CHAPTER 2

REVIEW OF LITERATURE

The demand for natural sand is quite high in developing countries since the available sand cannot meet the requirement of construction sector. Because of its limited supply the cost of natural sand has incredibly increased and its consistent supply cannot be guaranteed. Under these circumstances, quarry dust, a byproduct from the crushing process of stones (Blue metal) which is available abundantly from rock quarries at low cost in many areas, can be an economical alternative to the river sand.

2.1 SIGNIFICANCE OF QUARRY DUST

Quarry dust has been used for different activities in the construction industry such as road construction and manufacture of building materials like lightweight aggregates, bricks, tiles and autoclave blocks. Use of quarry dust as fine aggregate in concrete draws serious attention of researchers and investigators.

Radhikesh et al (2010) have conducted an experimental study to investigate the suitability of quarry dust as fine aggregate for producing paving blocks. The test results show that the replacement of fine aggregate by quarry dust up to 50% has a negligible effect on the reduction of physical and mechanical properties while there is a saving of 56% of money and the percentage of saving would be more for mass production of paving blocks.
Manasseh Joel (2010) have investigated the suitability of crushed granite fines to replace river sand in concrete production for rigid pavement. It is concluded that, based on economic analysis and strength test results, river sand replaced with 20% of crushed granite fines is recommended for production of concrete for rigid pavement.

The consumption of cement content, workability, compressive strength and cost of concrete made with quarry dust were studied by researchers. The studies (Ilangovan 2008) conducted on strength and durability properties of concrete containing quarry dust as fine aggregate revealed that the overall workability value of quarry dust concrete is less, when compared to conventional concrete. Quarry dust concrete experiences better sulphate and acid resistance and its permeability is less, compared to that of conventional concrete. However, the water absorption of quarry dust concrete is slightly higher than conventional concrete. The use of higher water cement ratio demands high cement content for a required strength. The effect of partial replacement of fine aggregate with crushed stone dust (particle size less than 75micron) was studied by Raman et al (2007) and it was observed that slump value decreased as the percentage of dust content increased. Also for higher dust contents, the compressive strength, flexural strength and impact resistance decreased gradually whereas absorption increased. The use of quarry sand is generally limited due to the high cement paste volume needed to obtain an adequate workability of concrete. The amount of additional paste content depends on shape, texture, grading and dust content of the sand. The increase of water demand of concrete mixtures produced by the adverse effects of shape and texture of quarry sand can be mitigated using a high-range water-reducing admixture also.

Ilangovan et al (2008) studied the usage of quarry dust as substitute for natural sand in concrete and conducted experiments to judge the
properties of fresh concrete and strength properties. Studies reported here have shown that the strength of quarry dust concrete is comparatively 10-12 percent more than that of similar mix of conventional concrete and durability of quarry rock dust concrete under sulphate and acid action is higher to that of conventional concrete. Permeability test results clearly demonstrate that the permeability of quarry rock dust concrete is less than the conventional concrete. The water absorption of quarry rock dust concrete was found to be slightly higher than conventional concrete.

Sahu et al (2003) have reported that concrete containing quarry dust as fine aggregate is promising greater strength, lower permeability and greater density which enable it to provide better resistance to freeze/thaw cycles and durability in adverse environment. As reported by Hameed et al (2009), the use of quarry dust as fine aggregate will also reduce environmental impact, if consumed by the construction industry in large quantities.

Raman et al (2007) examined the effect of partial replacement of river sand by 20% of quarry dust in flowing concrete and concluded that the use of quarry dust did not affect physical properties and flowability of the concrete. It was found that, the use of quarry waste caused a slight reduction in compressive strength due to excessive flakiness and lack in gradation and also resulted in higher initial surface absorption which was improved in presence of silica fume. Finally it was concluded that, quarry waste can be utilized to produce flowing concrete with 10% of silica fume as partial replacement of cement.

