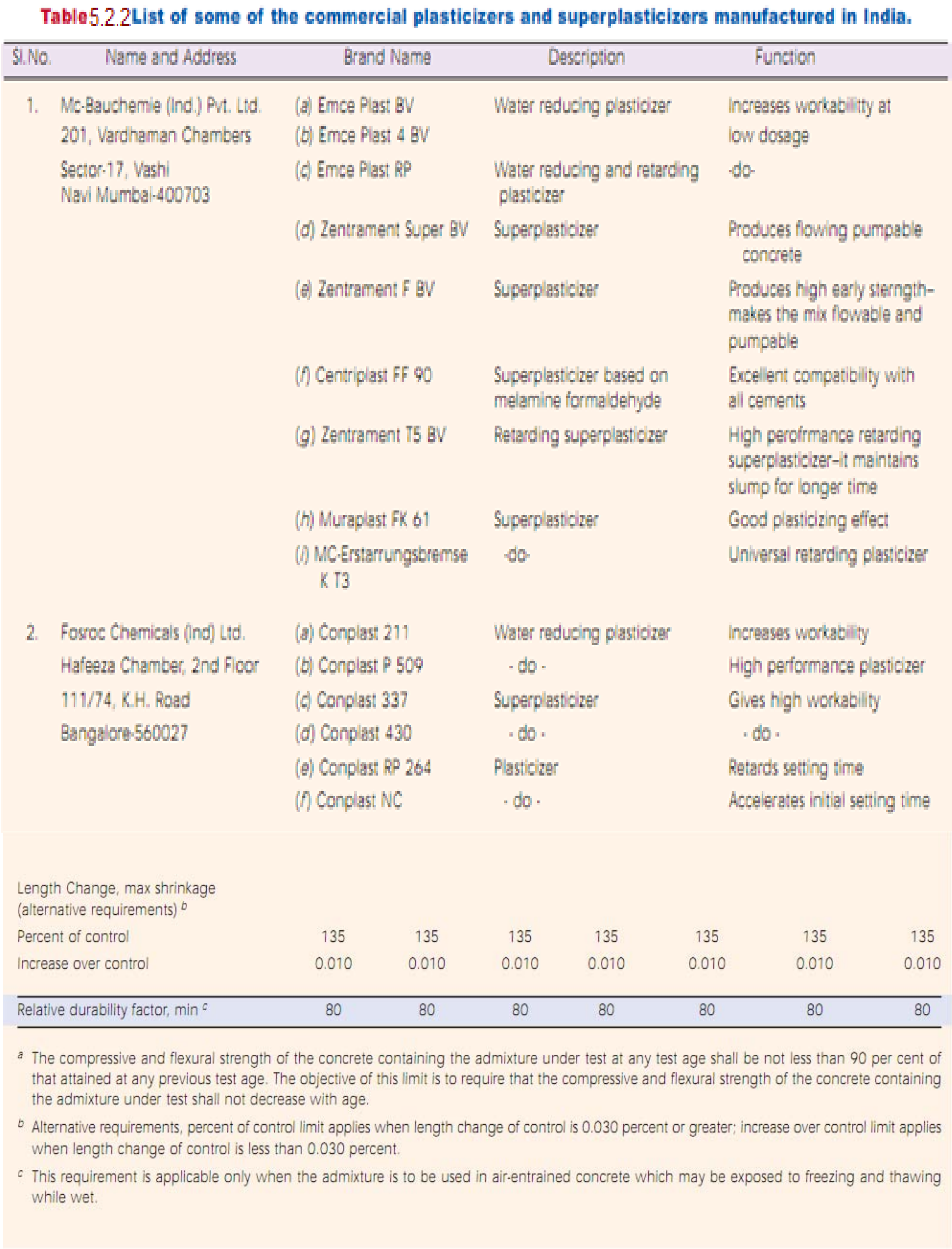


Table5.2.2List of some of the commercial plasticizers and superplasticizers manufactured in India.

Sl.No.	Name and Address	Brand Name	Description	Function
1.	Mc-Bauchemie (Ind.) Pvt. Ltd. 201, Vardhaman Chambers	(*a*) Emce Plast BV (*b*) Emce Plast 4 BV	Water reducing plasticizer	Increases workability at low dosage
	Sector-17, Vashi Navi Mumbai-400703	(*c*) Emce Plast RP	Water reducing and retarding plasticizer	-do-
		(*d*) Zentrament Super BV	Superplasticizer	Produces flowing pumpable concrete
		(*e*) Zentrament F BV	Superplasticizer	Produces high early sterngth–makes the mix flowable and pumpable
		(*f*) Centriplast FF 90	Superplasticizer based on melamine formaldehyde	Excellent compatibility with all cements
		(*g*) Zentrament T5 BV	Retarding superplasticizer	High perofrmance retarding superplasticizer–it maintains slump for longer time
		(*h*) Muraplast FK 61	Superplasticizer	Good plasticizing effect
		(*i*) MC-Erstarrungsbremse K T3	-do-	Universal retarding plasticizer
2.	Fosroc Chemicals (Ind) Ltd.	(*a*) Conplast 211	Water reducing plasticizer	Increases workability
	Hafeeza Chamber, 2nd Floor	(*b*) Conplast P 509	- do -	High performance plasticizer
	111/74, K.H. Road	(*c*) Conplast 337	Superplasticizer	Gives high workability
	Bangalore-560027	(*d*) Conplast 430	- do -	- do -
		(*e*) Conplast RP 264	Plasticizer	Retards setting time
		(*f*) Conplast NC	- do -	Accelerates initial setting time

Length Change, max shrinkage (alternative requirements) [b]							
Percent of control	135	135	135	135	135	135	135
Increase over control	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Relative durability factor, min [c]	80	80	80	80	80	80	80

[a] The compressive and flexural strength of the concrete containing the admixture under test at any test age shall be not less than 90 per cent of that attained at any previous test age. The objective of this limit is to require that the compressive and flexural strength of the concrete containing the admixture under test shall not decrease with age.

[b] Alternative requirements, percent of control limit applies when length change of control is 0.030 percent or greater; increase over control limit applies when length change of control is less than 0.030 percent.

[c] This requirement is applicable only when the admixture is to be used in air-entrained concrete which may be exposed to freezing and thawing while wet.

٥.١.٢.٢ Mineral admixtures and slag cement

Finely divided mineral admixtures, consisting mainlyof fly ash and silica fume, and slag cement have beenwidely used in high-strength concrete.

٥.١.٢.٢.١ Fly ash

Fly ash (pulverized fuel ash) is the spherically shaped amorphous, glassyresidue that results from the combustion of pulverized coal (Figure ٥.٢.٢). Itis the most commonly used pozzolan in concrete, and it has played asignificant role in high-strength concrete since its very birth. Specifications for fly ash include ASTM C ٦١٨, BS EN ٤٥٠–١, and CAN/CSA A٢٣.

