CHAPTER 1

INTRODUCTION

1.1 GENERAL

Cement is one of the most extensively used versatile materials in construction industry. The development of the construction industry at a global level needs more and more amount of Portland cement for sustainable development. Manufacturing of Portland cement is an energy intensive process and releases very large amount of greenhouse gases into the atmosphere, which affect the earth’s ecosystem. Efforts are being carried out to conserve energy by means of promoting the use of industrial wastes or by-products, which contain amorphous silica in its chemical composition, as mineral admixture for partial replacement of cement. The mineral admixtures in the form of finely ground siliceous material does not possess cementitious property in itself, but it will react with the excess calcium hydroxide produced during hydration process and converts it into a useful cementitious product such as C-S-H (Gel). The reduction of excess Ca(OH)$_2$ due to pozzolanic reaction improves the durability of concrete by making cement paste more dense and impervious one. The details of reaction mechanism are given below:

\[
\text{Cement} + \text{Water} \rightarrow \text{C-S-H (Gel)} + \text{Ca(OH)}_2 \\
\text{Ca(OH)}_2 + \text{Pozzolanic Material} + \text{Water} \rightarrow \text{C-S-H (Gel)}
\]
The pozzolanic materials are classified into two categories. They are natural pozzolans, which are of volcanic origin and man-made pozzolans, which include industrial by-products such as Fly Ash (FA), Rice Husk Ash (RHA), Silica Fume (SF), Ground Granulated Blast Furnace Slag (GGBS) etc. The use of pozzolanic material based blended cement concrete is growing rapidly in the construction industry, which will result in saving of energy, environmental protection and conservation of resources.

In India, the thermal power plants produce more than 100 million tonnes of FA every year. Apart from this, large quantity of RHA is also generated from the agricultural sector. These by-products develop serious environmental problems if not utilized properly. The partial replacement of cement by these by-products reduces the production cost of concrete and also addition of FA / RHA with cement has beneficial effect on workability, heat of hydration and permeability of concrete (Vanchi Sata et al 2007). The addition of admixtures not only improves the impermeability, but also acts as scavengers for penetration of chloride ions, which prevents corrosion of embedded rebar in the concrete. However, reduction of the compressive strength of concrete, flexural strength of concrete at the early ages and increasing carbonation of concrete are found to be major draw backs in the FA based blended concrete (Tikalsky et al 1988 and Pedro Montes et al 2005). The early age strength development and setting time of concrete are important parameters for quick removal of form works (Binu Sukumar et al 2008). Addition of second super fine mineral admixture like SF etc, improves the compressive strength and flexural strength of concrete at the early ages and reduces the carbonation of concrete because of pore filling and fast pozzolanic reaction (Bagel 1998 and Nabil Bouzoubaa et al 2004). Apart from this, ternary blends have excellent durability and rapid development of strength compared to plain cement concrete and binary blended concrete and
also it increases the resistance to chemical attack which minimize the maintenance costs of the concrete elements.

1.2 LITERATURE REVIEW

Mehta (1977) conducted experimental investigation to examine the suitability of RHA as supplementary cementitious material and concluded that the RHA containing silica in reactive form makes it a useful pozzolanic material and considered as an effective cement replacement material for preparation of concrete.

Ahmad and Shah (1985) conducted experimental investigation to predict the relationship between the structural properties of high strength concrete and developed new correlations. The correlations are given below:

\[
\begin{align*}
  f_t &= 0.46(f_c)^{0.55} \\
  f_r &= 0.44(f_c)^{2/3} \\
  E_c &= 8.8(f_c)^{0.325}
\end{align*}
\]

where,

- \( f_c \) = Compressive strength in MPa
- \( f_t \) = Splitting tensile strength in MPa
- \( f_r \) = Flexural tensile strength in MPa
- \( E_c \) = Elastic modulus in GPa

Ravina and Mehta (1986) conducted experimental investigation to ascertain the fresh properties of blended concrete. They observed that the addition of mineral admixture reduces the hydration process during initial period. They also concluded that the addition of FA affect the setting properties of blended concrete mixture during the initial hours.
Tikalsky et al (1988) conducted investigation to study the strength and durability properties of concrete using various mix proportion of concrete containing FA and concluded that the compressive and flexural strength of FA based blended concrete specimens have found to be slightly lower than the plain cement concrete at the early ages.