Murugesan et al (2006) examined the effect of super plasticizer in quarry dust replaced concrete and reported that the compressive strength and workability of quarry dust concrete can be improved with plasticizers. The quarry dust was mixed in various proportions, replacing sand by 30-90% in conventional concrete. Concrete cubes of grade M15 and M20 have been cast
and tested for compressive strength and the results were compared with conventional concrete. It was found that, 60% replacement of sand by quarry dust without plasticizer and 70% - 80% replacement with plasticizer produced the same compressive strength as that of conventional concrete. It is recommended that, to overcome the problem of poor workability with the large proportions of quarry dust in fine aggregate, super plasticizer at the dosage of 0.4% by weight of cement can be used.

Nagaraj and Zahida Banu (1996) have examined the effect of replacement of fine aggregate in cement concrete by quarry dust and manufactured sand. It was observed that sand and 50% quarry dust combination gives higher strength when compared than the conventional concrete due to the sharp edges of stone providing stronger bond with cement compared to the rounded shape of ordinary sand. It was observed that concrete using quarry fines shows improvement in higher flexural strength, abrasion resistance and unit weight which are very important for reducing corrosion or leaching.

Naidu et al (2003a) have conducted an experimental study to investigate the influence of partial replacement of sand with quarry dust in the compressive strength and pull-out force of concrete. Four types of concrete, with two water-binder ratios of 0.40 and 0.45 were undertaken in this study. Replacement proportion of 20% sand with quarry dust was practiced in all the concretes except in the controlled concrete mix. All concretes were cured by dry air in the curing room at 20°C, and their compressive strength and pull-out force were measured on the 7th, 14th, 28th and 56th day. Test results indicate that concrete incorporating quarry dust and without the inclusion any mineral admixtures exhibited a lower compressive strength but a higher pull-out force than the controlled concrete at all ages. Inclusion of fly ash as 10% binder into the quarry dust concrete resulted in an increase in the compressive
strength and pull-out force at almost all conditions. The quarry dust concrete incorporating 10% silica fume as binder exhibited the highest compressive strength and pull-out force in all conditions.

Raman et al (2005) have studied the suitability of quarry dust as partial replacement material for sand along with mineral admixtures in concrete. Results obtained indicate that the incorporation of quarry dust into the concrete mix as partial replacement material to river sand resulted in lower 28th day strength and the study also indicates that 20% quarry dust can be utilized as partial replacement material to sand. The results of the study also indicates that quarry dust can be utilized as partial replacement material to sand, in the presence of silica fume or fly ash to produce concrete with fair ranges of compressive strength.

Naidu et al (2003a) have investigated the influence of partial replacement of sand with 20% of quarry dust and mineral admixtures in the compressive and pull-out force of concrete. Test results indicate that concrete incorporating quarry dust and without the inclusion of mineral admixtures exhibited a lower compressive strength but a higher pull-out force then the controlled concrete at all the ages. Inclusion of fly ash as 30% binder into the quarry dust concrete resulted in an increase in the compressive strength and pull-out force at almost all the conditions. The quarry dust concrete incorporating 30% silica fume as binder exhibited the highest compressive strength and pull-out force in all conditions.

2.2 CORROSION OF STEEL IN CONCRETE

Durability of concrete may be defined as the ability of concrete to resist weathering action, chemical attack and abrasion while maintaining its desired engineering properties (Shetty 2008). Corrosion of reinforcing bar embedded in concrete causes most of the failures in concrete structures.
Corrosion of steel in concrete is one of the major causes of premature deterioration of reinforced concrete structures, leading to structural failure and a serious problem from both economical and structural integrity standpoints (Browne et al 1983). It is well known that steel in concrete is protected from corrosion by a microscopically thin oxide layer that is formed in the highly alkaline condition of the concrete pore solution (Schiessel 1988). This insoluble and highly stable protective film suppresses iron dissolution to negligibly low values. However, steel corrosion, even in well-constructed concrete, can be active when chlorides continuously accumulate at the depth of the steel. Once corrosion initiates, it propagates rapidly. Subsequent corrosion of steel produces rust products, which have a volume 3-8 times greater than that of the original metal. This generates stress, causing cracking and spalling of the concrete cover, which further accelerates corrosion (Santhakumar 2010).