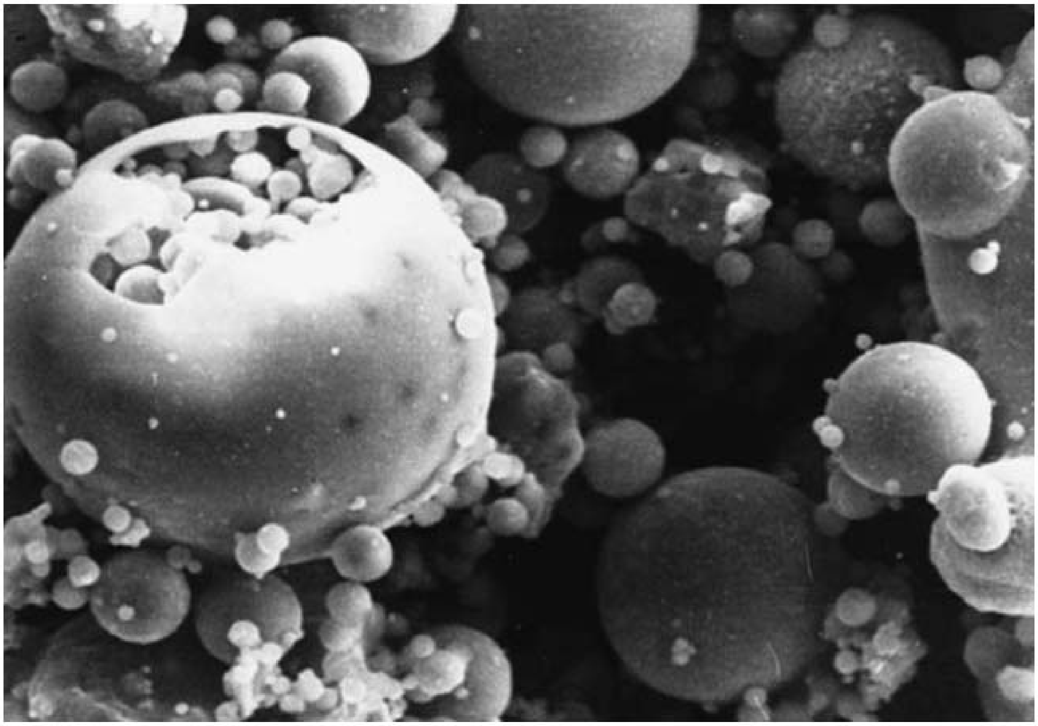


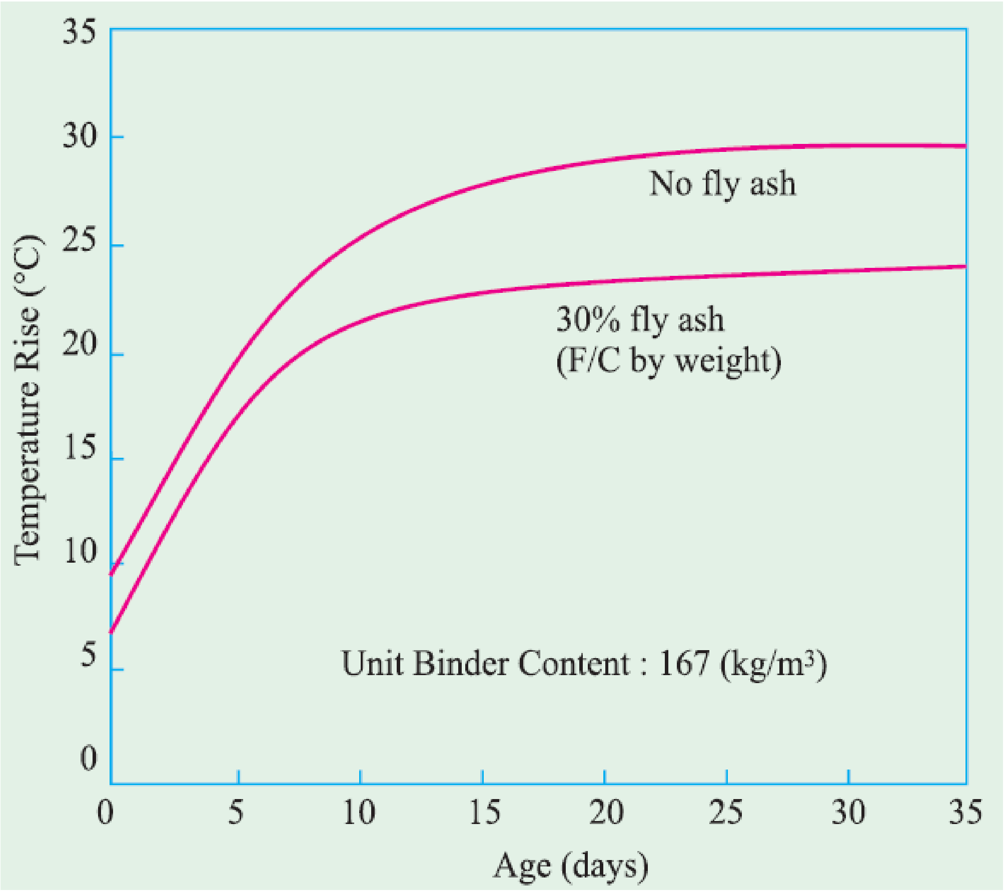
Figure 5.2.2 A micrograph of fly ash showing typical spherical particles. Field of view is 80 µm wide. Courtesy of Portland Cement Association.

Effect of fly-ash on fresh concrete:-

١. Use of right quality fly-ash, result in reduction of water demand desire slump.

٢. With reduction unit water content, bleeding and drying shrinkage will also be reduced.

٣. Since fly-ash is not highly reactive, the heat of hydration can be reduced through replacement of part of the cement with fly ash fig.٥.٢.٣ show the reduction of temperature rise for ٣٠% substitution of fly ash.



Effect of fly ash on hardened concrete:-

Fly ash, when used in concrete, contributes to the strength of concrete due to its pozzolanic reactivity. However, since the pozzolanic reaction proceeds slowly, the initial strength of fly ash concrete tends to be lower than that of concrete without fly ash. Due continued pozzolanic reactivity concrete develops greater strength at later age. Which may exceed concrete without fly ash? The pozzolanic reaction also contributes to making the texture of concrete dense. Resulting in decreasing water permeability and gas permeability. It should be noted the pozzolanic reaction can only proceed in the presence of water enough moisture should be available for long time. Fly ash for high-strength concrete isclassified into two classes. Class F fly ash is normally produced from burning anthracite or bituminous coal andhas pozzolanic properties, but little or no cementitiousproperties. Class C fly ash is normally produced fromburning lignite or subbituminous coal, and in addition tohaving pozzolanic properties, has some autogenous cementitious properties. While there are a number of differences in the chemical composition of each class of fly ash, in general the primary difference is that low calcium fly ash has little or no hydraulic properties of its own, while high calcium fly-ash does. When mixed with water, high calcium fly ash will hydrate and form calcium silicate hydrate. In conventional-strength concretes, fly ashes typically comprise ١٥ to ٣٠ percent by mass of cementitious material. In high-strength concrete, higher percentages are common, particularly when using high calcium fly ash. With respect to strength, for a given set of cementitious materials, the optimum quantity of fly ash in concrete depends largely on the target strength level desired, the age at which the strength is needed, and the chemical and physical properties of the fly ash and other cementitious materials used. For example, the optimum quantity of a given fly ash needed to maximize ٢٨-day compressive strength in a binary mixture containing ٣٠٠ kg/m٣ (٥٠٠ lb./yd٣) Portland cement and fly ash might be found to be ٢٥ percent by mass of the total cementitious materials content. On the other hand, in a high-strength concrete containing ٥٠٠ kg/m٣ (٨٥٠ lb. /yd٣) using the same materials, the optimum quantity of the same fly ash might be determined to be in the range of ٤٠ to ٥٠ percent of the cementitious material.

