CHAPTER 2

REVIEW OF LITERATURE

2.1 INTRODUCTION

In this chapter, a brief review of literature on effect of mineral admixtures on the strength, durability aspects such as, permeability, shrinkage, corrosion resistance, alkali silica reaction and impact resistance, self compactability and toughness of high performance concrete is reported and discussed.

2.2 INFLUENCE OF MINERAL ADMIXTURES ON FRESH CONCRETE

2.2.1 General

There are three mineral admixtures namely silica fume, metakaolin and fly ash were used in this research. Silica fume is a by product of the fabrication of silicon metal, ferrosilicon alloys and other silicon alloys. Since the particles of silica fume are very small, they can enter the space between the particles of cement and thus improve packing. Metakaolin is manufactured by the high temperature treatment of specially selected kaolin under controlled conditions. Fly ash is produced from burning of pulverized coal in thermal power plants. The literatures regarding the influences of these mineral admixtures on the properties of concrete in the fresh stage are discussed.

2.2.2 Influence of silica fume

It is essential that silica fume should be dispersed uniformly in the mix. The very large surface area of the particles of silica fume, which have to be wetted, increases the water demand, so that, in mixes with low water/cement ratio, it is necessary to use
superplasticizer for the necessary workability. But the effectiveness of superplasticizer is enhanced by the presence of silica fume. The presence of silica fume affects significantly the properties of fresh concrete. The mix is strongly cohesive and hence reduces bleeding or even none. But the reduced bleeding can lead to plastic shrinkage cracking under drying conditions. The cohesiveness of concrete containing silica fume makes it satisfactory for pumping and for underwater concreting, as well as for use as flowing concrete. Pinto and Hover (2000) found that reductions in cement content and increment in superplasticizer dosage tend to retard setting, while increases in silica fume content tend to accelerate setting. Yunxing Shi et al (2002) reported that the partial replacement of cement with silica fume can improve the fluidity and rheological property of HPC. Upto 12% of silica fume content, plastic viscosity and yield stress became the maximum, and concrete had lowest fluidity. But Roncero et al (2002) reported that the addition of 5% of silica fume by weight of cement leads to a significant increase in the superplasticizer demand due to higher specific surface area.

2.2.3 Influence of metakaolin

Although it is generally acknowledged that metakaolin adversely affects the workability of concrete, no detailed examinations have been reported till date on the water demand of metakaolin and its influence on the flow properties of concrete. Shirvill’s (1992) work indicates that the reduction of 5% sand content is necessary when 10% of cement is replaced by metakaolin. Caldarone et al (1994) observed that although the slump of concrete containing 10% metakaolin was reduced from that of concrete with PC only, the metakaolin concrete required 25-35% less high range water reducers (HRWR) than equivalent silica fume mixtures. This reduction in HRWR demand resulted in the
metakaolin concrete having less sticky consistency and better finish than the silica fume concrete. Zhang and Malhotra (1995) reported that, the quantity of superplasticizer required for 10% metakaolin incorporated concrete is same as that of silica fume concrete but setting times of metakaolin concrete was shorter than normal and silica fume concrete. Wild et al (1996) found that it is necessary to employ up to 3% superplasticizer to produce moderate slumps (75 mm) in metakaolin concrete with w/b ratio of 0.45. Sabir et al (1996) reported that although it was clear that metakaolin increased water demand, the standard workability tests, i.e., slump, compacting factor and Vebe time, were not capable of quantifying the influence on the overall flow properties of metakaolin concrete, particularly at the lower w/b ratios (w/b = 0.35). Martin (1998) concluded that the greater volume of cementitious material in metakaolin concrete increases its water demand but that can be offset by the use of a single dose of a standard low-cost plasticizer. Bai et al (1999) observed that there is a systematic decrease in both slump and compacting factor and a systematic increase in Vebe time as the PC replacement level by metakaolin in their concrete mixtures increased from 0% to 15% and there is larger changes in workability occurred for the concretes with the high w/b ratios.

2.2.4 Influence of fly ash

The influence of fly ash on the properties of fresh concrete depends upon the shape of the fly ash particles. A concrete mix containing fly ash is cohesive and has a reduced bleeding capacity. The action of fly ash is similar to the action of super plasticizers with respect to water demand. The fly ash disperses and adsorbs the particles of Portland cement. Fly ash in the mix has a retarding effect, typically of about 1 hour, caused by the release of SO$_3^-$ present at the surface of the fly ash particles. Because of this retarding
effect, only initial setting is delayed, the time interval between setting and final setting being unaffected. Dhir et al (1986) have demonstrated that the addition of fly ash improves the dispersion of the Portland cement particles, improving their reactivity. Cabrera and Plowman (1987) found that the depletion of calcium hydroxide (lime) with time and this reaction affects the long term gain in strength of fly ash concrete compared to a normal concrete. The reaction takes place both within the pores of the cement paste and on the surface of fly ash particles. Using fly ash in concrete will increase the setting time compared with an equivalent grade of normal concrete. Cengiz (2002) found that higher replacement level of fly ash will reduce the temperature rise and with high dosage of superplasticizer it will cause retardation in hydration.