Ha-Won Song and Velu Saraswathy (2007), have reported that many structures in adverse environments have experienced unacceptable loss in serviceability of safety earlier than anticipated due to the corrosion of reinforcing steel and thus need for replacement, rehabilitation or strengthening. In order to minimize the corrosion processes a number of procedures can be employed. There are many methods for protection against corrosion of steel in concrete, including addition of inhibitors, cathodic protection, metallic coatings for steel reinforcement and addition of mineral admixtures such as fly ash, silica fume, and slag to the concrete (Brown et al 2002). The methods adopted in this investigation to prevent rebar corrosion of steel in concrete containing quarry dust as fine aggregate are addition of mineral admixtures namely fly ash and GGBFS and addition of organic and inorganic inhibitors.
2.3 MINERAL ADMIXTURES

The use of mineral admixtures such as fly ash, silica fume, slag and metakaolin has been shown to enhance concrete durability (Toutanji and Delatte 2001), by increasing chloride binding (Lu et al 2002), decreasing chloride permeability (Choi et al 2006), elevating threshold chloride content (Manera et al 2008), and/or improving the distribution of pore size and shape of concrete matrix (Yang and Cho 2003). Since some of these materials are cheaper than Portland cement, there is also an economic advantage to wider use. Dhir et al (1997) used the low-lime fly ash to develop concrete mixes with improved chloride resistance, by improving the pore structure and binding capacity of the concrete. They found that ternary blends (cement and fly ash blended with silica fume or metakaolin) showed the highest chloride resistance. Hossain et al (2009) found that the incorporation of ultra-fine fly ash (UFFA) improved the strength and chloride penetration resistance of concrete, and the incorporation of silica fume had even more pronounced benefits. As such, a ternary blend (with cement, silica fume and UFFA) was developed to feature high early-age strength, improved durability, low slump and low free shrinkage.

2.3.1 Fly Ash

Fly ash (FA) is a byproduct of coal combustion in the generation of electricity, i.e., a finely segregated residue captured from the flue gas at coal-fired power plants. Fly ash provides a dramatic lubricating effect which greatly reduces water demand (2% to 10%). Most of the fly ash particles are spherical and amorphous, ranging in size between 10 and 100 microns. The spherical shape of fly ash particles causes an improvement in the workability and the particles alter the flocculation of cement resulting in lowering the quantity of water required (Rafat Siddique 2000). The use of quarry dust in concrete causes reduction in workability and hence increases in the quantity
of cement required whereas the use of fly ash in concrete offers improved workability and reduction in cement content (Raman et al 2004). Hence concurrent use of quarry dust and fly ash in concrete will lead to a wide range of economic and environmental benefits.

With increasing energy costs and heightened concerns about the impact of concrete construction and maintenance activities on the environment, there has been an attendant increase in interest and research activity on the use of FA and other recycled materials in concrete, including those targeting ASR prevention (Malvar and Lenke 2006).

Güneyisi et al (2006) investigated the rebar corrosion in concrete made of blended cements which contained various proportions of Portland cement clinker, blast furnace slag, natural pozzolans, and limestone powder. Relative to the plain cement concrete, the specimens with blended cements showed superior corrosion performance and generally longer time to corrosion cracking, which correlated very well with the splitting tensile strength data.

In general, FA addition in concrete is considered an effective measure to mitigate chloride-induced corrosion of rebar in concrete. For instance, using FA blended cement is known to reduce chloride permeability and improve sulfate resistance of concrete (Saraswathy and Song 2006). Dhir et al (1997) used the equilibrium method and found that the chloride binding capacity of cement paste increased with the increase in FA replacement level up to 50% and then declined at 67%. In the case of admixed chloride, the increase in chloride binding due to the replacement of FA was also found (Byfors 1986). The increase in chloride binding could also be ascribed to the production of more gel during hydration, which results in better physical adsorption of chloride (Kayyali and Hague 1988). Other researchers (Byfors et al 1986) also found that partial replacement of cement with FA has a
positive effect on the chloride binding when the cement paste was exposed to a chloride environment.

Ampadu et al (1999) found the partial replacement of cement by FA only showed significant benefits in reducing the chloride diffusivity in cement paste at later ages of curing and a 40% replacement level was the best. Saraswathy and Song (2006) investigated the effect of admixing activated FA on the corrosion resistance of concrete and found that the FA addition significantly improved the corrosion performance of concrete up to a critical moderate replacement level (20% to 30%) and the chemical activation of FA worked the best.