Figure ٥.٢.٤ illustrates the marked difference the chemical composition fly ash has in the ٢٨-day strength performance of conventional and high-strength concrete. The optimum quantity of fly ash with respect to compressive strength performance depends largely on the properties of the cement andfly ash used the quantity of fly ash used, the total cementitious materials factor, and the age of the concrete. For example, the low calcium fly ash used in the Figure ٥.٢.٤ study exhibited decreased ٢٨-day strength when comprising more than ٢٥ percent replacement in conventional-strength concrete. On the other hand, no decrease in ٢٨-day strength was observed using the same fly ash in a moderately high-strength concrete. By ٥٦ days, no decrease in strength was observed up to the ٤٠ percent maximum replacement level studied. The optimum proportions for one fly ash may be quite different than for another; therefore, laboratory trial batches should be made to establish optimum performance.Prescriptive specifications commonly view fly ash as a replacement for Portland cement, with maximum replacements usually in the range of ١٥ to ٢٠ percent by mass. For special durability needs, such as increased resistance to sulfate attack or alkali reactivity, low calcium fly ashes have comprised ٣٠ to ٤٠ percent of the binder content. In high-strength concrete, optimum post-٢٨-day strengths have been achieved using fly ash contents much higher than the usual ١٥ to ٢٥ percent maximum allowed by many specifications. Specifications for fly ash are covered in **ASTM C ٦١٨**. Methods for sampling and testing are found in**ASTM C ٣١١**. Variations in physical or chemical properties of mineral admixtures, although within the tolerancesof these specifications, may cause appreciable variationsin properties of high-strength concrete. Such variationscan be minimized by appropriate testing of shipmentsand increasing the frequency of sampling. **ACI ٢١٢.٢R**provides guidelines for the use of admixtures in concrete.It is extremely important that mineral admixtures be tested for acceptance and uniformity and carefully investigated for strength-producing properties and compatibilitywith the other materials in the high-strength concretemixture before they are used in the work.

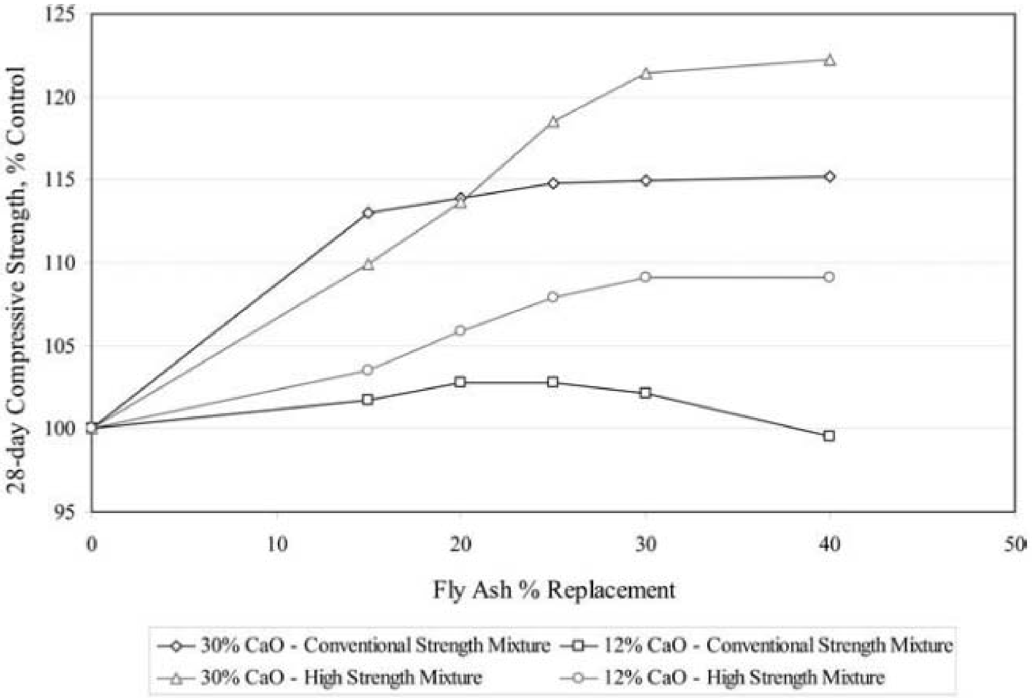


Figure 5.2.4 Compressive strength of concretes produced with fly ash containing 12 percent and 30 percent calcium oxide in conventional-strength and moderately high-strength concrete. The total binder content of the conventional and high-strength mixtures were 250 kg/m^3 (420 lb/yd^3) and 385 kg/m^3 (650 lb/yd^3), respectively. All batches were produced at a target slump of 125 mm (5 in).

٥.١.٢.٢.٢ Silica fume(micro silica)

Silica fume and admixtures containing silica fume have been used in high-strength concretes for structural purposes and for surface applications and as repair materials in situations where abrasion resistance and low permeability are advantageous. Silica fume is a by-product resulting from the reduction of high-purity quartz with coal in electric arc furnaces in the production of silicon and ferrosilicon alloys.

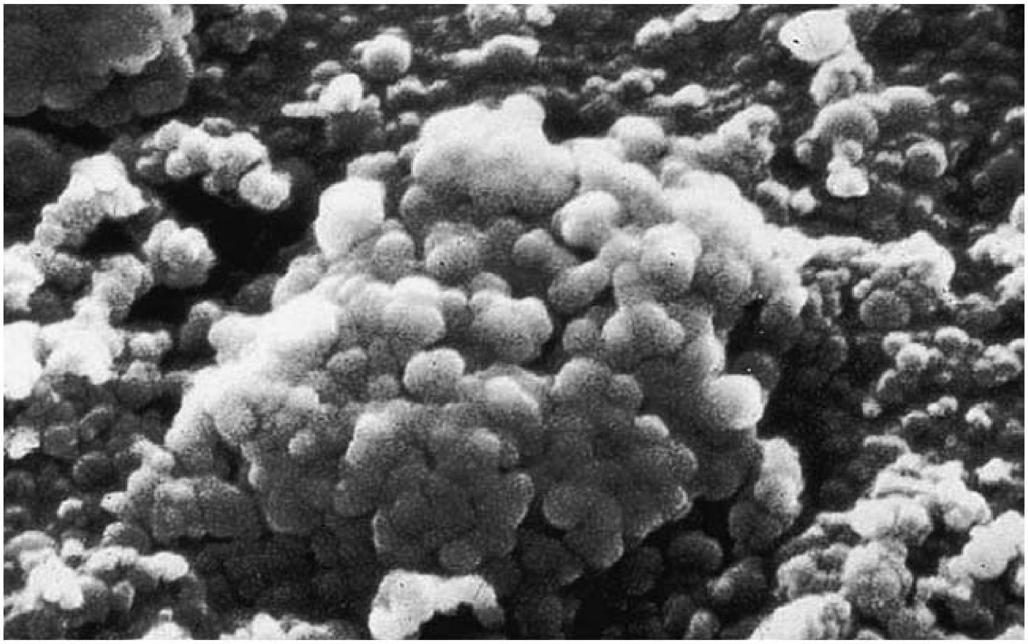


Figure 5.2.5 Scanning electron microscope micrograph of silica fume particles at 20,000×. Courtesy of Portland Cement Association.

The fume, which has a high content of amorphous silicon dioxide and consists of very fine spherical particles, is collected from the gases escaping from the furnaces. Silica fume consists of very fine vitreous particles with a surface area on the order of ٢٠,٠٠٠ $m^٢$/kg. The particle-size distribution of a typical silica fume shows most particles-size to be smaller than one micrometer (١ µm) with an average diameter of about ٠.١ µm, which is approximately ١٠٠ times smaller than the average cement particle. The specific gravity of silica fume is typically ٢.٢, but may be as high as ٢.٥. The bulk density as collected is ١٠ to ٢٠ lb./ft^٣ (١٦٠ to ٣٢٠ kg/m^٣); however, it is also available in densified or slurry forms for commercial application. Silica fume, because of its extreme fineness and high silica content, is a highly effective pozzolanic material. The silica fume reacts pozzolanically with the lime during the hydration of cement to form the stable cementitious compound calcium silicate hydrate (CSH). The availability of high-range water-reducing admixtures has facilitated the use of silica fume as part of the cementing materialin concrete to produce high-strength concretes. Normal silica fume content ranges from ٥ to ١٥ percent of Portland cement content. Both laboratory and field experience indicate that concrete incorporating silica fume has an increased tendency to develop plastic shrinkage cracks. Thus, it is necessary to quickly cover the surfaces of freshly placed silica-fume concrete to prevent rapid water evaporation. High-strength concrete with silica fume will gain strength faster during the first ٢٨ days than a similar high-strength concrete mixture without silica fume. Compressive strengths of high-strength concrete with silica fume replacements of ٥ to ٢٠ percent of the mass of cement and after ٧ days of moist curing were ٣٤ to ٥٧ percent higher than high-strength concrete without silica fume. The higher the silica fume content (up to ٢٠ percent),the higher is the compressive strength after ٧ days of moist curing. Beyond ٢٨ days, the strength gain of concretes with silica fume is somewhat slower than concretes without silica fume. Beyond ٥٦ days, high-strength concrete with silica fume gains additional strength very slowly, probably due to the effects of self-desiccation. There is general agreement among researchers that the positive influence of silica fume on the strength gain of high-strength concrete occurs mostly during the early age of the concrete (i.e. the first ٢٨days after placement).