2.3 STRENGTH CHARACTERISTICS OF HIGH PERFORMANCE CONCRETE

2.3.1 General

In high performance concrete with a very low water/binder ratio, hydration stops within the concrete long before 28 days due to lack of water or when the partial pressure of water vapour within the pores has reached the 80% limit below which hydration is slowed down very significantly (Powers and Brownyard (1948)). Aitcin, Sarkar and Laplante (1990) found that there is some small retrogression in strength due to the drying of a very thin layer of the skin of the high performance concrete. This strength retrogression of HPC is due to severe drying conditions. Hence it is emphasized that proper early water curing is much more important for HPC, especially when most of the hydration reactions are taking place. Larrard and Aitcin (1993) found that some high
performance concrete laboratory specimens experienced a slight decrease in compressive strength after a long period of curing in air, particularly those containing silica fumes. Rougeron and Aitcin (1994) reported that one of the highlighted properties of high performance concrete is early age strength which can be achieved by decreasing water content and increasing binder content with superplasticizer. The effect of silica fume, metakaolin and fly ash on the strength characteristics of HPC is discussed from the previous literature.

2.3.2 Effect of silica fume

High compressive strength is generally the first property associated with silica fume concrete. The report by Sellevold and Radjy (1983) showing that the addition of silica fume to a concrete mix will increase the strength of that mix by between 30% and 100% dependent on the type of mix, type of cement, amount of silica fume, use of plasticizers, aggregate types and curing regimes. Silica fume concrete is very susceptible to temperature variations during the hardening process. The optimum silica fume content to achieve higher strengths seems to range between 15 and 20%. Feldman and Cheng (1985), Cohen and Klitsikas (1986) and Cohen (1990) studied that there are three mechanisms namely (i) strength enhancement by pore size refinement and matrix densification, (ii) strength enhancement by reduction in content of CH and (iii) strength enhancement by cement paste-aggregate interfacial refinement are believed to be responsible for the strength development of concrete and mortars containing silica fume. (Yogendran et al. (1987), Hooton (1993), Sabir (1995) reported that the strength development in concrete with condensed silica fume is higher in the range of 12%-28%.
Hooton (1993) found that the high early reactivity of silica fume has dense microstructure of the hydrated cement paste makes it difficult for water to enter from outside, if available, to penetrate towards the unhydrated remnants of Portland cement and silica fume particles. In consequence, strength development ceases much earlier than with Portland cement alone. The contribution of silica fume to the early strength development upto 7 days is probably through improvement in packing, that is, acting as filler and improvement of the interface zone with the aggregate (Bentz et al (1992)). Larbi and Bijen (1990) explained that silica fume tends to affect the pattern of crystallization and degree of orientation of CH crystals at the aggregate surface during the first few days of cement hydration. At higher w/b ratio (0.45), with 30% silica fume the pastes exhibit higher strength between 1 and 180 days. It has been reported that lower compressive strengths were achieved at the age of 3 days, while higher strengths at 7 and 28 days with silica fume mortars (Cong et al. (1992)). Bayasi and Zhou (1993) reported that the addition of silica fume enhances the rate of cement hydration at early hours due to release of OH⁻ ions and alkalis in the pore fluids. Silica fume accelerates both C₃S and C₃A hydration during the first few hours. Calcium silicate hydrates (C-S-H) plays a vital role in influencing the characteristics of cement paste. Hydration proceeds faster in pastes with silica fume, due to both CH and non-evaporable water contents at the early ages of 3 and 7 days. However, the hydration reactions in mortar terminate earlier. After 28 days, the non-evaporable water content continues to increase significantly in plain cement concrete (Mak et al. (1995)). Ganesh Babu and Surya Prakash, (1995) had reported that the efficiency of silica fume depends on the replacement levels. But, Gutierrez and Canovas (1996) developed a model of the compressive strength of silica fume concrete.
assuming that the efficiency of silica fume is constant Ojha (1996) recommended the maximum percentage replacement is 10-15% of total binder content by weight. Shannag (2000) reported that high and very high strength concrete can be achieved with 15% silica fume and 15% natural pozzolan.

Khan and Lynsdale (2002) reported that the incorporation of silica fume content increases the early strength, but 8-12% silica fume yielded the optimum strength values. It has been reported that silica fume in concrete/mortar is an efficient pozzolanic material which results in more impermeable pore structure when compared to plain cement paste. Sinan Caliskan (2003) explained that 20% silica fume replacement with cement and addition of superplasticizer to the mortar produced a thinner interfacial zone than the plain cement mortar. That is due to silica fume densifies the microstructure by acting as a filler as well as providing secondary hydration products, while superplasticizer provides deflocculation of the cement and silica fume particles.