Kamal et al (2006) have investigated the efficiency of mineral admixtures in mortar and reported that, the spherical shape of fly ash particles causes an improvement in the workability, and the particles alter the flocculation of cement which results in lowering of the quantity of water required. Quan (2005) have concluded that the addition of fly ash causes a reduction in the water required for a given slump, typically in the order of 5-15 % when compared with a portland cement mix. Shigeyoshi Nagataki and Yukikazu Tsuji (2000) recommended that compared with conventional concrete, the concrete with 30 to 50 percent cement replacement by fly ash shows substantial increase in strength and corrosion resistive properties.

2.3.1.1 Effect of fly ash on workability

Mora et al (1993) examined the workability of fly ash mixes and reported that there is a gradual increase of water volume in control mortar and in fly ash replacing mortar from 150 to 225 ml imply greater flow table spread (FTS) i.e. workability is increased when part of cement is replaced by fly ash and coarser fractions gave less FTS values than finer ones. FTS increases as
do specific surface and decreases with mean diameter and for finest fraction FTS were smaller than expected.

Joshi and Lohtia (1997) reported the work of Brown on the workability of four concretes of different water-cement ratios in which ash was substituted for cement on an equal volume basis and found that the workability increased with the increased ash substitution. The changes were found to depend upon the level of ash substitution and on water content. An empirical estimate which indicates that for each 10% of ash substituted for cement, the compacting factor changed to the same degree as it would be increasing the water content of the mix by 3 to 4 percent. In another series of experiments, Brown determined the effects of ash substitution for equal volumes of aggregate or sand in one concrete, keeping all other mix proportions constant. The test concrete was modified by replacing 10, 20 or 40% of the volume of sand by ash or 10, 20 or 40% of the volume of the total aggregate by ash. The replacement of 40% of the total aggregate gave a mix that was unworkable.

Malhotra and Berry (1986) reported the work of Owen that with the use of fly ash, containing large fraction of particles coarser than 45µm or a fly ash with high amount of unburnt carbon exhibiting loss on ignition more than 1%, increasing water demand is observed. Water demand is increased to maintain the desired level of fluidity.

2.3.1.2 Effect of fly ash on segregation and bleeding

Malhotra and Berry (1986) reported in his compilation that concrete using fly ash reduced segregation and bleeding more satisfactory than plain concrete when placed by pumping. He further reported the work of Johnston that the use of fly ash particularly in the harsh mixes, which are deficient in fines, would resolve the problem of excessive bleeding by increasing the
overall paste volume by the addition of fly ash in concrete as mineral admixture.

From the study on high volume fly ash concrete mixes, Joshi and Lohtia (1997) reported that the fly ash concrete mixes were more cohesive than control mixes. During the slump test, the fly ash concrete mixes subsided more slowly and gradually than the control mixes which exhibited abrupt fall or subsidence.

2.3.1.3 Effect of fly ash on time of setting

Tarun and Singh (1997) studied the effects of various sources of class C fly ashes on the setting and hardening characteristics of concrete, and concluded that the addition of fly ash up to a certain level (typical upto about 60% replacement) caused significant delay in the times of initial and final setting of concrete and beyond which a reverse trend was observed. The times of setting varied greatly from fly ash to fly ash.

2.3.1.4 Effect of fly ash on compressive strength

Lame et al (1998) investigated the effect of replacing cement (0 to 55%) by fly ash taking three series of concrete mixes with water-cementitious material ratio (W/C) of 0.3, 0.4 and 0.5 respectively. They concluded that fly ash contributed little to strength at early ages. At 3 days, compared to Portland cement concrete, the cube compressive strength was reduced by 16% in average for a 15% fly ash replacement, and by 66% for 55% fly ash replacement. At 28 days, the strength of 15% fly ash mixes was only slightly lower (4% in average) than Portland cement mixes, although 55% fly ash replacement still resulted in a 44% strength reduction. At the later ages, the contribution of fly ash to compressive strength development became significant.
In a laboratory study, Joshi and Lohtia (1997) tested a large number of fly ash concrete mixes made by using three different fly ashes containing about 10% CaO. The replacement level was between 40 to 60% by weight of cement. The results indicated that with fly ash replacement level up to 50% by weight of cement, concrete with 28 days strength ranging from 40 to 60 MPa can be produced. Swamy and Mahmud (1986) also reported that concrete containing 50% low calcium bituminous fly ash as cement replacement and using a superplastisizer is capable of developing 60 MPa compressive strength at 28 days and strength of 20 to 30 MPa at 3 days.