٥.١.٢.٢.٣ Metakaolin

Metakaolin (Figure ٥.٢.٦) is a highly reactive aluminosilicate with thecapability of producing mechanical and durability-related properties similarto silica fume.The raw material necessary for the manufacture of metakaolin is kaolinclay (also known as “china clay”). In its purest form, kaolin clay is a fine,white mineral, comprised primarily of hydrated aluminum di-silicate ($Al_{٢}Si_{٢}O_{٥}$ $(OH)_{٤}$). Metakaolin has been shown to be a quality enhancing Supplementary cementitious material that exhibits high performance properties comparable tosilica fume.Aside from the potential to achieve high strength and low permeability on an order of magnitude to that of silica fume,[١٥] more favorableconstructabilityrelated properties can be derived using metakaolin. Theseadvantages are mainly due to its particle size and color. Having an averageparticle size ٢٠ to ٣٠ times larger than the average particle size of silicafume, the water demand with metakaolin is lower, and the need to offsethigh water demand with high-range water-reducing admixtures is lower.

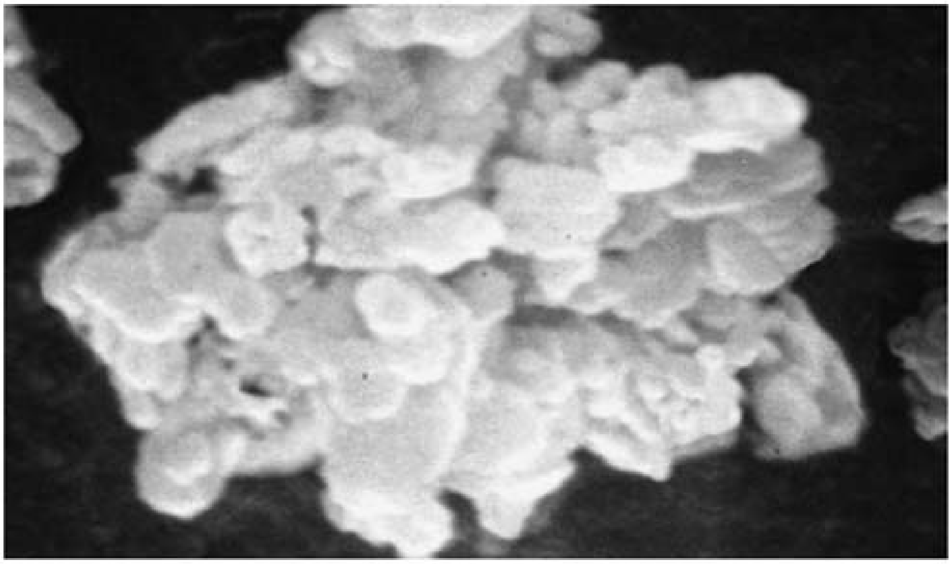


Figure 5.2.6 Scanning electron microscope micrograph of metakaolin particles at 20,000×. Courtesy of CTLGroup.

The result is a high-strength concrete having improved workability, finishability, and a reduced tendency for surface dehydration and plastic cracking.Being much lighter in color than most silica fumes, metakaolin will notdarken the color of the paste or mortar, and opens up opportunities todevelop high-performance architectural concretes.In order to offset high water demand, it is a customary industry practiceto utilize a high-range water-reducing chemical admixture (HRWR). The practice of using HRWRs in conjunction with silica fume is considered a necessity. Rarely would silica fume concrete ever be used without the aid of HRWR. Being a reactive pozzolan with significantly larger sized particles, metakaolin concrete of equal consistency to that of silica fume concrete could be produced using less HRWR, resultingin enhanced workability and lower cost. In addition, concrete containing silica fume does not bleed significantly because of the particle size, leadingto a significant risk of plastic shrinkage cracking. The larger particle size ofmetakaolin is less prone to plastic cracking, and exhibits enhancedfinishability.Metakaolin has a very promising future in the industry as a quality enhancing additive for high-strength, high-performance concrete. It shouldbe noted that, although the water demand associated with metakaolin isnot as high as that of silica fume, when used in the ٥ to ١٢ percent range(by mass of total cementitious material), water demand increases will usuallynecessitate the use of HRWR, though perhaps not as much.

٥.١.٢.٢.٤ Slag cement

Ground slag cement is producedonly in certain areas of the United States and Canada.Specifications for ground granulated blast furnace slagare given in **ASTM C ٩٨٩**. The classes of Portland blastfurnace slag cement are covered in **ASTM C ٥٩٥**. Slagappropriate for concrete is a nonmetallic product that isdeveloped in a molten condition simultaneously with ironin a blast furnace. When properly quenched and processed, slag will act hydraulically in concrete as a partialreplacement for Portland cement. Slag can be interground with cement or used as additional cement atthe batching facility. Blast furnace slag essentially consistsof silicates and alumino-silicates of calcium and otherbases. Research using ground slag shows much promisefor its use in high-strength concrete.

٥.١.٢.٢.٥ Evaluation and selection

Mineral admixturesand slag cement, like any material in a high-strength concrete mixture, should be evaluated using laboratory trialbatches to establish the optimum desirable qualities.Materials representative of those that will be employedlater in the actual construction should be used. Particularcare should be taken to insure that the mineral admixture comes from bulk supplies and that they are typical.Generally, several trial batches are made using varyingcement factors and admixture dosages to establish curveswhich can be used to select the amount of cement andadmixture required to achieve the desired results. When fly ash is to be used, the minimum requirementis that it comply with ASTM C ٦١٨. Although this specification permits a higher loss on ignition, an ignition lossof ٣ percent or less is desirable. High fineness, uniformity or production, high pozzolanic activity, and compatibility with other mixture ingredients are items of primary importance.

٥.١.٣- Aggregates

Both fine and coarse aggregates usedfor high-strength concrete should, as a minimum, meetthe requirements of **ASTM C ٣٣**. Fine aggregates for HSC should be selected to reduce the water demand. Rounded particles are thus preferred to crush rock fines where possible. The silt, clay and dust content ofboth fine and coarse aggregates should be kept as low as possible. As most HSC concrete mixes contain a large amount of fine material in the cement(often greater than ٥٠٠ kg/m^{٣}), it is accepted practice to utilize slightly coarser gradings of fine aggregate than is normal for conventional structural concrete. The finest fractions of the fine aggregate are no longer essential to increase workability or prevent segregation; a coarser grading (fineness modulus ٢.٧ to ٣.٠ or BS ٨٨٢ Class C) (British Standards Institution, ١٩٩٢) is therefore appropriate. The gradings curve of the fine aggregate should, however, generally be smooth and free of gap grading to optimize the water demand.

The requirements for coarse aggregates have been examined earlier. However, the particle shape should ideally be equidimensional (i.e. not elongated or flaky) and the grading should once again be smooth with no gaps in the grading between fine and coarse fractions. A maximum aggregate size of ١٠–١٤ mm is usually selected although aggregates up to ٢٠ mm may be used if they are strong and free of internal flaws or fractures. This can, however, only be evaluated from trial mixes.