2.3.3 Effect of metakaolin

Some researchers (Andriolo and Sgaraboza (1986), Gold and Shirvill (1992)) reported that the incorporation of metakaolin improves the strength of concrete significantly. The results of their work indicated that the optimum level of replacement lie somewhere between 5% and 10%. Palomo and Glasses (1992) confirmed that the partial replacement of metakaolin contributes to the strength of concrete due to the filler effect, the acceleration of hydration of cement and due to the pozzolanic reaction. The use of metakaolin in high strength concrete has been proposed by a number of researchers (Balogh (1995), Calderone et al (1994)). They reported 28 day strengths of 110 MPa for concrete containing 10% metakaolin and superplasticizer. Caldarone et al (1994)
produced concretes, with 5% and 10% metakaolin, which showed enhanced strengths at ages up to 365 days. They reported that their MK-PC concretes exhibited strengths, which were slightly greater than SF-PC mixtures at the same levels of cement replacement by the pozzolans. Optimum replacement of metakaolin to give maximum long-term strength was reported by Zhang and Malhotra (1995) as 20% (referred by John and Choo (2003)). Similar influences of metakaolin on the strength of concrete have been reported by Wild et al (1996). The authors identified three elementary factors, which influence the metakaolin to improve the concrete strength. Those are the filler effect, which is immediate, the acceleration of PC hydration, which occurs within the first 24 hours, and the pozzolanic reaction, which has its maximum effect within the first 7-14 days for all metakaolin levels between 5% and 30%. In a recent study by Brooks et al (2000) has shown that as with silica fume and fly ash, metakaolin has the effect of retarding the setting time of high strength concrete. In general, as replacement levels of the pozzolanas were increased, there was greater retardation in setting times. However, for the concrete containing metakaolin, this was only observed up to a replacement level of 10% (Xiaoqian qian and Zongjin Li, 2001). But, Shreeti et al. (2003) reported that for w/b ratio, 0.3, the 10% replacement by weight of cement yields maximum strength and for other trial tests, strength increases even with 15% metakaolin.

2.3.4 Effect of fly ash

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 to continued pozzolanic reactivity of fly ash in concrete, it develops greater strength at later
age, which may exceed that of the concrete without fly ash. Quantified predictions of the influence of fly ash on strength are not possible. Portland Cement Association (PCA) reported that the positive influence of fly ash upon strength even as late as one year and excessive content of fly ash is not beneficial from the point of view of strength development. Gopalakrishnan et al. (2001) reported from their work that the 7 day compressive strength of concrete mixes, having fly ash as cement replacement material up to 25 percent is slightly less than that of the control concrete mix, and marginally more than that of the control concrete mix at the age of 28 days. Potha Raju and Janaki Rao (2001) mentioned that, the 28 day compressive strengths were equal or slightly more in 20% fly ash replaced concrete at elevated temperatures up to 250° C than in no fly ash concrete.

2.4 DURABILITY OF HIGH PERFORMANCE CONCRETE

2.4.1 General

One of the principal reasons for the deterioration of many concrete structures stems from the fact that, in the past and even now, too much importance has been given to concrete compressive strength when designing concrete structures and not enough to the environmental factors that the structure will have to face while performing its structural function. However, in recent years a new attitude can be perceived towards durability in various national codes of Japan, Australia, Europe (Rostam and Schissel (1993)) and Canada. When looking at concrete from a durability point of view, it has been found that the high slumps achieved when using superplasticizers create a new type of heterogeneous zone along the forms or at the top surface of the concrete. This zone has
become known as the 'concrete skin' (Kreijger (1987)), 'outer skin' (Bentur and Jaegermann (1991)), 'concrete cover' (Halvorsen (1993)) or simply as 'covercrete'. Parrot (1992) recognised the importance of concrete skin (the outermost 5 to 10 mm) from the durability point of view, in spite of the fact that the concrete skin does not have exactly the same composition and microstructure as the interior of the concrete, owing to the so-called 'wall effect'. When a high performance concrete is plastified so that its slump is maintained, there is a little risk of segregation, because the mix is quite rich and quite thixotropic, but it is observed that the wall effect is greatly increased when the slump increases. The use of permeable forms seems to be an option very often used in Japan (Katayama and Kabayashi (1991), Sugawara et al. (1993)) to improve the durability and aesthetics of concrete skin. Shannag and Shaia (2003) reported that HPC that contains silica fume and natural pozzolan can provide a good balance between strength and durability.

Among the various mineral additives used in concrete structures, silica fume is highly favoured for its superior concrete durability properties (Durning (1991) and Wolsiefer (1991)). The influence of silica fume on permeability is more than on compressive strength. The reduction in the diffusivity of chlorides due to the presence of silica fume in hydrated cement paste is larger at water/cement ratio greater than 0.4. The sulphate resistance of concrete containing silica fume is good, partly because of a lower permeability, and partly in consequence of a lower content of calcium hydroxide and of alumina, which have become incorporated in C-S-H. Silica fume is particularly very effective in controlling expansive alkali-silica reaction. Shrinkage of concrete containing silica fume is somewhat more than in Portland cement concrete.
John Newman and Ban Seng Choo (2003) reported that metakaolin is a very reactive pozzolan. In the presence of water, it reacts with calcium hydroxide to produce stable, insoluble cementitious hydrates. This pozzolanic reaction reduces the permeability and porosity of cement paste making it stronger and significantly more durable. The use of metakaolin as a partial replacement for cement in suitably designed concrete mixes improve acid resistance, sulphate resistance, freeze-thaw resistance, increase resistance to the penetration of chloride ions and eliminate alkali-silica reaction.

Initially, the concrete with fly ash has a higher permeability than concrete without fly ash with a similar water/cement ratio. However, with time, fly ash concrete acquires a very low permeability. High fly ash contents with water/cement ratio between 0.27 and 0.39 have shown a very good resistance to chloride penetration. Fly ash in adequate quantity is reducing the alkali-silica reaction.

