CHAPTER THREE

HSC, MATERIAL & PROPERTIES

3.1 Introduction

This chapter deals with HSC basic component materials, HSC special materials, their mechanism of work, HSC special production techniques, properties of HSC and its mix design procedures & proportions.

3.2 Materials Used in High Strength Concrete (HSC)

Basic component materials of HSC are the same used with NSC (i.e. cement, fine aggregate, coarse aggregate, & water), however, quality of these materials has special requirements to consistently meet the requirements of workability and strength development. Some additional special materials sometimes will be used such as (super plasticizer, silica fume & fly ash). Features of the basic and additional special materials required for HSC are discussed below.

3.2.1 Basic Component Materials of High Strength Concrete (HSC)

The special requirements of basic component materials required for producing HSC are discussed here under:

3.2.1.1 Cement

The choice of cement requires greater attention for High-Strength Concrete than it does for Normal-Strength Concrete because of the greater sensitivity of High-strength concrete to cement properties that are not evaluated or specified by the ASTM C 150, specification for portland cement. Under ASTM C 150, cements are

evaluated at w/cm ratios of about 0.5, without the use of super plasticizers, resulting in a cement paste matrix that is significantly different from that obtained at lower w/cm ratios with super plasticizers. Key properties of cement for use in High-strength concrete include C_3S, C_3A, and sulfate contents, as well as fineness. High C_3A contents limit flow characteristics at low water content. The sensitivity of High-Strength Concrete to the properties of the cement leads naturally to a need for uniformity in the properties of the brand selected. Variations in properties, reported under the provisions of ASTM C 917, should be limited to 4% for C_3S, 0.5% for ignition loss, 0.2% for sulfate content, and 375 g/cm^2 for Blaine fineness.

Although increases in cement fineness will increase the early rate of reaction, very high fineness is not desirable because it will increase the water demand and may have a negative effect on both the flow characteristics and the long-term strength that can be obtained for given cement content. Similarly, the choice of Type III cement may not be advantageous unless high early strengths are required.

As with Normal-Strength Concrete, it is desirable to limit the cement content of High-strength concrete to the lowest value compatible with attaining the desired strength. For High-Strength Concrete, however, this consideration is more important since increasing cement to lower the w/cm ratio offers diminishing returns; the increased surface area obtained at high cement contents ultimately requires higher water content, while the increased cement content itself results in the generation of additional heat of hydration. Values at the upper end of this range are not desirable, and concretes with cement contents greater than 600 kg/m^3 represent unduly expensive and impractical mixtures. Proper mix proportioning, including the use of super plasticizers and higher coarse aggregate contents than used for many Normal-Strength Concretes, will result in the production of High-

Strength Concretes with not only cement contents, but total cementitious material contents, in the lower half of the range (Mindess et al, 2003).

3.2.1.2 Aggregate

The properties that define high-quality aggregates for Normal-Strength Concrete are also desirable for aggregates used to make High-Strength Concrete. However, unlike Normal-Strength Concrete, which can be made with poorly graded and even weak aggregates using a somewhat higher cement content, High-Strength Concrete generally requires higher-quality aggregates. Since it is possible that the cement paste constituent in High-Strength Concrete will be stronger than many natural aggregates, aggregate strength becomes significantly more important as concrete strength increases. It is highly desirable that aggregate particles, especially the coarse particles, have no weak planes; that would cause the aggregate to fail in a brittle manner as the concrete is loaded. To aid in workability, the aggregate particles should be as close to spherical or cubical in shape as possible. It is generally desirable that the coarse aggregate be angular to improve paste-aggregate bond strength, but that the fine aggregate be rounded to aid in workability and limit the paste required to coat the smaller particles (Mindess et al, 2003).

3.2.1.2.1 Fine Aggregate

As a general rule, fine aggregate contents are lower for High-strength concretes than for Normal-strength concretes due to both the higher cementitious material content and a higher coarse aggregate content compared to conventional mixes. ASTM recommended reducing the paste required to coat the fine aggregate particles. Because of the high cementitious material contents used in High-strength

concretes, significant workability is provided by the cement paste constituent of the concrete. As a result, coarser sands are preferred for High-strength concretes, with values of fineness modulus in the range of 2.5 to 3.2, and values of 3.0 or greater generally recommended. Sands with values of fineness modulus below 2.5 are undesirable since they increase both paste and total water requirements and often produce concrete with a sticky consistency. For a given fineness modulus, the lower the void content, the higher the workability. The relationship between void content and workability ties in with the relationship between void content and angularity. A reduction in angularity leads to a reduction in void content and an increase in the lubricating capability of the fine aggregate (Mindess et al, 2003).