Oluokun et al (1991) conducted experimental investigations to correlate the relationship between mechanical properties of concrete at early ages and suggested that the splitting tensile strength is not necessarily proportional to 0.5 power of compressive strength as given in the ASTM C 496 and found that the value was 0.79. The relationship between compressive strength and tensile strength is given below:

\[ f_t = 0.584(f_c)^{0.79} \]  

(1.4)

where,

- \( f_t \) = Splitting tensile strength (MPa)
- \( f_c \) = Compressive strength (MPa)

They also found that the elastic modulus versus compressive strength results exactly fitted with the 0.5 power relationship.

Weiping Ma et al (1994) performed calorimetric study of blended cements containing class F type FA and found that the reaction of FA with Ca(OH)\(_2\) was initiated only after few days. During this incubation period, the FA behaves as an inert material. They observed that the 17% class F type FA mixed blended concrete evolved 60% - 65% heat compared to control concrete during the first 24 hours of hydration.
Bagel (1998) conducted experimental studies to evaluate the properties of GGBS and SF based ternary blended cement concrete and observed that the flowability of SF based ternary blended fresh concrete decreased due to more water demand of SF. They also concluded that SF provides a dense micro structure and improved mechanical properties at early ages due to fast pozzolanic reaction.

Bentz (2000) conducted experimental investigation to study micro structural properties of SF based blended concrete and observed that permeability of secondary C-S-H gel produced by SF was 25 times lesser than the primary C-S-H gel produced by normal hydration process. They have also found that the concrete containing optimum replacement level of mineral admixture showed good resistance to chloride penetration due to pore filling action of mineral admixture and also the formation of dense concrete due to the secondary C-S-H gel.

Gopalakrishnan et al (2001) investigated the effect of partial replacement of cement using FA and found that the addition of FA as supplementary cementitious material increases the denseness of concrete matrix and refines the pore structure which improves the rheology of fresh concrete. They concluded that the strength reduction in the early age (7 days) might be attributed to slower pozzolanic reaction of FA. They also concluded that 25% replacement level of class F type FA reduces the saturated water absorption (SWA), porosity and sorptivity.

Ferraris et al (2001) examined the rheological properties of binary blended concrete mixed with various mineral admixtures such as FA and SF. They concluded that the addition of FA improved the workability of concrete considerably due to the ball bearing action of spherical shaped FA particles
whereas the addition of SF reduced the workability marginally due to the high specific surface area and more water demand of SF particles.

Saraswathy et al (2001) studied the durability properties of normal strength concrete with various admixtures using half-cell potentiometer and concluded that the concrete without admixture shows a very high negative potential with SCE. Meanwhile the steel bar embedded in concrete, which contain admixtures, showed less negative potential with SCE than the threshold value of -270mV.

Khan and Lynsdale (2002) conducted experimental investigation to study the strength properties of concrete blended with SF and reported that incorporation of SF increases the strength properties at early age and the optimum replacement level of SF was found to be in the range of 8% - 12%. They have reported that the addition of SF improved impermeable pore structure compared to plain cement concrete.

Bleszynski et al (2002) conducted experimental investigation to study the durability properties of SF and GGBS based binary and ternary blended concrete and reported that the shortcoming of setting time characteristics and early age strength of GGBS based binary blended concrete was compensated by the addition of SF due to the filler effect and fast pozzolanic reaction.

The mechanical properties of high strength concrete were studied by Rashid et al (2002) and the following relationships were developed:

\[
f_t = 0.47(f_c)^{0.56} \quad (1.5)
\]
\[
f_r = 0.42(f_c)^{0.68} \quad (1.6)
\]
\[
E_c = 8.9(f_c)^{0.33} \quad (1.7)
\]
where,

\[ f_c = \text{Compressive strength in MPa} \]
\[ f_t = \text{Splitting tensile strength in MPa} \]
\[ f_f = \text{Flexural tensile strength in MPa} \]
\[ E_c = \text{Elastic modulus in GPa} \]

Ismail and Soleymani (2002) conducted chloride attack study and observed that corrosion rate of control concrete specimens was 1.8 to 4.3 times higher than SF based ternary blended concrete. They found that the permeability of chloride ion through SF based ternary blended concrete was lesser than the control concrete and it is mainly due to the pore filling effect of SF and formation of secondary C-S-H gel.

Bai et al (2003) conducted chloride ingress and SDF studies using blended concrete with pulverized fuel ash / metakaolin. They concluded that the blended concrete had shown lower chloride permeability and reduced SDF compared to control concrete due to the pore filling effect of finer materials.

Han-Young Moon et al (2003) investigated the performance of blended cement mortar exposed to various type of sulphate solutions and concluded that the addition of SF improved the compressive strength and reduced the expansion of specimen compared to control mortar when subjected to sulphate attack.