The pozzolanic reactivity reduces the calcium hydroxide content, which results in reduction of passivity to the steel reinforcement and at the same time the additional secondary cementitious material formed makes the paste structure dense; and thereby gives more resistance to the corrosion of reinforcement. Sufficiently cured concrete containing good fly ash shows dense structure and offers high resistivity to the infiltration of deleterious substances.

Thomas (1990) reported that cores taken from 30 year old structures in general have performed well; such structures must have been made with unclassified fly ashes over which minimal control of fineness, loss of ignition (LOI), etc. would have been exercised.
2.4.2 Effect of mineral admixtures on permeability

Permeability is defined as the ease with which external elements such as liquids and gases penetrate concrete, which is considered to be one of the most important properties affecting concrete durability.

In studies of Sellevold et al (1982 a) the efficiency factor with respect to durability for silica fume concrete was between 6 and 8. This indicates that the physical size and high reactivity of the silica. The ASTM test C1202:1944 has been used to assess the ability of metakaolin concrete to resist the penetration of chloride ions. As the silica fume reacts, and produces the calcium silicate hydrates, the voids and pores within the concrete are filled as the crystals formed bridge the gaps between cement grains and aggregate particles. Coupling this with the physical filling effect it can be seen that the matrix of the concrete will be very homogenous and dense, giving improved strength and impermeability (Diamond (1986)). Calderone et al. (1994) and Zhang and Malhotra (1995) reported that the resistance of metakaolin concrete to the penetration of chloride ions was significantly higher than that of plain concrete. The influence of silica fume upon the permeability of concrete is greater than the tests on hydrated cement pastes because in the former case, silica fume reduces the permeability of the transition zone around the aggregate particles, as well as the permeability of the bulk paste (Khayat and Aitcin (1992)). HRM exhibits performance similar to that containing silica fume in terms of strength and permeability (Caldarone et al and Marsh (1994)).

Austin (1997) found that the silica fume concrete's permeability reduced more rapidly during the first two months, due to the pore refining effect in this period. Hassan et al (2000) in their report, gave the beneficial effect of hot weather curing on condensed silica...
fume concretes is clearly reflected in the permeability and strength measurements. 10% silica fume enhances the early ages as well as the long term properties of concrete. It reduces the permeability by 71% and 87% at 1 and 365 days, respectively, when compared to normal concrete.

2.4.3 Effect of mineral admixtures on corrosion resistance

The phenomenon of reinforcement corrosion and consequent damage to concrete is increasingly being recognized as one of the menacing durability problems in reinforced concrete structures. Since the time the problem was identified, considerable research works have been carried out worldwide and a reasonable understanding is now available on the process, mechanism and influencing factors of reinforcement corrosion. Building Research Station, UK said that accelerated normal corrosion is due to the presence of free calcium chloride and stress corrosion takes place in presence of free calcium chloride (Rengaswamy and Rajagopalan (1977)). In 1997, Mullick stated that supplementary cementing materials reducing the incidence of corrosion of reinforcement in concrete due to the formation of a denser microstructure of the C-S-H. This denser microstructure formation is due to additional hydration products formed by the pozzolanic reactions of supplementary cementing materials. He also stated that the supplementary cementing materials like fly ash, GGBS and silica fume possessing lower electrical conductivity thus increases the resistance to the flow of corrosion currents in concrete. Recently, in 2002, he explained the other aspect that the addition of fly ash reduces the diffusivity and correspondingly reduces the penetration of chloride ions from external sources inside concrete. Coleman and Page (1997) have shown that cement pastes blended with 10% or 20% metakaolin exhibited higher capacities than plain PC pastes, to bind chloride ions.
introduced by contamination of the mix water, thus reducing the Cl\textsuperscript{−} concentration in the pore solution. Hence he concluded that inclusion of up to 20% metakaolin will have little effect on the risks of chloride induced corrosion of embedded steel. The use of silica fume in concrete improves the resistance to corrosion of steel because of electrical resistivity by the pore filling effect (Selvaraj et al (2003)). Cement should be chosen suiting particular application of concrete and depending on the nature of aggressive environment prevailing in or around the concrete (A.K. Gupta (2003)).

2.4.4 Effect of mineral admixtures on the shrinkage of concrete

Shrinkage is a common phenomenon generally encountered in almost every cementitious product due to contraction of total mass upon loss of moisture. Though it is a multidimensional contraction, the drying shrinkage of concrete is normally measured in the largest dimension of the body. In concrete, the shrinkage is related to the aggregate volume and aggregate quality and many reports are available. The incorporation of silica fume in concrete always lead to water demand and, therefore, it is generally used with a super-plasticizer. The resulting concrete has a greater tendency of plastic shrinkage cracking (ACI 226 (1987)). This occurs when there is rapid surface drying due to environmental conditions, and little or no bleed water is available for replacing the lost moisture. Curing the concrete under water can prevent this type of shrinkage.