3.2.1.2.2 Coarse Aggregate

In the development of mix designs for High-strength concrete, it is possible to take advantage of the extra lubrication provided by high cementitious material contents and super plasticizers by increasing the coarse aggregate contents above quantities that would be used for Normal-strength concrete. Values for coarse aggregates with maximum sizes ranging from 9.5 mm to 25 mm are included for sand with values of fineness modulus between 2.5 and 3.2 are included. The volumes are significantly higher than recommended for Normal-strength concretes. For example, for 9.5mm aggregate, the recommended fractional volume is 0.65 for High-strength concrete compared to 0.46 for Normal-strength concrete for a fineness modulus of 2.80. For 25-mm aggregate, the respective fractional volumes; are 0.75 and 0.67.

It is generally agreed that the compressive strength of High-strength concrete will decrease as the coarse aggregate size increase, as illustrated for a series of

commercial mixes in Figure (3.1). According to ACI 211.4R, coarse aggregates with maximum sizes of 19 or 25 mm can be used for concretes with compressive strengths up to 60 MPa aggregates with maximum sizes of 9.5 or 12.5 mm should be used for concretes with higher strength. However, additional experience indicates that higher compressive strengths up to 100 MPa can be obtained using the larger aggregates. As described in Figure (3.1), an increase in total coarse aggregate content (more easily attainable with an increase in the maximum size of the aggregate) has the advantage of improving the tensile and fracture properties of concrete, as long as the aggregate is of high quality. Therefore, steps in mix design that enable the use of increased quantities or a larger coarse aggregate will provide benefits for structural applications in terms of higher tensile, and bond strength (Mindess et al, 2003).

3.2.2 High Strength Concrete Special Materials

HSC special materials are divided into two main types. These are; mineral admixtures and chemical admixtures.

3.2.2.1 Mineral Admixtures

Mineral admixtures can be used to replace a portion of the cement, since they contribute more to strength than an equal quantity of cement, especially at later ages. Fly ash, natural pozzolans, and silica fume are used as mineral admixtures in High-Strength Concrete.
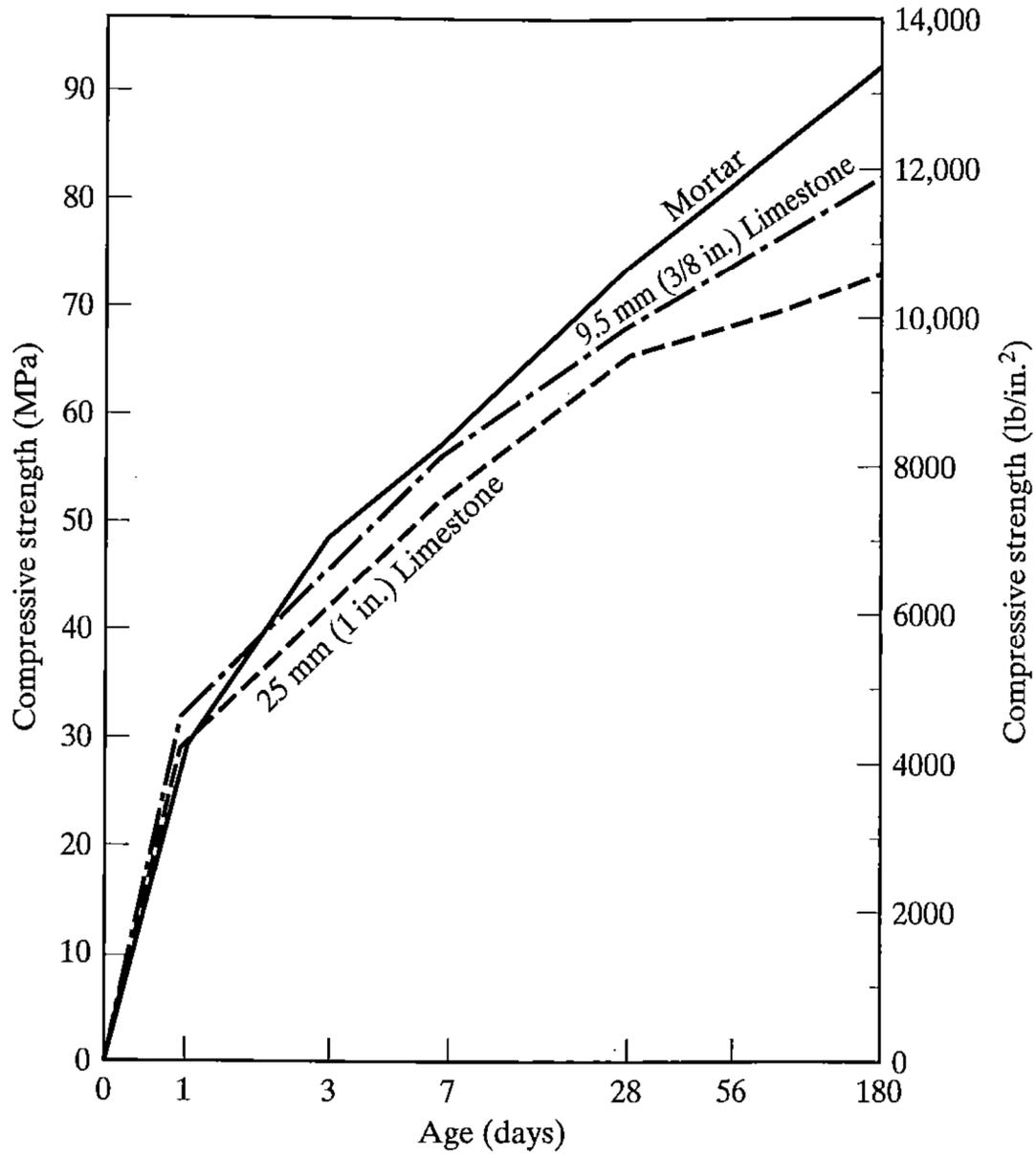
Figure (3.1): Compressive Strength versus Age for Mortar and Concretes with Two Size of Coarse Aggregate, w/c Ratio = 0.32 (Mindess et al, 2003).