As the influence of aggregates on the performance of high strength concrete is of particular significance it may not be possible to achieve the required strength on a project using local aggregate supplies alone. Importation of aggregate supplies or blending materials from a number of sources may be required in order to optimize performance.

٥.٢- Concrete mix design

Whilst a number of studies have considered the development of a rational or standardized method of concrete mix design for HSC, no widely accepted method is currently available. The main requirements for successful and practical HSC are a low water/cement ratio combined with high workability and good workability retention characteristics. In the absence of a standard mix design method, the importance of trial mixes in achieving the desired concrete performance is increased. The following factors should, however, be considered when designing a high strength concrete mix (see Table ٥.٢.٣):

- The appropriate free water/cement ratio should be selected either from experience or by reference to published data. This will typically be in the range ٠.٢٥–٠.٣٠.

- The cement composition should be selected to maximize strength and other performance requirements. At its simplest this will be Portland cement blended with ٥–١٠ per centsilica fume.

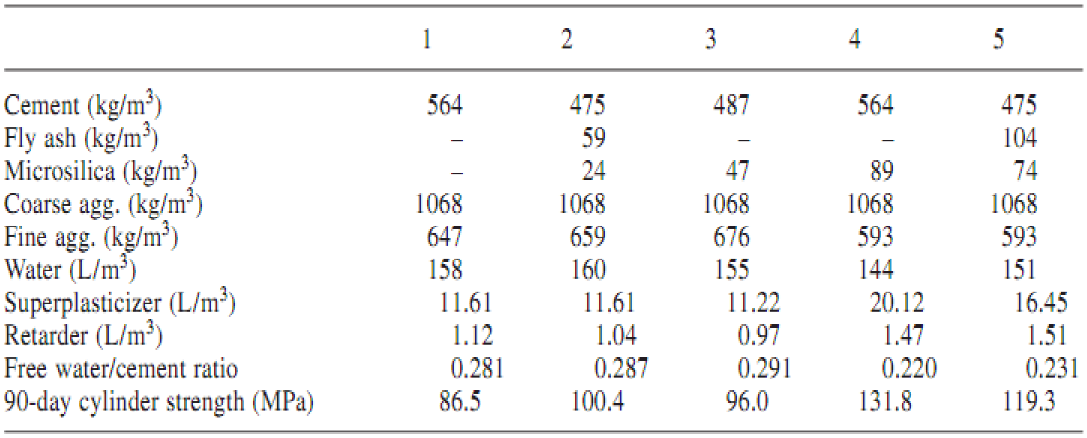
- Proportion coarse and fine aggregates to give a smooth overall grading curve in orderto keep the water demand low. The proportion of fine aggregate is generally around ٥ per cent lower (as a proportion of total aggregate) than for normal strength concrete. Care must be taken, however, not to make the mix too deficient in fine aggregate, particularly where the concrete is to be pumped.

- Use the saturation dosage of admixture (or admixtures), determined with a flow cone,to produce workability. It should be noted (see section ٣.٥) that most HSC is also high workability concrete, of, say, ٦٠٠ mm flow table spread.

Trial mixes should be made and strength, workability and workability retention measured. Modifications can then be made to the mix to optimize the concrete’s performance.

Table ٥.٢.٣ Commercial HSC mix designs from North America

(Data from Burg and Ost, ١٩٩٢)



	1	2	3	4	5
Cement (kg/m^3)	564	475	487	564	475
Fly ash (kg/m^3)	–	59	–	–	104
Microsilica (kg/m^3)	–	24	47	89	74
Coarse agg. (kg/m^3)	1068	1068	1068	1068	1068
Fine agg. (kg/m^3)	647	659	676	593	593
Water (L/m^3)	158	160	155	144	151
Superplasticizer (L/m^3)	11.61	11.61	11.22	20.12	16.45
Retarder (L/m^3)	1.12	1.04	0.97	1.47	1.51
Free water/cement ratio	0.281	0.287	0.291	0.220	0.231
90-day cylinder strength (MPa)	86.5	100.4	96.0	131.8	119.3

٦-Special methods of making high strength concrete:-

١. Seeding.
٢. Revibration.
٣. High speed slurry mixing.
٤. Use of admixtures.
٥. Inhibition of cracks.
٦. Sulphur impregnation.
٧. Use of cementitious aggregates.

٧- Properties of HSC

٧.١ Fresh concrete

Normal practice (particularly in North America, but also in Europe), is to produce high workability HSC. Slumpsin excess of ٢٠٠ mm are common, particularly where HSC is used in areas of congested reinforcement. In most cases, however, the flow table is a more appropriate way of assessing the workability of the concrete on site than is the slump test. It has been found that HSCs often appears to require more effort to compact than a more conventional concrete of a similar slump (often termed ‘sticky’). This is probably due to a combination of high cement content and high levels of admixture. HSC is essentially thyrotrophic in that whilst it flows easily under the influence of vibration, flow ceases once the vibration is removed. HSC is also characterized by significantly lower bleeding than more conventional concretes. If the concrete contains a high silica fume content (> ١٠ per cent of total cement), bleeding may be eliminated altogether. The absence of bleeding can lead to difficulties with finishing and also increase the importance of effective early curing in order to prevent plastic cracking. As the total content of cementitious materials in HSC is typically high (often in excess of ٥٠٠ kg/m^{٣}), the heat of hydration of the concrete would also be expected to be high. In fact, whilst the heat generation is higher than for lower strength concrete, it does not rise in proportion to cement content. The low water content of a typical HSC may not enable all the cementitious material to hydrate fully. Consequently the inhibition of continued hydration also acts to limit the generation of heat. However, if HSC is used in massive sections, the normal precautions will still be required to minimize thermal cracking.

٧.٢ Hardened concrete

٧.٢.١ Strength

HSC is obviously characterized by high ultimate compressive strength. When measured on standard water cured cubes, however, the rate of early strength gain is similar to that lower strength concrete. If metakaolin is used, the strength gain may be slightly more rapid than for microsilica-based HSC. In some cases when retarding admixtures or very high superplasticizer levels are used the early strength gain may even be lower than normal. Another characteristic of HSC (particularly when containing silica fume) is that continued strength gain beyond ٢٨ days is often very small, and this is even more so when in-situ strength is considered. However, long-term strength gain is dependent on the type and combination of cementitious materials in the concrete. The build-up of heat within structural elements accelerates the hydration of the cement and hence the development of strength. Using temperature-matched curing techniques to monitor the development of in-situ strength has indicated that in-situ strength can rise rapidly from about ٨ hours after casting (see Figure ٧.٢). Greater than ١٠٠ MPa has been recorded at an age of ٢٤ hours.