Many investigators (Buil and Acker (1985), Paulson et al. (1991), de Larrard and Malier (1992)) have found that total shrinkage under drying conditions decreases with increase in silica fume content and compressive strength. Others have observed that it does not change much (ACI 226 (1987)) as long as the water cementitious ratio is constant. Due to the difference in particle size between Portland cement and silica fume, Cohen et al.
(1990) reported that maximum tensile capillarity pressure in Portland cement paste with 0% and 15% silica fume content was 0.02 and 4 MPa, respectively. Also, the plastic shrinkage cracking in paste with 85% Portland cement and 15% silica fume was several times higher than plastic shrinkage cracking in cement paste without silica fume. The incorporation of metakaolin in concrete reduces the drying shrinkage because of the reduced water loss on drying. This is due to the cementitious matrix containing cement and metakaolin is of low porosity and permeability. Caldarone et al (1994) showed that the drying shrinkage of metakaolin concrete was lower than that of plain concrete but similar to that of concrete containing micro silica. Al-Sugair (1995) stated that the incorporation of silica fume increases the drying shrinkage by some amount that depends greatly on the drying conditions, the temperature and relative humidity. Hammer (2001) from his experimental results stated that, the content of silica fume in a high strength concrete (HSC) up to 15% by cement weight, added as volume replacement for cement, does not have significant effect on plastic shrinkage at moderate drying conditions. He also reported that no significant effect on the pore pressure development at the surface, while 15% may have an accelerating effect on the pore pressure decrease, and thus, the development of the tensile strain capacity. Jianyong and Yao Yan (2001) reported that creep and drying shrinkage will be greatly reduced by use of silica fume. From their report, it is understood that the amount of creep and drying shrinkage of HPC containing silica fume is much smaller than that of high strength concrete without the supplementary binders under the same conditions.
2.4.5 Effect of mineral admixtures on impact strength

Although plain as well as fiber reinforced concrete have shown to be stress rate sensitive under all modes of loading, the significant variability in the published literature; the data appear to be strongly dependent on the type of machine to find the impact strength used. In addition, the exact mechanisms responsible for the stress rate sensitivity are poorly understood. Therefore, a need to continue our efforts to understand the fundamental properties of concrete under impact loads.

ACI committee 544 recommends the use of a repeated impact drop weight test to qualitatively estimate the impact resistance of composites. Dellaripa and Reddy (1987) reported that the addition of fibers improves the fracture and impact resistance of concrete to a great extent. Balasubramanian et al (1996) found that the impact resistance of the concrete was significantly improved with the addition of steel fibers. Tensing et al (2002) reported that the addition of 2% steel fibers by weight and 20% fly ash increases the impact strength by 2.5 times than that of normal concrete without fly ash and steel fibers.

2.4.6 Effect of mineral admixtures on alkali silica reaction

Alkali silica reaction (ASR) is more wide spread, and is more harmful to the mechanical properties of concrete. ASR is an internal chemical reaction between the alkaline components in the cement and active silica-based mineral constituents of some aggregate. The reaction results in the formation of a gel that absorbs water, expand, and therefore exerts internal pressure which sometimes can be far in excess of what concrete can sustain, thereby causing the formation of micro-cracks. The normal dosage of microsilica, i.e. 10% by weight of cement, can negate the main factors that could lead to alkali-
silica reaction and many reports are available (Asgeirsson and Gudmundsson (1979), Perry and Gillott, (1985)) also confirm this. Andriolo and Sgaraboza (1986) found that the use of metakaolin prevented expansion due to alkali-silica reaction. They reported additional beneficial effects resulting from the use of metakaolin such as (i) Substantially increased compressive strength of concrete, permitting a reduction in the amount of binder used (ii) Reduced bleeding of the concrete (iii) Substantially reduced temperature rise in mass concrete. For coarser fly ashes, a minimum of 30% fly ash may be required to ensure sufficient surface area to prevent ASR. Even when total alkalis within the concrete are as high as 5 kg/m³, fly ash has been found (Alasali and Malhotra (1991)) able to prevent ASR. The effect of alkalis from external sources on the alkali-silica reaction has also been demonstrated by Walters and Jones (1991). Kostuch (1993) confirmed from their laboratory experiments that the ASR can be suppressed by using metakaolin in concrete containing reactive combinations of aggregates. Concrete Society Technical Report 30, (1999) reported that ASR is a potentially very disruptive reaction within concrete. It involves the higher pH alkalis such as sodium and potassium hydroxides reacting with silica, usually within the aggregates, producing gel. This gel has a high capacity for absorbing water from the pore solution causing expansion and disruption of the concrete. Further, it has been reported by Kostuch et al (1993) and Gruber et al (2001) that metakaolin prevents expansion due to ASR even when reactive aggregates and high alkali cements are used. Aquino et al (2001) found that silica fume and high reactivity metakaolin performed similarly in controlling expansion due to alkali silica reaction in mortar bars. Marzouk and Langdon (2003) concluded that the effect of alkali aggregate reaction on the mechanical properties of high strength concrete were
minimal. The superior performance of high strength concrete can be explained by the improved microstructure and decreased permeability of the calcium silicate hydrate gel that resulted from the pozzolanic reaction.

2.5 MIX PROPORTIONING FOR HIGH PERFORMANCE CONCRETE

2.5.1 General

The mixture proportioning method for high performance concrete only provides a starting mix design that will have to be more or less modified to meet the desired concrete characteristics. There are some drawbacks to apply the procedure given in ACI 211-1-91(1993) for usual concrete to high performance concrete. They are

- The slump of HPC is essentially dependent not only on mixing water but also on the amount of superplasticizer.
- Coarse aggregate should be selected as small as possible.
- The suggested values in ACI 211-1 not appropriate to make HPC freeze-thaw resistant.
- Water cement ratio used in ACI 211 no longer valid because supplementary cementing materials are used.