3.2.2.1.1 Fly Ash

Fly ash is used as a supplementary cementitious material (SCM) in the production of Portland cement concrete. A supplementary cementitious material, when used in conjunction with Portland cement, contributes to the properties of the hardened concrete through hydraulic or pozzolanic activity, or both. As such, SCM's include both pozzolans and hydraulic materials. A pozzolan is defined as a siliceous or siliceous and aluminous material that in itself possesses little or no cementitious value, but that will in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds having cementitious properties.

Historically, fly ash has been used in concrete at levels ranging from 15% to 25% by mass of the cementitious material component. The actual amount used varies widely depending on the application, the properties of the fly ash, specification limits, and the geographic location and climate. Higher levels (30% to 50%) have been used in massive structures (for example, foundations and dams) to control temperature rise.

Fly ash is a by-product of burning pulverized coal in an electrical generating station. Specifically, it is the unburned residue that is carried away from the burning zone in the boiler by the flue gases and then collected by mechanical separators.

Fly ash is a pozzolanic material. It is a finely-divided amorphous alumino-silicate with varying amounts of calcium, which when mixed with portland cement and water, will react with the calcium hydroxide released by the hydration of Portland

cement to produce various calcium- silicate hydrates (C-S-H) and calcium-aluminate hydrates (Mindess et al, 2003).

The American Society for Testing and Materials (ASTM) recognizes tow general classes of fly ash:-

•**Class C:** (Normally produced from lignite or sub bituminous coal, some class C fly ash may have **Cao** in excess of 10%. In addition to pozzolanic properties, class C fly ash also possesses cementitious properties) (Nawy, 2003).

•**Class F:** (normally produced from bituminous coals, usually has less   than 5% Cao. Class F fly ash has pozzolanic property only) (Nawy, 2003).

(a) Effect of Fly Ash on the Properties of Fresh Concrete

Workability The use of good quality fly ash with a high fineness and low carbon content reduces the water demand of concrete and, consequently, the use of fly ash should permit the concrete to be produced at lower water content when compared to a Portland cement concrete of the same workability. Although the exact amount of water reduction varies widely with the nature of the fly ash and other parameters of the mix, a gross approximation is that each 10% of fly ash should allow a water reduction of at least 3 %.

A well-proportioned fly ash concrete mixture will have improved workability when compared with a Portland cement concrete of the same slump. This means that, at a given slump, fly ash concrete flows and consolidates better than a conventional Portland cement concrete when vibrated. The use of fly ash also improves the cohesiveness and reduces segregation of concrete (Mindess et al, 2003).

(b) Effect of Fly Ash on the Properties of Hardened Concrete:

Compressive Strength Development

Figure (3.2) shows the text book effect on compressive strength of replacing a certain mass of portland cement with an equal mass of low-calcium (Class F) fly ash and maintaining a constant w/cm. As the level of replacement increases the early-age strength decreases. However, long-term strength development is improved when fly ash is used and at some age the strength of the fly ash concrete will equal that of the portland cement concrete so long as sufficient curing is provided. The age at which strength parity with the control (portland cement) concrete that achieved, is greater at higher levels of fly ash. The ultimate strength achieved by the concrete increases with increasing fly ash content, at least with replacement levels up to 50%. Generally, the differences in the early-age strength of portland cement and fly ash concrete are less for fly ash with higher levels of calcium, but this is not always the case. In many cases, concrete is proportioned to achieve a certain minimum strength at a specified age (typically 28 days). This can be achieved by selecting the appropriate water-to-cementitious materials ratio w/cm for the blend of cement and fly ash being used. The w/cm required will vary depending on the level of fly ash replacement, the composition of the ash, and the age and strength specified (Mindess et al, 2003).
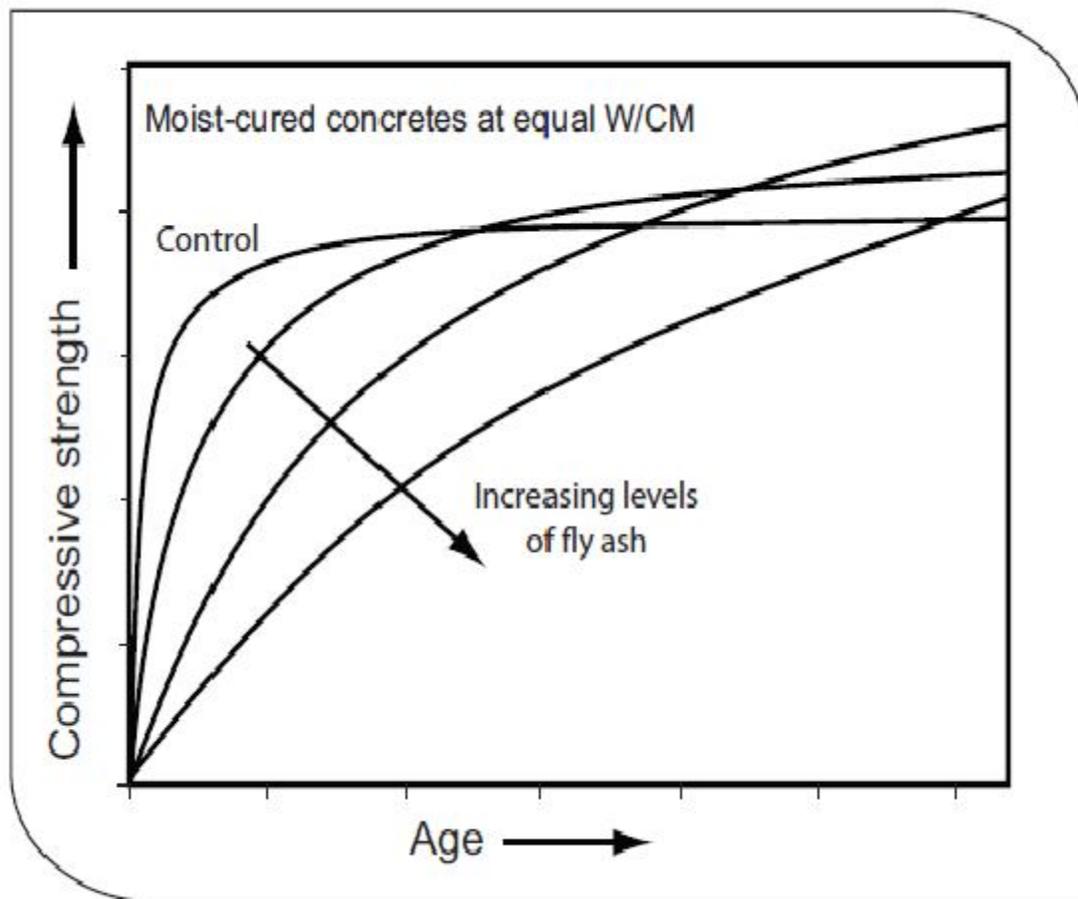
Figure (3.2): Text Book Effect of Fly Ash on Compressive Strength and Development of Concrete (Mindess, 2003).

If the specified strength is required at 28 days or earlier this will usually require lower values of w/cm when using higher levels of fly ash. A lower w/cm can be achieved by a combination of (i) reducing the water content by either taking advantage of the lower demand in the presence of fly ash, or by using a water-reducing admixture, or both; and (ii) increasing the total cementitious content of the mix. When the strength is required at early ages (for example, 1 day) the use of an accelerating admixture may be considered.

3.2.2.1.2 Silica Fume

Silica fume, also referred to as micro silica or condensed silica fume, is a byproduct material that is used as a pozzolan .This byproduct material is a result of the reduction of high-purity quartz with coal in an electric arc furnace in the manufacture of silicon or ferrosilicon alloy. Silica fume rises as an oxidized vapor from the 2000°C (3630°F) furnaces. When it cools it condenses and is collected in huge cloth bags. The condensed silica fume is then processed to remove impurities and to control particle size.