Nabil Bouzoubaa et al (2004) studied the permeability of FA and SF based binary and ternary blended concrete and concluded that 20% FA and 4% SF blended ternary concrete showed better results than control and binary blended concrete. They also concluded that in ternary blended concrete, the presence of SF reduces the chloride-ion penetrability at early ages and FA reduces the chloride-ion penetrability at later ages.
Tiwari and Bandyopadhyay (2004) studied the effect of permeability of chloride ions on the corrosion of rebars embedded in the concrete and observed that the addition of FA, GGBS and SF mineral admixture reduces the ingress of chloride ions. They found that control concrete was approximately 20 times more permeable than FA based blended concrete.

Suwimol Asavapisit and Nittaya Ruengrit (2005) conducted investigation on the setting time of RHA blended cement concrete and found that the presence of RHA increases the initial and final setting time of blended concrete than the control concrete and they concluded that the rate of strength development of RHA blended concrete was less during the first 14 days of curing.

Kayali and Zhu (2005) conducted corrosion performance of SF based reinforced concrete using chloride solution and observed that the SF blended concrete produces secondary C-S-H gel which fills the capillary pores and reduces the permeability of moisture and oxygen into concrete. They have also noted that the addition of 10% SF possesses high corrosion resistance.

Roman Okelo and Yuan (2005) conducted experiments to study the bond strength of concrete and found that it is mainly depends on the characteristics of concrete and also the shape, surface condition and embedded length of the rebar. Their results have shown that the bond strength is proportional to the square root of the compressive strength.

Muralidharan et al (2005) conducted macrocell corrosion study to determine the amount of chloride ion present in the control and binary blended concrete and concluded that more amounts of free chloride ions and
total chloride content were present in control concrete compared to the FA and slag based blended cement concrete. They also noticed that the reduction of chloride ions might be due to the lower permeability of dense secondary C-S-H gel.

Poon et al (2006) studied the mechanical and durability properties of high performance concrete using various mineral admixtures and observed that the early age strength of metakaolin and SF blended concrete were high due to the fast pozzolanic reaction. Whereas the strength of FA based blended concrete was found to be low at early age due to slow pozzolanic reaction.

The effect of partial replacement of RHA on preparation of high strength concrete was investigated by Salim Ahmed Barbhuiya et al (2006) and found that the fineness of RHA is an important factor, which affects the strength of concrete. Based on the experimental results, they concluded that 15% of cement can be replaced by RHA and further replacement level of RHA resulted in a reduction of compressive strength due to the reduction of calcium hydroxide content in the blended concrete.

Mustafa Sahmaran et al (2006) conducted experiments to study the properties of self compacting mortar using mineral admixtures and concluded that the addition of FA significantly increased the initial and final setting time of the blended mortar more than 90% and 50% respectively.

Khunthongkeaw et al (2006) conducted carbonation of concrete under various environmental conditions with different CO₂ concentration and they observed that the carbonation depth of control concrete and FA based blended concrete upto 30% replacement level were found to be approximately equal. However, more than 30% replacement of FA showed much higher carbonation depth.
Prasad et al (2006) reviewed critically about the principle reactions of sulphate attack on concrete. Initially sulphate reacts with Ca(OH)$_2$ develops gypsum. Then the gypsum reacted with Calcium Aluminate Hydrates and forms Calcium Sulpho Aluminate known as Ettringite. The details of reaction mechanism are given below:

\[
\text{Na}_2\text{SO}_4 + \text{Ca(OH)}_2 + 2\text{H}_2\text{O} \rightarrow \text{CaSO}_4 \cdot 2\text{H}_2\text{O} + 2 \text{NaOH} \\
\text{(Gypsum)}
\]

\[
3\text{CaO.Al}_2\text{O}_3.12\text{H}_2\text{O} + 3(\text{CaSO}_4.2\text{H}_2\text{O}) + 13\text{H}_2\text{O} \rightarrow 3\text{CaO Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 31\text{H}_2\text{O} \\
\text{(Ettringite)}
\]

They noticed that the addition of pozzolanic materials consumes part of Ca(OH)$_2$ produced during the hydration process of cement, which reduces the formation of gypsum and ettringite, hence the expansion of blended concrete due to sulphate attack reduced considerably.

Saraswathy and Ha-Won Song (2007) conducted experimental investigation to study the corrosion performance of RHA blended concrete and found that 15% replacement level of RHA had shown lowest value of coefficient of water absorption. Based on RCPT experimental results, they found that the permeability of chloride ions through RHA based binary blended concrete was less compared to control concrete. They also found that the 28 days cured RHA based blended concrete showed higher bond strength than the control concrete.