Langley et al (1989) have reported the results of the investigations carried out to determine the effects of incorporating high volumes of ASTM class F fly ash on concrete with 56% replacement level of cementitious materials by fly ash. Tests results indicated that fly ash concretes show substantial increase in compressive strength, split tensile strength and flexural strength from the ages of 28 to 365 days. Haque et al (1988) reported that for concrete mixes with 40 to 75% bituminous fly ash replacing cement, the increase in flexural strength was slightly less than the increase in compressive strength between 28 days and 91 days of curing.

2.3.1.5 Effect of fly ash on permeability

Naik et al (1994) have evaluated the influence of the addition of a class C fly ash on concrete permeability by replacing cement with fly ash in the range of 0-70% by weight in concrete mixtures. On the test results for air permeability, they have concluded that at lower ages upto 28 days, the high volume fly ash concrete showed higher levels of ingress of air relative to the plain Portland cement concrete. When curing was extended upto 91 days, the 50% fly ash concrete, showed maximum permeability and out-performed the reference concrete without fly ash. This is due to the pozzolanic contribution
of fly ash in concrete. This may be primarily due to the presence of Ca(OH)$_2$ hydrated lime in concrete.

On water permeability test results, they have reported that concrete water permeability decreased with age. All the three concrete mixtures showed fair resistance to water permeability upto the ages of 14-40 days. At 91-day age, the high volume (50%) fly ash concrete exhibited lower water permeability to that of plain Portland cement concrete. This is probably due to increased pore grain refinements of fly ash concrete system (upto 50% cement replacement) that occurred due to pozzolanic reaction of fly ash. They observed that chloride permeability decreased with age. The 50% fly ash concrete showed the lowest permeability to chloride ions amongst all the mixture tested. The concrete mixtures with 50 and 70% cement replacements, with fly ash were superior to the no-fly ash concrete at 91 days with respect to chloride-ion permeability.

Malhotra and Berry (1986) reported the work of Kanitakis on permeability of concreted with and without a low-calcium fly ash (CaO, 2.0%). Absorption measurements are made at 7, 17, 28 and 56 days of curing. It was found that at early ages, fly ash concrete behaves as a lean-mix concrete and is thus permeable. At later ages, permeability is reduced as the pozzolanic action proceeds.

Kasai et al (1983) studied the air/gas permeability of mortar made with blended cements containing fly ash and blast furnace slag and concluded that at early ages upto 7 days, blended cement mortars exhibited more permeability than plain cement mortars. However, with increased curing age, the permeability of blended cement mortars decreased.
2.3.1.6 Effect of fly ash on resistance to corrosion of reinforcing steel in concrete

Maslehuddin Mohammed et al (1988) reported corrosion resisting characteristics of the concrete mixture, in which fly ash was used as an admixture (an equal quantity of sand replaced). The corrosion rates of the reinforcing bars in plain and fly ash concrete specimens after about 4 years of immersion in the salt solution were noted. They have concluded that the corrosion rates of reinforcing bars in plain concrete specimens were higher than that of fly ash concrete. The corrosion rates of reinforcing bars in plain concrete specimens were about 13 to 19 times the corrosion rates of those in fly ash (30% sand replaced) concrete. Further, the data indicated that the corrosion rate increased with the increasing water-cement ratio in both plain and sand replaced fly ash concrete.