The relative density of silica fume is generally in the range of 2.20 to 2.5. portland cement has a relative density of about 3.15. The bulk density (uncompacted unit weight) of silica fume varies from 130 to 430 kg/m^3. Silica fume is sold in powder form but is more commonly available in a liquid. Silica fume is used in amounts between 5% and 10% by mass of the total cementitious material. It is used in applications where a high degree of impermeability is needed and in High Strength Concrete. Silica fume must meet ASTM C 1240. ACI 234 (1994) and SFA (2000) provide an extensive review of silica fume (Mindess et al, 2003).

Properties of Silica Fume

Properties of silica fume concrete (SFC): The principle physical effect of silica fume in concrete is that of filler, which because of its fineness can fit into space between cement grains in the same way that sand fills the space between particles of coarse aggregates and cement grains fill the space between sand grains. The important properties of silica fume concrete (SFC) in fresh and hardened states are presented below:

(a) Workability

The property of concrete which determines the amount of useful internal work necessary to produce full compaction is known as workability. The workability of fresh concrete depends mainly on the material, mix proportion and environmental conditions. Fresh concrete containing silica fume is more cohesive and less prone to segregation than concrete without silica fume. As the silica fume content is increased, the concrete may appear to become sticky. (Bayasi and Zhou, 1993) reported that it has been the general practice of researchers and designers to alter the mixture proportion of plain concrete (without silica fume) upon the incorporation of silica fume. This has been done to overcome the adverse effect of silica fume on fresh mixture workability. (Srivastava et al, 2012) concluded that at 10% replacement of cement by silica fume, the workability increased in the range of 5 - 6.25% even after reduction of super plasticizer's dose (Mindess et al, 2003).

(b) Compressive strength

Strength of silica fume concrete is affected by several factors viz. Type of cement, quality and proportion of silica fume and curing temperature. The main contribution of silica fume to concrete strength development at normal curing temperature takes place from about 3 to 28 day. The contribution of silica fume to strength development after 28 day is minimal (ACI, 234R- 96, 1996). (Sengupta and Bhanja, 2003) reported that inclusion of silica fume in the range of 5-25% increases compressive strength about 6-30% for water/cement ratio in the range of 0.26-0.42, (Srivastava et al, 2012) reported that at 10% replacement level, compressive strength increased in the range about 10-17% at different water/cement ratio (0.25-0.45). (Mindess et al, 2003).

3.2.2.2 Chemical Admixtures

Chemical admixtures are essential for the production of High-Strength Concrete. Because of the high surface area of cement, it is impossible to attain workable mixtures with low w/cm ratios without the use of High Range Water-Reducing Admixtures (HRWRA) or super plasticizers. High cement factors also increase the cost of concrete and increase problems related to the high heat of hydration. Thus, chemical admixtures are used to increase workability, decrease the w/cm ratio, and reduce cement content.

In North American practice, High-Strength Concrete produced during the 1970s used combinations of water reducers and retarders to attain workable, low w/cm ratio mixes. Today, however, virtually all High -Strength Concretes use super plasticizers to attain the desired workability and w/cm ratio. These ASTM C 494 Type F admixtures are often used in combination with conventional water reducers (Type A), retarders (Type B), combination water reducers and retarders (Type D), and combination super plasticizers and retarders (Type G). In the mix design process, the water in the admixtures should be included in the calculation of the w/c or w/cm ratio. All super plasticizers do not behave in the same way, and the behavior of an individual super plasticizer alone or in combination with other admixtures may change depending on the dosage level and the composition of the cement (especially C_3A, C_4AF and sulfate). Accelerators (ASTM C 494 Type C admixtures) are not recommended for use in the manufacture of High-Strength Concrete.

In the mixing operation, a portion of the admixtures should be added as the concrete is batched to assist in initial mixing. The initial dose may consist of any or

all of the admixtures used to reduce the water requirement or retard set or both. The balance of the admixtures is normally added al the job site. The total dosage rate used in High Strength Concrete usually exceeds the manufacturer's "recommended rate." The use of a water reducer or super plasticizer during initial mixing is necessary to insure adequate mixing at the low w/cm ratio. The addition of super plasticizer at the job site not only helps gain the required workability for placement, but also results in a reduction of the amount of admixture required, since super plasticizers are more efficient when added after the cement has been wetted. The sensitivity of concrete properties to combine cement-admixture system requires that trial batches be used to establish optimum dosage rates. If concrete workability is lost during the construction process, super plasticizers can be added to regain the lost workability (Mindess et al, 2003).

(a) Effects of "HRWR" on The Properties of Fresh Concrete

High Range Water Reducing Admixtures (HRWRA) cause dramatic increase in workability as measured by slump test, or alternatively allows very large decrease in water/cement ratio to be made while maintaining workability. Slumps (exceeding 150 mm) can be achieved with conventional water reducers only by using over sanded mixes with very high cement contents. The use of super plasticizer allows higher slumps to be achieved using mix proportions typical of normal slump concretes without occurs of excessive segregation and bleeding. The admixture is added after initial mixing to bring the slump up to the desired level. (This is in contrast to the use of other chemical admixtures that are added with the mix water). If concrete is overdosed with a super plasticizer, it may result in a mix that is so fluid that it segregates. Fortunately, this problem can be corrected by

continuing mixing until the concrete stiffens enough to regain its cohesive properties (Mindess et al, 2003).