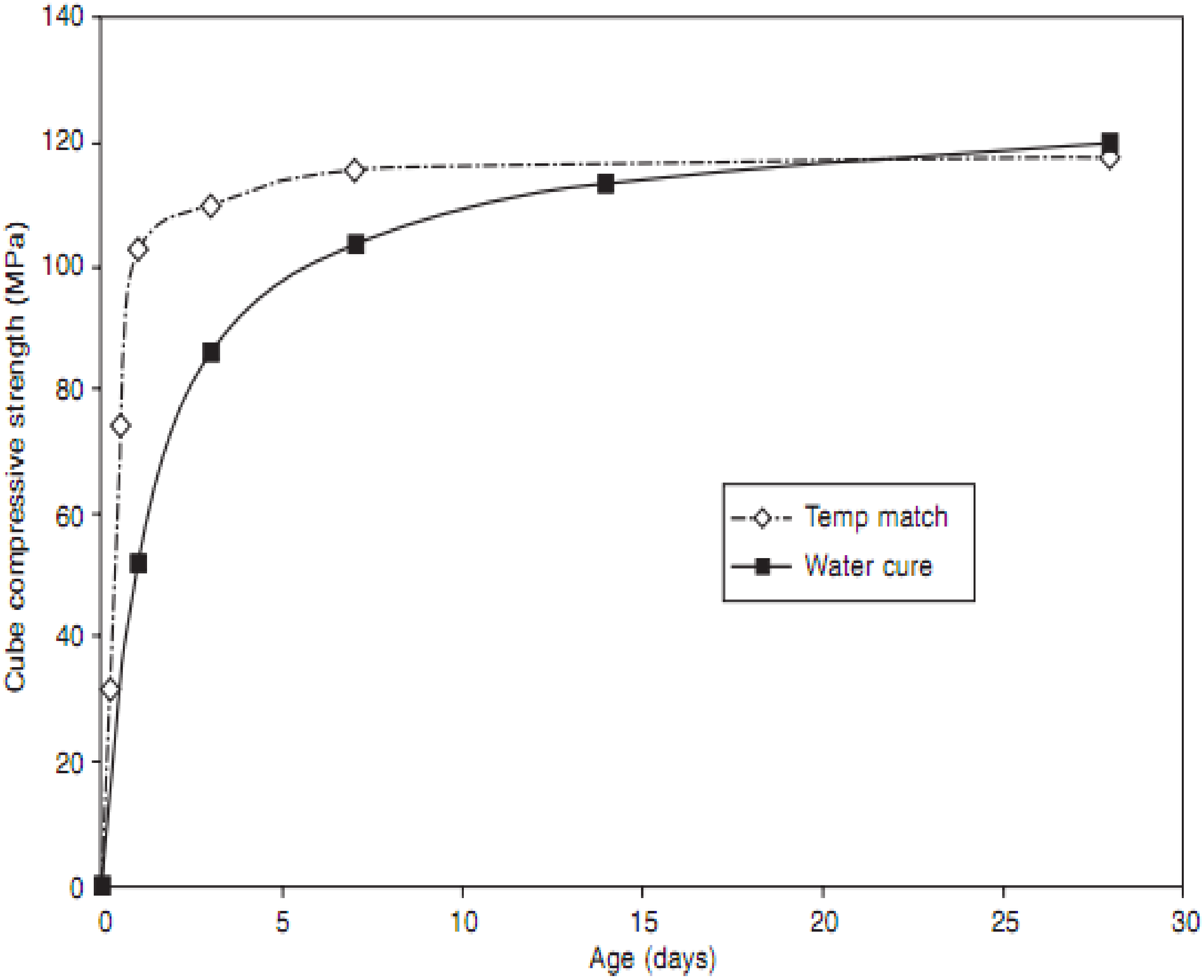


Figure ٧.٢ Strength development of a high strength concrete slab

As with conventional normal strength concrete, the tensile strength of HSC increases as compressive strength rises. However, care should be taken in extrapolating existing relationships between compressive and tensile strengths, as the tensile strength does not increase pro-rata with compressive strength. Factors such as aggregate shape and composition will also have an influence.

٧.٢.٢ Elastic modulus and stress–strain behavior

The elastic modulus of HSC is generally higher than that of normal strength concrete. The increase of elastic modulus is not pro-rata to increases in compressive strength and some existing relationships between these properties are thought to overestimate the elastic modulus at compressive strengths over ١٠٠ MPa (American Concrete Institute,١٩٩٢). The effects of the shape and mineralogy of the coarse aggregate also has a significant influence over elastic modulus (Aitcin and Mehta, ١٩٩٠). Stiffer aggregates such as siliceous flints etc. will achieve a much higher modulus than softer granites and limestones at a given level of compressive strength (Nielsen and Aitcin, ١٩٩٢). It is recommended that if elastic modulus is an important factor in the design, the modulus of the concrete is actually measured on the concrete proposed for use in the project(Concrete Society, ١٩٩٨). It is generally recognized that the stress–strain behavior of HSC differs from that of normal strength concrete. In HSC, the ascending part of the stress–strain curve becomes steeper and more linear, remaining linear to a higher proportion of the ultimate stress (see Figure ٧.٣). The increased compatibility in elastic modulus between a high strength binder and aggregate particles reduces the degree of microcracking around the aggregate during loading. This in turn results in increased linearity of the ascending limb. The strain at maximum stress is slightly higher than for normal strength concrete but the descendingportion of the curve is, however, significantly steeper.

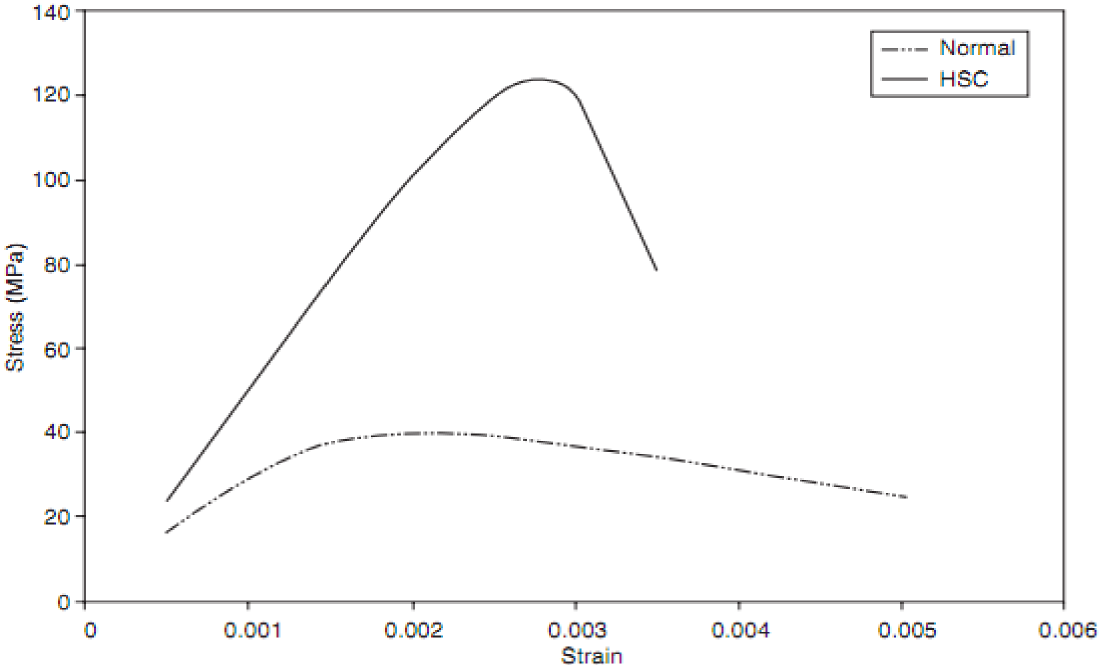


Figure ٧.٣ Idealized comparisons of stress–strain curves of high strength and normal strength concrete.

The brittle behaviour of HSC has implications in terms of secondary reinforcement details, for ensuring ductile behavior of structures (Concrete Society, ١٩٩٨).

٧.٢.٣ Creep and shrinkage

The creep of HSC (expressed as either specific creep or creep coefficient) appears to be significantly lower than that of normal strength concrete. However, the available information on creep of HSC is relatively limited and further research is required. Relatively little information is available on the drying shrinkage characteristics of HSC. However, in general due to the low initial water content of the concrete and its low intrinsic vapor permeability, drying shrinkage is thought to be lower than for normal strength concrete. On the other hand, autogenously shrinkage of HSC can be significant. Autogenously shrinkage is a reduction in volume occurring without loss of water to the atmosphere. The combination of low initial water content and silica fume leads to self-desiccation when sufficient water for continued hydration is not available and hence shrinkage. Autogenously shrinkage in HSC is also more rapid than in normal strength concrete. In one study, the autogenously shrinkage of a ١٠٠ MPa concrete was ١١٠ micro strain, compared with only ٤٠ microstrain for a ٤٠ MPa concrete. In certain circumstances, the high autogenously shrinkage may be a significant influence on the proposed design.