Then ACI 363 Committee (1993) proposed a mix design for High strength concrete in which the maximum size of aggregate suggested was 19 or 25 mm for concrete with strength less than 65 MPa and 10 or 13 mm for concrete made with strength greater than 85 MPa. The formula has been suggested to find the dry weight of coarse aggregate. A computerized programme has been developed from this method and is currently used in France under the trade name of BETONLAB (Sedran and Larrard, 1996).
Mehta and Aitcin (1990) proposed a simplified mix proportioning procedure that is applicable for normal weight concrete with compressive strength values of between 60 and 120 MPa. The method is suitable for the coarse aggregates varying a maximum size between 10 and 15 mm and slump values of between 200 and 250 mm. It assumes that non-air which can be increased to 5 to 6% when the concrete is air-entrained. The optimum value of aggregate is suggested to be 65% of the volume of the high performance concrete. Aitcin (1998) proposed a very simple method which can be used for both air entrained and non-air entrained high performance concrete. The procedure involves the following steps: water binder ratio (from the graph), water content (from table depending upon the saturation point of superplasticizer), superplasticizer dosage (assume 1% if saturation point is not known), coarse aggregate content as a function of its shape and entrapped air content (assumed value).

Francois de Larrard and Thierry Sedran (2002) proposed a mix proportioning for high performance concrete considering packing density and segregation ability of dry packing particles. They focused on the properties of fresh concrete and the mechanical properties of hardened concrete using a model of aggregate particles surrounded by a cement-based matrix. The practical example is also presented, dealing with the design of special HPC for pavement application.

2.5.2 Mix proportioning based on the efficiency factor for mineral admixtures

The efficiency of a pozzolan is generally defined in terms of the strength characteristics with the control concrete as the reference. However, knowing the improvement in durability due to the addition of pozzolanas, it is well recognized that other characteristics like durability factors can also be used for such an evaluation, though the exact
methodology of the durability test has to be clearly defined. But it is accepted that, in general, the strength of the concrete is a reasonable indicator of the durability for at least the well-designed concretes. Smith (1967) proposed a factor known as the cementing efficiency \( k \) such that a mass \( f \) of fly ash would be equivalent to a mass \( kf \) of cement in terms of strength development. He found that the strength and workability of the fly ash concrete with effective w/b ratio \( w/(c+ kf) \), is comparable to that of the conventional concrete without fly ash having same water content and w/b ratio. Based on his experimental results, the value of the cementing efficiency factor \( k \) was reported to be 0.25 up to 25% fly ash as MA. The effectiveness of superplasticizer (SP) depends on the dosage used, ambient temperature, cement chemistry, fineness and other characteristics of the binder. When the water content decreased in a concrete mix for a given w/c ratio, correspondingly the cement content decreases but at the same time the amount of SP needed to achieve the desired workability increases. Thus the saving in the cost of cement can compensate for the extra cost of SP (Rougeron and Aitcin (1990)). Hence it is necessary to obtain optimum dosage of superplasticizer to achieve the required workability. A recent study on concretes containing different cements and fly ashes (fly ash contents up to 28% and with water cement ratios varying between 0.5 and 0.65) has shown that a value of 0.5 is more appropriate for the efficiency factor (Schiessl and Hardtii (1991)). They pointed out some variation in efficiency factor with percentage replacement and age. One important contribution of this work was that it defined explicitly the consequent reduction in water cementitious materials ratio of fly ash concrete as compared to the water cement ratio of the reference concrete.
The CEB-FIP model code (1994) proposed an efficiency value as 0.4 for replacement levels between 15% and 40% fly ash. Munday et al (1983) observed that this method based on efficiency was insensitive to the type of cement, curing conditions etc., and hence not suitable for rich mixes. Ganesh Babu and Siva Nageswara Rao (1993) reported that the contribution of the fly ash is not a constant determined solely by its physical and chemical characteristics but also varies depending on the type of cement, w/c ratio etc. Siva Nageswara Rao (1996) proposed two efficiency factors, first, a general efficiency factor and the second factor, correspond to the percentage replacement. If the efficiency factor is known, the strength of MA mixes can be determined by modifying the Bolomey (1927) equation referred by Bharatkumar et al (2001) as

\[
S = \frac{A_1}{c/w} + A_2 \quad \text{for no MA Mix} \\
S = \frac{A_1}{(c+kf)/w} + A_2 \quad \text{for MA Mix}
\]