(b) Effects of "HRWR" on The Properties of Hardened Concrete

When admixtures are used to lower water requirements, increases in compressive strength can be anticipated. These increases can be observed in as early as one day if excessive retardation does not occur. It is generally agreed that increases in compressive strength are up to 25% greater than would be anticipated from the decrease in w/c ratio alone. Probably, this reflects the developments of more uniform microstructure when the cement is dispersed. Some refer to this phenomenon as increasing the efficiency of the cement. Thus, when used at low w/c ratios, Super plasticizers can modify type **I** cement to behave as super-high early-strength cement exceeding even the strength of a type **III**. It should be emphasized that this is result of both greater cement efficiency and greatly reduced void cement; the rate of hydration need not be increased (Sidney et al, 2003).

Very High strengths concrete can be achieved when w/c ratios are lowered below (0.4). To do this economically and without excessive generation of heat requires the cement content to be kept to normal level, while providing an acceptable slump. Super plasticizers are well suited to achieve these objectives and are used in most concretes with 28 day compressive strength exceeding 80 MPa.

Low w/c ratios also improve the rate of strength gain at early ages and can be very useful in precast concrete plant. After 24 hours of normal curing, it is possible to obtain compressive strengths that take 8 days to develop using a higher w/c ratio (e.g. 0.5). Even larger gains are realized if steam curing is used also (Mindess et al, 2003).

3.3 Production of High Strength Concrete (HSC)

3.3.1 High Strength Concrete Production Techniques

In general, there are two methods of producing HSC:-

(I) Lowering the w/c ratio, with better selection of components materials.

(II) Using chemical of mineral admixtures such as super plasticizers, fly ash and silica fume.

The most important point in increasing the strength of concrete is by proper adjustments of the mix proportions such as water/cement ratio & cement/sand ratio. Supplementary cementitious materials such as silica fume & Fly ash in combination with high range water reducing admixtures can be used to produce HSC and their use has been increased considerably during the past decade (Lee, 1993).

3.4 Construction

High-quality construction with High-strength concrete involves the same procedures used for high-quality construction with Normal-strength Concrete. However, because of the higher cementitious-material contents and the use of super plasticizers, certain aspects of the construction process should be emphasized to provide for thorough mixing and adequate consolidation, finishing, and curing.

3.4.1 Batching and Mixing

Because of the sensitivity of High-Strength Concrete to the materials used, it is especially important to have an adequate supply of all materials on hand, with minimum variations in uniformity. Cement uniformity should be evaluated in

accordance with ASTM C 917, and mineral admixtures should meet their respective ASTM specifications. Variations in fine-aggregate gradation should be limited to changes in fineness modulus of ±0.2, as applies to Normal-strength concrete.

Prior to batching, it is best to saturate all aggregate and then account for the free surface moisture in the batch weights. Saturated aggregate prevents additional slump loss during mixing and placing operations, and water in aggregate pores can serve as a reservoir for water of hydration after the concrete has set. Prevention of slump loss due to continued absorption of mix water by aggregates is especially important for High-strength concrete, since super plasticizers maintain slump for only a short period of time. Provision may be needed for dispensing a super plasticizer at the job site.

The batching and mixing sequence should be planned to ensure thorough dispersion and mixing of all component. High slump is often used, through the addition of super plasticizers, to aid in the mixing process. Most admixtures are more effective when added after the cement has been wetted. However, some plasticizing admixture is usually needed to obtain initial mixing of water and cement.

Temperature control is more important for High-strength concrete than it is for Normal-strength concrete, with placement recommended at concrete temperatures of 15 to 25°. Placement at a higher temperature risks a significant reduction in the setting time due to the heat generated by the high cement content and the progressively limited working life of super plasticizers as temperature rises (Sidney, Francis, David, 2003). Below 10°C, naphthalene super plasticizers become

viscous, causing problems with their dispersion in water, and excessive retardation may occur. If necessary, during placement, slump should be maintained by reducing with a super plasticizer since such additions will restore workability and usually result in an increase in compressive strength.