Ghrici et al (2007) conducted experimental investigation to study the mechanical and durability properties of ternary blended mortar and concrete containing 30% natural pozzolana and 20% limestone powder. They concluded that the ternary blended mortar specimen reduces the sorptivity of
concrete due to reduction of capillary pores by the formation of secondary C-S-H gel. The lower chloride ion permeability was observed for ternary blended concrete when RCPT experiment was conducted. They also found that the addition of 30% natural pozzolana reduced the mass loss upto 75% compared to control mortar specimen when immersed in 3%H₂SO₄ solution for the period of 180 days and also noted that the addition of natural pozzolana improved the sulphate resistance. Based on experimental results the following relationship between flexural tensile strength and compressive strength of blended mortar was developed:

\[ f_r = 0.45(f_c)^{0.76} \]  \hspace{1cm} (1.8)

where,

\[ f_r = \text{Flexural tensile strength in MPa} \]
\[ f_c = \text{Compressive strength in MPa} \]

Anurag Misra et al (2007) studied the sorptivity characteristics of FA based blended concrete by varying the FA content upto 50% and concluded that the addition of FA with lower w-c ratio reduced the sorptivity due to the secondary pozzolanic reaction. They concluded that the porosity of concrete was reduced due to secondary C-S-H gel and filler effect of un-hydrated FA particles.

Mullick (2007) has made a detailed review analysis for the use of mineral admixtures like FA, GGBS and SF on durability properties of blended concrete. Based on the analysis, he concluded that the additions of mineral admixtures have render good early performance and greater durability of blended concrete and also observed that the IS code of practices for concrete specifications were not explicit to ternary blends.
Praphakar et al (2007) have conducted experimental investigation to study the effect of concrete grades on chloride permeability and concluded that the resistance for chloride ion ingress was higher for lower grade concrete such as M 20 grade compared to higher grade concrete. They have also noted that the incorporation of FA for any grades of concrete reduces the depth of chloride ion penetration.

Tae-Hyun Ha et al (2007) conducted open circuit potential measurement and macrocell corrosion current study to evaluate the corrosion performance of steel rebar embedded in FA blended concrete and found that the control concrete had shown a maximum macrocell current than the 20% FA based blended concrete. They also noted that the addition of 30% FA drastically reduces the pH value from 13.00 to 11.10.

Sahmaran et al (2007) conducted experimental investigation to study the effect of mix composition and w-c ratio on the sulphate resistance of blended cements and observed that the addition of class F type FA reduced the quantity of Ca(OH)$_2$ content and hence the formation of gypsum and secondary ettringite were reduced. They also noticed that the FA and natural pozzolana mixed ternary blended concrete showed lesser expansion compared to control concrete when immersed in 5% Na$_2$SO$_4$ solution for a period of 80 weeks.

Chindaprasirt et al (2007) conducted experimental investigation to study the sulphate resistance of FA and RHA blended cement mortar and found that the incorporation of FA reduces the pore size of cement mortar. From the experimental results they noticed that the expansion of control cement mortar was much higher than the blended cement mortar when immersed in 5% Na$_2$SO$_4$ solution.
Vanchai Sata et al (2007) investigated the influence of admixtures on the mechanical properties of blended concrete and observed that the addition of FA or RHA yielded lower compressive strength than that of control concrete during the early age (7 days). They have also noticed that the compressive strength of FA and RHA concretes increased with increasing the period of curing, which is mainly due to the pozzolanic effect of FA and RHA.

The chloride penetration and drying shrinkage of blended cement with 25% cement replacement level of FA and 40% cement replacement of GGBS and OPC (43 and 53 grade) concrete were studied by Raguprasad et al (2007) under marine environment and they concluded from their results that the workability of blended concrete and RCPT value were better than control concrete.

Shweta Goyal et al (2008) conducted experimental investigations to determine the properties of FA and SF based binary blended concrete and observed that the presence of FA reduced the water demand of concrete due to its spherical shape, which reduces the frictional forces among the angular cement particles, whereas addition of SF requests more amount of water for getting the same slump. They noticed that the slump value decreases with increase in SF content for the same w-b ratio due to high specific surface area and also concluded that the addition of SF improves the early age compressive strength due to effect of fast pozzolanic reaction and fineness.

Jayobroto Burman Roy (2008) conducted accelerated carbonation study of binary (6% SF) and ternary (15% FA and 6% SF) blended concrete and based on the results it was found that the carbonation depth of ternary blended concrete was low compared to binary and control concrete.
Durability characteristics of High-strength blended concrete was studied by Ramadoss and Nagamani (2008) and reported that the addition of SF reduces the water absorption and air content of blended concrete. They also concluded that the addition of SF with lower w-c ratio reduced the permeability characteristics of the concrete.