(2.1) (2.2)

where \(S\) is the compressive strength in MPa, \(c\) is the cement content in kg/m³, \(f\) is the MA content in kg/m³, \(k\) is the efficiency factor and \(A_1, A_2\) are arbitrary constants. These arbitrary constants are reported to be influenced by type, size and grading of aggregate, type of cement, period of curing etc (Gilkey (1961)). Hence, it is necessary to obtain strength to effective w/b ratio relationship for a given set of materials and for the same workability. Babu et al (2000) proposed a method to assess the efficiency of the pozzolanas under various conditions at the different percentages of replacement. Also a new method suggested for the proportioning of concretes with pozzolanas using those efficiency factors. Bharatkumar et al (2001) proposed a mix proportioning method to
obtain strength to effective w/b ratio relationship for a given set of materials and for the same workability. When MA is used, its effect on the strength of concrete varies significantly depending on the properties of MA and with the characteristics of concrete mixture. Bhanja and Sengupta (2002) developed a mathematical model to predict a 28 day compressive strength of silica fume for w/c = 0.3 to 0.42 with 5% to 30% silica fume. They obtained the 28 day strength ratio between silica fume and control concrete as

$$f_{SF}/f_c = 1.0063 + 0.0159 \text{ (SF %)} + 0.0007 \text{ (SF %)}^2 - 0.00003 \text{ (SF %)}^3$$  \hspace{1cm} (2.3)

Papadakis et al (2002) proposed a faster procedure for experimental determination of the $k$ value using the concept of pozzolanic activity index.

2.6 SELF COMPACTING HIGH PERFORMANCE CONCRETE

2.6.1 General

While designing the mix proportions for self compacting concrete without segregation and bleeding some test methods to be followed for evaluation. And also some viscosity modifiers can be added if necessary.

Test methods to evaluate self-compactability

There are many test methods developed by different researchers to check the self compactability. Kuroiwa (1993) suggested the slump cone test which could be assumed to be a measure of material viscosity to measure the time to reach a slump flow of 500 mm and called it as flow speed. A value of flow speed between 4 and 10 seconds was recommended. Sakomoto et al (1993) used a similar approach but suggested a slump flow of 600 mm to assess the flow speed and recommended that it should be reached in 10-20 seconds. Yonezawa et al (1989) and Mitsui et al (1995) developed a handy
Viscometer suitable for field applications called L-flow tester which is a modification of conventional slump flow tests. According to Mitsui et al (1995), concretes with the same slump are expected to have the same shear yield stress. When such mixtures are tested in an L-flow meter, shear stress histories do not differ very much but the shear strain rates are expected to vary during deformation. The L-flow velocity is a parameter related to the plastic viscosity of concrete and characterized the differences in shear strain rates of the different mixtures. Kim et al (1996) have opted for a flat-bottomed box instead of U tube for the assessment of fillability and L box to assess the compactability of concrete.

**Viscosity-enhancing admixtures:**

Viscosity enhancing admixtures (VEA), also known as thixotropic agents, anti-washout admixtures, are relatively new admixtures used to enhance the cohesion and stability of cement-based systems. Such admixtures can reduce the risk of separation of the heterogeneous constituents of concrete during transport, placement and consolidation and provide added stability to the cast concrete while in a plastic state.

Mailvaganam (1995) categorized anti-washout admixtures and pumping aids into five classes according to their physical actions in concrete. Khayat (1998) critically reviewed the types and modes of action of commonly used viscosity-enhancing admixtures and highlighted their influence on the rheological properties of water and cement paste. He reported the influence of various types of viscosity-enhancing admixture on high-range water reducer demand, resistance to water dilution, static and forced bleeding, segregation, settlement, setting time and air entrainment.
2.6.2 Mix proportioning of self compacting concrete

In 1989, Ozawa et al produced the first SCC using superplasticizer and viscosity agent. They again identified the factors controlling self compactability namely coarse and fine aggregate content, and presented the paper at Canada Centre for Mineral and Energy Technology (CANMET). Okamura and Ozawa (1994) developed slump flow, funnel flow and box and U test apparatus for fillability. They recommended that while the w/b ratio of SCCs must be decided based on strength considerations, the water-powder ratio governs the self compactability in most cases. Sakata et al (1995) proposed a method of proportioning of SCC with limestone powder and concluded that the quantity of aggregate is independent of w/c and water content.