3.4.2 Placing, Finishing, and Curing of High Strength Concrete

Due to the rapid loss of workability exhibited by High-Strength Concretes, speed is important in all aspects of the construction process. The cohesive consistency of most High-Strength Concretes often makes it "stick" so that it is difficult to provide a smooth trowel finish. A special area of difficulty involves the use of High-strength concrete containing silica fume in flatwork, such as overlays for highway bridges and parking structures. The lack of bleeding means that, as the surface water evaporates it is not replaced from below, so that these concretes are particularly susceptible to plastic shrinkage cracking. In such cases, the area of placement needs to be limited, finishing operations completed, and protective covering provided before plastic shrinkage cracking can occur. The use of fog spray and evaporation retardants are highly advantageous in reducing the rate of evaporation.

At the low w/cm ratios used for High-strength concrete, complete hydration cannot take place. This however, does not mean that curing is unimportant, since problems involved with surface drying should not be added to drying that occurs due to self-desiccation. Ponding provides the best option for curing, followed by covering with a wet absorbent material, such as burlap, that is in turn protected from loss of moisture by a plastic membrane. After initial curing, preferably for at least seven days, continued curing under ambient conditions provides adequate strength gain

in most cases due to the ability of the low-permeability concrete to maintain initial moisture contents at depth (Mindess et al, 2003).

3.5 Properties of High Strength Concrete "HSC"

High-strength Concrete differs from Normal-Strength Concrete principally in its higher density, its greater uniformity, and the lower porosity of the cement paste matrix. The unhydrated cement particles, which are stronger than the surrounding hydration products, add significantly to strength while also reducing the permeability of the paste. As strength increases, the stiffness of the paste constituent becomes progressively closer to that of the aggregate particles. When silica fume is used, the structure of the interface between cement paste and aggregate is densified, resulting in an increase in bond strength and decrease in permeability. Ultimately, these changes affect the engineering properties of High-Strength Concrete.

3.5.1 Properties of Plastic Concrete

Plastic High-Strength Concrete looks and behaves differently from Normal-Strength Concrete. Because of the high cementitious material content, the low w/cm ratio, and the use of super plasticizers, the cement paste constituent of plastic High-strength concrete has a generally sticky, honey-like consistency, resulting in a more cohesive mixture than is obtained for conventional concretes. This is true even at high slumps. When silica fume is used, the concrete exhibits very low bleeding, which often has a negative impact in the formation of plastic shrinkage cracks unless special precautions are taken to limit the rate of evaporation from the concrete surface. The cohesiveness of the mix is evident in the slump test in which, upon lifting the slump cone, the concrete is seen to slowly displace over a period of

several seconds. The sticky consistency of the concrete can make the attainment of a smooth finish difficult.

For High-Strength Concrete containing portland cement and fly ash, ACI 211.4R recommends slumps of 25 to 50 mm prior to the addition of a super plasticizer and 50 to 100 mm if a super plasticizer will not be used. For many applications, however, water contents significantly below those needed to give measurable slumps are used, requiring the use of a water reducer or super plasticizer to allow initial mixing. While 50 to 100 mm slumps are often used for High-strength concretes, it is becoming more and more common to use 180 to 200mm slumps when placing concretes with w/cm ratios in the range of 0.2 to 0.35. The higher slumps not only aid in consolidation, but also help ensure thorough mixing, which is critical in the production of High-strength concrete. Since most High-strength concrete uses a super plasticizer to attain the desired workability, mix design and construction procedures must take into account the potential for rapid slump loss. The rate of slump loss cannot be predicted for a particular mix, since this behavior depends on many factors. As a result, direct observation of the tendency for slump loss is required during laboratory and field testing to ensure that problems will not develop at the construction site. When added at the correct level, super plasticizers do not increase segregation, but overdosing the mixture can result in severe segregation and retardation of the mix. These problems can usually be overcome by continuing the mixing process until the concrete begins to set, although this may require several hours (Mindess et al, 2003).

3.6 High Strength Concrete (HSC) Mix Proportions

The procedures used for the design and production of HSC differs from those used for NSC, due principally to the greater sensitivity of higher concrete strengths to the specific materials and construction methods used.

HSC_S have a much lower w/c ratios and total water contents than conventional concretes. Since mineral admixtures are nearly always used in HSC, the water/cementitious material ratio w/cm rather than w/c ratio should be used in mix design. Values of w/cm ratio in the range of 0.2 to 0.35 are commonly used, with water contents in the range of 125 to 135 kg/m^3. The production of low w/cm ratio mixes requires the use of super plasticizers in turn allow for the production of concrete with a 180 to 230 mm slump (Mindess et al, 2003).

3.6.1 Cement Proportions

The cement quantity proportioned into a high-strength mixture has been determined best by the fabrication of trial batches. Common cement content in HSC test programs range from 392 to 569 kg/m^3. In evaluating optimum cement content, trial mixes usually are proportioned to equal consistencies, allowing the water content to vary according to the water demand of the mixture (ACI committee 363, 1992).