٧.٢.٤ Durability

It is not possible to give a detailed description here of the durability aspects ofHSC. However, this can be summarized as follows:

- The low free water/cement ratio required to produce HSC also generally confersenhanced durability on the concrete. When combined with the use of silica fume (present in most, if not all, HSC), significant reductions in water permeability and chloride ingress have been observed. HSC is often used in parking structures in North America in order to prevent deterioration resulting from the extensive use of deicing salts.

- Other areas, in which HSC has found applications on durability grounds, are as a consequence of its improved abrasion resistance compared to normal strength concrete and its increased resistance to attack by aggressive chemical.

- When used in severe freezing and thawing conditions, some air entrainment should still be used even though adequate protections will be achieved at a lower air contend than that required by normal strength concrete. An entrainment is more difficult in low water content, super plasticized pastes and higher than normal amounts of air-entraining admixtures may be needed to establish a satisfactory air void system. In typical UK conditions, non-air entrained HSC will be resistant to frost damage.

- Although HSCs generally contain high cement contents, the presence of silica fume is thought to prevent ASR(Alkali-silica reaction). The very low internal moisture content of the concrete will also prevent the swelling and expansion of anygel formed if potentially reactive aggregates are used.

٨- Production and use of HSC

٨.١ Production

The key to successful production of HSC is maintaining a consistent and low water/cement ratio together with effective mixing. HSC has been produced successfully in both wet batch and dry batch plants but in all cases, stringent control of all sources ofwater in the mix is critical. These include:

- Added mix water.
- Water in liquid admixtures or silica fume slurry.
- Free moisture on fine and coarse aggregates. It should be noted that small changes in the moisture content of the fine aggregate have a proportionately greater effect on water/cement ratio and hence strength of HSC, than it does for normal strength concrete.
- Other sources of water such as washout or cleaning water in mixers and transport vehicles.

In order to maximize the workability retention of HSC, it was formerly common practice in the INDIA, USA, and UK and elsewhere to add only a part of the total admixture dose to the concrete at the batching plant. When the concrete arrived on-site, the workability was assessed (usually visually) and further superplasticizer (not water) added, to increase the workability to the required level and keep the workability retention time as long as possible. The introduction of new-generation super plasticizers with significantly improved workability retention, particularly those based on polycarboxylate ethers (Concrete Society, ٢٠٠٢ has significantly reduced the need for this procedure. When transporting high workability HSC it is common practice to carry reduced loads, i.e. ٤ $m^٣$ of concrete in a ٦ $m^٣$ capacity drum. This reduces the wear and tear on the drum and ring gear (caused by the increased density of HSC) and also reduces the risk of spillage during transport. Production of HSC requires particular attention to detail as factors causing only second-order effects in normal strength concrete can have major implications at very high strength levels. HSC is relatively a high-cost material, but it can produce overall savings when used in appropriate situations. Producers should be selected on the basis of proven experience with HSC specifically, rather than general experience or cost alone.

٨.٢ Use on-site

Properly proportioned HSC can be easily placed by skip and has been successfully pumped over large distances at only slightly higher pump pressures than normal. The possibility of limited workability retention time must, however, also be kept in mind. The behavior of HSC is different in certain respects from conventional strength concrete. As mentioned earlier, it tends to be very cohesive and requires more effort to compact at a given level of slump. The concrete also tends to stop moving as soon as the vibrator is removed (i.e. it is thyrotrophic). Consequently poker vibrators see (fig. ٨.٢.١) must be inserted at closer spacing's and immersed longer than normal. Particular attention must be given to the interface between two batches of concrete (these will not just flow together) and in instances where small amounts of concrete are used to fill low areas etc., vibration will be required in these locations in order to prevent cold joints. The low bleed of typical HSC can cause problems with finishing, as the concrete tends to stick to trowels etc. If finishing is delayed too long, the concrete surface often dries and tears. To avoid early age (plastic) cracking, prompt and effective curing, for as long as the concrete is plastic, is essential. Covering exposed surfaces in wet hessian and polythene sheeting is preferred to curing membranes application and early application of water curing is also suggested as a means of reducing autogenously shrinkage (Aitcin, ١٩٩٩). Finishing must follow compaction and be itself followed by curing in a continuous sequence with no delays. HSC is not very tolerant of delays and plastic cracking is almost inevitable, unless finishing and curing are promptlycarried out.

Fig.٨.٢.١ poker vibrator

٨.٣ Testing

٨.٣.١ Fresh concrete

Test regimes for acceptance of HSC on site do not differ significantly from normal strength concrete. The flow table test (British Standards Institution, ٢٠٠٠a) is much more appropriate (and sensitive) for high workability HSC than the slump test (British Standards Institution, ٢٠٠٠b). A high rate of sampling is prudent at the start of any project but this may be relaxed as construction procedures.

٨.٣.٢ Hardened concrete

Concrete test specimens should be made in rigid molds and compacted by vibration. The use of ١٠٠ mm cubes (or ١٠٠ mm diameter × ٢٠٠ mm cylinders) is common with HSCas a means of reducing the required load capacity of testing machines. Test specimens should be kept moist and at the correct temperature until transferred to the laboratory curing tank. Test specimens should not be moved until they have properly hardened, as high levels of admixture addition may delay setting. ACI ٣٦٣.٢R (American Concrete Institute, ١٩٩٨) recommends specimens should not be moved until at least ١٦ hours and not more than ٤٨ hours. If temperature-matched curing is being considered, sealing the test specimens from contact with external water during curing will provide a more accurate estimate of in-situ strength (Price and Hynes, ١٩٩٦). Cores and cylinders (American Concrete Institute, ١٩٩٨) should have the ends ground rather than capped as the evidence is that the use of low strength capping compound increases variability and reduces the measured strength (American Concrete Institute, ١٩٩٨). High strength capping materials applied as thin (٢ mm) caps have been used successfully

(American Concrete Institute, ١٩٩٨). In general testing HSC requires more attention to detail, as small changes in procedure can cause proportionally very large changes in the measured strength. Compression test machines must be of sufficient load capacity such that cube failure occurs within the optimum working range. The lateral stiffness of the machine should also be high enough to allow the load to be maintained right up until failure (American Concrete Institute, ١٩٩٨). As explosive failures are common with HSC, testing machines should incorporate safety guards to protect personnel from flying concrete fragments.

٩- Examples of use of HSC

High strength concrete has been utilized in many structures around the world (CEB, ١٩٩٤), but perhaps the most common use of the material has been in the columns of high-rise buildings, particularly in North America and Australia. HSC columns often with reduced reinforcement are an economical solution to providing heavily loaded elements in high-use buildings. The dimensions of columns can also often be reduced by using HSC although possible buckling of very slender elements needs consideration (Concrete Society, ١٩٩٨). This enables the amount of rentable floor space to be maximized and also minimizes interruption of parking spaces in basement garages.In India Vidya Sagar Setu at Kolkuta where longest cable styed bridge was built using HSC see figure ٩.٥. Presently (year ٢٠٠٠) in India, concrete of strength ٧٥ Mpa is being used for the first time in one of the flyover at Mumbai.Other notable example of using HSC in India is in the construction of containment Dome at Kaige Power Project. In Chicago, a number of tall buildings have utilized HSC in columns included ٣١١ S.Wacker Drive