The influence of glass powder on durability characteristics of FA based ternary blended concrete was carried out by Nathan Schwarz et al (2008) and found that the addition of glass powder improved the sorptivity characteristics and alkali silica reaction and also concluded that the 20% replacement of FA was found to be optimum replacement level for preparation of blended concrete based on durability properties.

Pipilikaki and Katsioti (2009) conducted durability studies of quaternary blended cement mortar / concrete and based on the results, is noticed that the quaternary blended cements have a better performance against chloride penetration and also sulphate attack. Meantime, they also observed that the presence of FA reduces the amount of portlandite due to pozzolanic reaction which leads to increase the carbonation of FA based blended concrete.

Shi Hui-sheng et al (2009) studied the influence of mineral admixtures on compressive strength and carbonation of HPC. The beneficial effects on compressive strength was observed only at a later curing period and also noted that the optimum replacement of FA for HPC was 15%. They observed that the addition of FA decreases carbonation resistance of HPC.

1.3 BACKGROUND OF THE PROBLEM

The addition of pozzolanic materials with OPC is an alternative practice in the construction industry. It was recognized long time ago that the suitable pozzolans can be used in appropriate amount to modify certain
properties of fresh and hardened cement mortar and concrete. The longevity of old monuments, constructed before the invention of cement, proves the efficiency of the lime blended material. After the invention of cement, attempts have been made by many investigators to develop blended cement concrete using various industrial by-products. The literature studies had shown that the addition of FA or RHA for preparation of concrete improves the mechanical and durability properties at later age. Apart from this, partial replacement of cement by these by-products reduces the production cost of concrete, however reduction of the compressive strength of concrete, flexural strength of concrete at the early ages and increasing carbonation of concrete are found to be major draw backs mainly due to slow pozzolanic reaction (Tikalsky et al 1988 and Pedro Montes et al 2005). In order to overcome this problem, from the literature, it is found that the addition of a super fine mineral admixture such as SF improved the early age performance of binary blended concrete (Nabil Bouzoubaa et al 2004, Poon et al 2006 and Shweta Goyal et al 2008).

Though a few authors studied FA based ternary blended concrete with various mineral admixture combinations such as FA and GGBS, FA and SF, FA and natural pozzolana, the study results on various mechanical properties and its relationships and durability properties are limited (Bagel 1998, Bleszynski et al 2002, Nabil Bouzoubaa et al 2004, Raguprasad et al 2007, Sahmaran et al 2007 and Jayobroto Burman Roy 2008). Apart from this, many authors found that the relationship between the compressive strength and tensile strength / elastic modulus of concrete mentioned in various codes are not fitting with their results (Oluokun et al 1991, Rashid et al 2002, Ghrici et al 2007 and Mullick 2007).

From the literature evidences, it is found that the complete and comprehensive analysis of FA / RHA and SF based ternary blended concrete such as reduction of air content and setting time, relationship between
compressive strength and tensile strength / elastic modulus, corrosion performance, reduction of chloride ingress, reduction of chemical attack and carbonation is limited. Therefore a realistic assessment is needed for ternary blended concrete and hence in this present research a detailed investigation has been carried out to study the mechanical and durability properties of ternary blended concrete with the help of available industrial by-products such as FA, RHA and SF.

1.4 OBJECTIVES OF THE STUDY

- To develop binary blended M 20, M 30 and M 40 grade normal strength concrete by using optimum replacement level of FA / RHA based on compressive strength.

- To develop ternary blended M 20, M 30 and M 40 grade concrete by conducting investigations on fresh concrete properties such as workability, air content and setting time and hardened properties such as compressive strength, splitting tensile strength, bond strength and elastic modulus by varying percentage of SF and to compare the performance of ternary blended concrete with control and FA / RHA based binary blended concrete.

- To develop ternary blended M 20, M 30 and M 40 grade concrete by conducting investigations on durability properties such as corrosion performance, sulphate and acid resistance, chloride attack and carbonation of ternary blended M 20, M 30 and M 40 grade normal strength concrete by varying the percentage of SF and to compare the performance of ternary blended concrete with control and FA / RHA based binary blended concrete.
• To develop the empirical relationship between compressive strength and splitting tensile strength / elastic modulus.

• To determine the optimum mix proportion of M 20, M 30 and M 40 grade normal strength ternary blended concrete.