3.6.2 Aggregate Proportions

In the proportioning of HSC, the aggregates have been a very important consideration since they occupy the largest volume of any of the ingredients in the concrete.

(a) Fine Aggregate

In proportioning a concrete mixture, it is generally agreed that the fine aggregates or sand have considerably more impact on mix proportions than the coarse aggregate. The fine aggregate contain a much higher surface area for a given weigh than do the larger coarse aggregate. Since the surface area of all the aggregate particles must be coated with a cementitious paste, the proportion of fine to coarse can have a direct quantitative effect on paste requirements. Furthermore, the shape of these sand particles may be either spherical, sub angular, or very angular. This property can alter paste requirements even though the net volume of the sand remains the same. (ACI 211-4R), recommends coarse sands for High Strength Concrete, with values of fineness modulus in the range of 2.5 to 3.2, and values of 3.0 or greater generally preferred (ACI committee 363, 1992).

(b) Coarse Aggregates:

The optimum amount and size of coarse aggregate for given sand will depend to a great extent on the characteristics of the sand. Most particularly it depends on the fineness modulus (FM) of the sand. This is brought out specifically in Table (3.1), which is taken from (ACI 211-4R). Table (3.1) might be increased by up to 4 percent if sands with low void contents are used. If the sand particles are very angular, then it is suggested that the amount of coarse aggregate should be decreased by up to 4 percent from the values in the table. Such adjustments in the proportion of the coarse aggregate and sand have been intended to produce concretes of equivalent workability, although such changes will alter the water demand for a given slump (ACI committee 363, 1992).

Table (3.1):- Volume of Coarse Aggregate (Rodded) per Unit Volume of Concrete for HSC (From ACI 211.4R).

Maximum size of coarse aggregate in (mm)	Volume of Dry-Rodded coarse aggregate per unit volume of concrete for sands with fineness modulus from (2.4 to3)			
	2.4	2.6	2.8	3.0
9.5	0.5	0.48	0.46	0.44
12.5	0.59	0.57	0.55	0.53
19	0.66	0.64	0.62	0.6
25	0.71	0.69	0.67	0.65

3.6.3 Water Content

To achieve a high strength with reasonable cement content requires both a low water-cementitious material ratio and low water content. For higher strengths, efficient mix designs are produced by significantly lowering the water content to values below 145 kg/m^3, preferably in the range of 125 to 135 kg/m^3.

3.6.4 Water-Cementitious Material Ratio

The production of High-Strength Concrete requires, quite simply, the use of a low w/cm ratio. The value of the w/cm ratio depends on the desired strength, the age at which the desired strength is to be achieved, and the strength-producing properties of the particular combination of materials used in the concrete, including the

cement-admixture combination and the aggregate quality, grading, and maximum size. Depending on the required strength, the w/cm ratio may range from 0.22 to 050. The need to run trial batches is emphasized by the scatter in strength versus w/cm ratio relationships. (Neville, 2002) point out that a w/cm ratio of about 0.22 represents the optimum for current cements and admixtures; above 0.22, the w/c ratio law governs, while below 0.22, a sufficiently dense cement-paste matrix cannot be obtained using current methods of field placement and consolidation. ACI 211.4R provides recommended maximum values of the w/c ratio for concretes containing super plasticizers. Below w/cm = 0.4, full hydration of the cement will not occur because of space limitations. The concern, however, is to ensure maximum possible hydration to reduce capillary porosity. The dense microstructure that develops may limit the access; of water to the interior and require longer moist curing to maximize hydration.

3.6.5 Admixtures Proportions

Nearly all HSCs have contained admixtures. Changes in the quantities and combinations of these admixtures affect the plastic and hardened properties of HSC. Therefore, special attention has been given to the effects of these admixtures. Careful adjustments to mix proportions have been made when changes in admixture quantities or combinations have been made. Material characteristics have varied extensively, making experimentation with the candidate materials necessary. Some of the more common adjustments are described below:

3.6.5.1 Supplementary Cementitious Materials

Are often used as a cement replacement. In (HSCs) they have been used to supplement the portland cement from 10 to 40 percent by weight of the cement

content. The use of fly ash has often caused a slight reduction in the water demand of the mixture, and that reduction in the volume of water (if any) has been compensated for by the addition of sand. The opposite relationship has been found to be true for other pozzolanic materials. Silica fume, for example, dramatically increases the water demand of the mixture which has made the use of super plasticizing admixtures a requirement (ACI 363, 1992).

3.6.5.2 Super plasticizers or High-Range -Water-Reducing Admixtures:

Adjustments to HSC made with high range water reducers have been similar to those adjustments made when conventional water reduces are used. These adjustments have typically been larger due to the larger amount of water reduction, approximately (12 to 25 percent) (ACI 363, 1992).