(see Figure ٨.١) where high strength columns (Design strength ٨٣ MPa (cylinder)) were used at the base of the building, with lower strength concrete (٦٩ and ٦٢ MPa) being used in the more lightly loaded upper floors (Russell, ١٩٩٤). The HSC was used in conventionally reinforced columns and nearby all the concrete was placed using pumps. In Seattle, a different form of construction with HSC has been employed. Large-diameter (٣ m) steel tubes form the core of the building with smaller steel tubes around the perimeter. These tubes contain shear studs on the internal face but not reinforcement. High strength concrete (Design strength ٩٧ MPa (cylinder)) is pumped into the tubes from the bottom of each storey and without any vibration. This forms a very economic and stiff structure. During the construction of٢ Union Square in Seattle (see fig. ٨.٤), a ٥٨-storey structure (Russell, ١٩٩٤), the designer also wished to achieve an elastic modulus of at least ٥٠ GPa. Consequently the actual strength of the concrete was much higher than the design strength in order to produce the desired modulus. Long-term compressive cylinderstrengths in excess of ١٣٠ MPa (approximately equivalent to cube strength of ١٤٥ MPa) were measured during construction. In addition to well documented examples in North America, HSC has been used in all tall buildings in Australia, Germany, India and South-east Asia (CEB, ١٩٩٤). Whilst the most widespread application of HSC technology has been in high-rise buildings, offshore structures have been utilizing concrete with ever increasing strength for many years. Bridges and in particular prestressed concrete bridges have also used the benefits of HSC. One experimental footbridge near Tokyo (Price, ١٩٩٩) incorporates ١٠٠ MPa concrete to achieve a span/depth ratio of ٤٠:١. HSC can enable the span of bridge beams to be increased or to reduce the number of beams required for a given span (increase girder spacing) and to decrease beam depth. This can, in turn, lead to a lower unit cost for a given length of bridge. In the UK, HSC has not been used to construct any major structures (high-rise structures being comparatively rare), but has found applications in providing chemical resistance, or resistance to abrasion in industrial facilities and in the remediation of structures. Combining the use of HSC with temperature matched curing to monitor in-situ strength development is particularly effective for reducing the time before roads and bridges can be reopened to traffic. The use of HSC will probably always remain a very small proportion of overall concrete consumption worldwide. However, the properties of HSC offer additional options to designers and contractors to utilize concrete in overcoming engineering challenges.

Figure ٩.١ ٣١١ South Wacker Drive, Chicago – high strength concrete used in columns.

At over ١٥٠ stories, and utilizing concrete with a specified compressive strength as high as ٨٠ MPa (١١,٦٠٠ psi), the "super skyscraper" Burj Dubai (Figure ٩.٢) in Dubai will be the world's tallest building. Figure ٩.٢ illustrates. The breakthrough height of Burj Dubai in relation to other buildings that have held the title of "worlds tallest." Architecturally, it would not have been practical to construct this all-concrete frame building without incorporating high-strength concrete. Concrete building frames, particularly those incorporating high-strength concrete instead of structural steel, a cost prohibitive material, significantly improves the economic feasibility for constructing tall buildings. Construction of Burj Dubai is scheduled for completion in ٢٠٠٨.

Figure ٩.٢ At this point in its construction, the "supeskyscraper" Burj Duba had already attained the title “world’s tallest building.” Courtesy of Samsung Engineering and Construction.

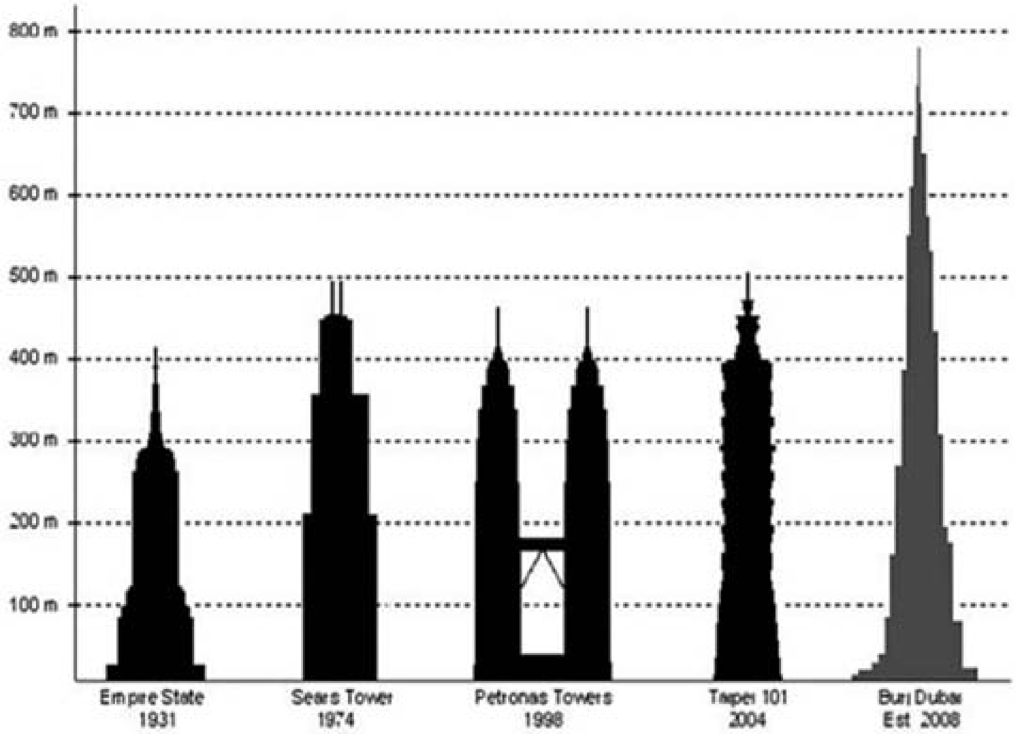


Figure **9.3** With the aid of high-strength concrete, Burj Dubai represents an extraordinary increase in attainable building height. When determining building height, spires are included whereas antennas are not.

Figure 9.4 Two Union Square, Seattle. Courtesy of Portland Cement Association.

Figure ٩.٥ India Vidya Sagar Setu at Kolkuta where longest cable styed bridge was built using

١٠- Conclusion

High-strength concrete is one variety of concrete categorized under the much broader term “high-performance concrete,” or “HPC”.High strength concrete (HSC) is made possible by the development of high strength cementing materials and superplasticizing admixtures. Fly ash and slag cement are usually the supplementary cementitiousmaterials chosen first for high-strength concrete. When combined with ahigh-strength Portland cement, these materials have been used for economically producing binary concretes with specified compressive strengths of atleast ٧٠ MPa (١٠,٠٠٠ psi). For higher strength, ternary mixtures containingvery fine, paste densifying pozzolans such as silica fume, metakaolin, orultra-fine fly ash can be quite advantageous.The selection of constituent materials is critical in achieving a high compressive strength, but compressive strength in excess of ١٠٠ MPa is now routinely achievable in the USA, UK and elsewhere. Maintaining a consistent low water/cement ratio is the most important factor for successful production. The decreased permeability of high-strength concrete presents opportunitiesfor improving durability and increasing service life.The economic advantages of using high strength concrete in the columns of high-rise buildings have beenclearly demonstrated by applications in many cities. Theability to reduce the amount of reinforcing steel incolumns without sacrificing strength and to keep, thecolumns to an acceptable size has been an economicbenefit to owners of high-rise buildings. HSC can be used with most conventional construction techniques, but special attention must be given to avoiding delays during placing, finishing and curing. HSC is also characterized by an increased elastic modulus and tensile strength as well as lower drying shrinkage. Autogenous shrinkage, however, can be very high. The main applications of HSC have been in the columns of high-rise buildings, offshore structures and long-span bridges.The most common problems resulting from adverse material interactionsinclude premature loss of workability (early stiffening), erratic settingbehavior (rapid set or extended set), poor strength development, and poorair-void system characteristics. The interactions occurring between C٣A andsulfate during the early stages of cement hydration forms the basis of manyincompatibility problems. The mechanisms causing such problems can behighly complex and are often interrelated. Often there is a very fine linebetween normal behavior and incompatible behavior, and there is usuallyno simple method of reliably determining the risk of incompatibility. It isprecisely for this reason that trials should be conducted using candidatematerials under actual job conditions.

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