Khayat et al (1996) developed statistical models to predict flowability, wash out resistance and strength of highly flowable under water concrete. They suggested a factorial design with 8% silica fume and 20% fly ash. They concluded that VEA content, cementitious materials, dosage of SP and other coupled effects, influence the slump flow and wash out mass loss. Petersson et al (1996) identified three main criteria for the design of SCC namely (i) construction criteria (ii) void content (iii) blocking criteria. They suggest a theoretical model between blocking volume ratio of aggregate volume and ratio of clear spacing between the reinforcement to aggregate fraction size. Mortsell et al (1996) modeled fresh concrete as two-phase material with matrix of particles < 125 μm and particle phases composed of aggregates, and proposed an expression for workability parameter. Sakata et al (1996) studied the basic properties and effect of welan gum on SCC, which was found to be useful in stabilizing the rheological properties and mobility of SCC mix. General mix design methods for SCC were proposed by Petersson and
Billberg (1996), and Sedran and Larrad (1999), Yurugi and Sakai (1998). These researchers concluded that by using welan gum (a kind of Poly scharide) at 0.05% of unit water content stable flowability can be achieved. They developed both optical and capacitance type sensors for detecting filling condition in the formwork. Chai (1998) checked whether the fresh properties of SCC mixed by proposed method in this study comply with the requirements specified by the Japanese Society of Civil Engineering (JSCE,1998) Laboratory tests, such as the slump flow, V-funnel, U-box and L-flow tests were conducted, using materials from Taiwan. According to the design method for conventional self compacting concrete proposed by Okamura et al. (2000), the volume of coarse aggregate, fine aggregate and paste consisting of powder (< 0.125mm) and water are approximate 50%, 20 % and 30 % by volume. They discussed the procedure for adjusting w/p and SP dosage to achieve desired properties. They found that for mortars, the ratio of slump flow index to funnel flow index to almost constant with respect to volume of water to powder ratio for a given value of SP to powder ratio. Saak et al (2001) suggested that interparticle separation is a critical parameter for design of SCC in addition to particle packing distance. They proposed a segregation control theory considering static and dynamic (flowing condition). They measured yield stress of cement pastes using a shear vane, and the test results showed that concrete had the greatest fluidity at the lowest paste yield stress and viscosity, where segregation is avoided. In 2001, Grunewald and Joost Walraven proposed a mix design for SCC reinforced with steel fibers. They discussed the suitability test methods and the effect of coarse aggregate content, the content and type of steel fibers on the workability of SCC. Bruce (2001) stated that free fall of concrete from 46 m height directly over
rebar does not cause segregation and reduce compressive strength. Subramanian and Chattopadhyay (2002) developed SCC with 50-60 MPa strength using fly ash, SP, naphthalene formaldehyde/ acrylic polymer based SP, Welan gum and locally available aggregates in India. Gettu et al (2002) proposed a four step methodology for mix proportioning of self compacting concrete with fly ash. Jagadish Vengala et al. (2003) suggested a sequential method of starting with a high slump, non superplasticized concrete by replacing part of the coarse aggregate with fine fly ash for obtaining SCC. They also concluded that VEA may not be strictly necessary for obtaining SCC and also reported that, when VEA is added the strength increase was not maintained fully but VEA added SCC showed higher strength to the reference mix.

2.7 TOUGHNESS OF HIGH PERFORMANCE CONCRETE

Toughness, the energy absorption capacity can be computed from the area under the load-deflection curve obtained by conducting two point loading flexural test on beams. Many investigators (Bharatkumar et al. (1995), Balaguru and Shah (1992), Joens and Nemegeer, (1991), Mansur Paramasivam (1985), Prasad Shivananda (2001), Ronald Zollo (1997)) have studied the effect of fiber types, fiber volume fraction, fiber length and aspect ratio, influence of testing conditions, influence of deflection measurement method and age on the toughness characteristics of fiber composites. Plain concrete has two major deficiencies; a low tensile strength and a low strain at fracture. Presence of numerous micro cracks reduces the tensile strength of concrete. Toughness as a measure of absolute energy is capable of distinguishing among composites with different fiber types and fiber volume fractions. Increase in fiber content results in consistent increase in
ductility and energy absorption capacity which in turn gives higher toughness indices (Balaguru et al (1992), Gopalarathnam et al (1991), JCI (1983), JSCE(1984), Ramakrishnan et al (1989)). Mitsunori Kawamura et al (1986) reported that the flexural strength of glass fiber reinforced concrete with silica fume has little effect on the durability. To properly evaluate the toughness (i.e. ductility and brittleness) of glass fiber reinforced concrete, two toughness indices are proposed. Both these toughness indices can be easily evaluated from flexural tests (Shah et al (1987)). Shah et al (1987) proposed two methods to quantify the ductility of glass fiber reinforced concrete panels. But those toughness indices can be evaluated from flexural tests. Ramakrishnan et al (1989) investigated the behaviour of the steel fiber reinforced concrete with different types of fibers. Balaguru et al (1992) observed that the increase in the fiber content results in consistent increase in ductility and energy absorption capacity. The addition of fibers significantly alters the concrete’s physical characteristics, especially toughness, ductility and resistance to shrinkage cracking (Ramakrishnan (1997)). Laboratory studies and field applications have demonstrated that advanced composites can reduce structural damage due to extreme loadings.

2.8 NEED FOR THE PRESENT STUDY

From the literature review, it was understood that all the three mineral admixtures such as silica fume, metakaolin and fly ash are performing well with respect to strength and durability characteristics. Silica fume have high early compressive strength when compared to other two mineral admixtures. Metakaolin is also performing similar to silica fume in achieving the strength almost. 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 to continued pozzolanic reactivity, concrete develops greater strength at later age, which may exceed that of the concrete without fly ash. Addition of fly ash improves the workability but retards the setting time of concrete. Whereas silica fume and metakaolin mixed concrete requires superplasticizer to improve the workability especially at low water cement ratio. There are some controversies about the optimum replacement level of these three mineral admixtures.

The need for the present study arises from the requirement to improve the overall utilization of these three mineral admixtures in correct proportions in concrete structures particularly in aggressive environment depending upon the requirements. The effect of those three mineral admixtures towards strength, durability, self compactability and toughness of HPC need to be done. The draw backs if any in using those mineral admixtures are to be identified and the remedial measures to overcome those ill effects are to be recommended. The efficiency factors for the mineral admixtures are to be determined for different replacement levels at different ages. A simple economical mix design procedure is to be developed for high performance concrete considering the efficiency factor of three mineral admixtures. Self compacting high strength concrete is to be developed using those three mineral admixtures. The toughness of concrete with mineral admixtures is to be studied.