Al-Saadoun et al (1993) reported the corrosion resisting characteristics of reinforcement of four plain and 36 fly ash blended cement concretes. Three fly ash of bituminous, sub-bituminous and lignite origin have been used in conjunction with four plain cements having C$_3$A contents of 2%, 9%, 11% and 14%. The 36 blended cements were formulated such that each of the four blended cements had 10% 20% and 30% cement replacements by each of three fly ashes. They have concluded that for the type V 2% blended cement, with the fly ash 3 and 30% replacement level, the corrosion protection performance of fly ash blended cement concrete in terms of corrosion-initiation time is over three fold better compared to that of plain cement concrete. Also for the three type 1 cements, for the same fly ash 3 and 30% replacement level, the average performance of fly ash bended cement concrete is 2 times superior to that of the corresponding plain cement concretes.
Andrade (1986) tested concrete mixes with and without fly ash for corrosion using polarization resistance technique. The addition of fly ash promoted the corrosion of steel in mortars but had no effect on concrete specimens. The decrease in the alkalinity due to introduction of fly ash was reported to have a major effect in promoting corrosion in the fly ash mortar mixes.

2.3.2 Ground Granulated Blast Furnace Slag

Ground granulated blast-furnace slag (GGBFS) is a byproduct of making iron and steel, i.e., a fine powder grounded from the glassy, granular material that forms when molten iron blast furnace slag is air quenched with water or steam. Due to its glossy nature and chemical composition which make it pozzolanic and cementitious material GGBFS is an accepted mineral admixture for use in concrete. GGBFS features fineness similar to cement particles and contains very limited amount of crystals. GGBFS is highly cementitious in nature and its use in mortar and concrete has been specified by ASTM C 989. Partial replacement of cement by GGBFS up to 80% was observed to reduce the compressive strength of concrete during the first 28 days while the later-age strength increased with the slag replacement up to 60% (Khatib and Hibbert 2005). Partial replacement of cement by GGBFS up to 80% has demonstrated to improve the corrosion performance of concrete and the 50% replacement level in concrete imparted the best corrosion resistance, which featured the corrosion initiation time of steel rebar 3.2 to 3.8 times as long as the control (depending on the tricalcium aluminate (C₃₆A) content in cement) (Al-Saadoun 1993). The effect of GGBFS addition on the sulfate resistance of concrete was more complex, depending on the replacement level and the cement composition (Al-Saadoun 1993). GGBFS was found to considerably improve the pore structure of concrete, increase its chloride binding capacity, and reduce its chloride diffusivity (Luo 2003).
While the slag addition improves both chemical and physical binding of chloride it decreases the pH of the pore solution (Cheng 2005).

Pal et al (2002) reported that this cementitious material enhances the strength and durability characteristics when used in concrete. The time to initiate corrosion is determined largely by the amount and the quality of concrete cover as well as the permeability of concrete.

Shariq et al (2008) have proved that the partial replacement of ordinary portland cement by GGBFS results in greater long-term strength, lower chloride ion impermeability, less creep, greater sulfate attack resistance, greater alkali silica reactivity durability, enhanced workability, less bleeding, lower heat of hydration and increased steel corrosion resistance. Pavia and Condren (2008) suggested that the strength and corrosion protection characteristics of quarry dust concrete can be further improved by the partial replacement of cement by GGBFS.

Cheng et al (2005) investigated the corrosion behavior of reinforced concrete prismatic beams subjected to sustained loadings (37% and 75% of the ultimate load) and 3.5% NaCl solution and found the slag concrete to exhibit lower corrosion rate for a given reduction percentage in flexural rigidity (relative to the control). The partial replacement of cement by GGBFS reduced the electrical charge passing through the concrete (during the rapid chloride penetration test) and the water permeability of concrete. This was the result of GGBFS reacting with water and Portlandite to form extra CSH gel and more refined microstructure. A study of slag concrete after 25 years of exposure in a marine tidal zone (Thomas et al 2008) confirmed the beneficial role of slag in dramatically reducing the chloride ion penetration, especially at relatively high replacement levels (45% to 65%) and low w/c ratio (0.40).
The general GGBFS literature indicates that the replacement of OPC by GGBFS typically results in lower early strengths (7 to 28 days), greater long term strengths, lower chloride ion permeability, less creep, greater sulfate attack resistance, greater alkali silica reactivity durability, enhanced workability, less bleeding, lower heat of hydration, and increased steel corrosion resistance. According to Bush et al (2000), the proportion of GGBFS in a mix depends on the following: 1) the purpose for which the concrete is being used, 2) the curing temperature, 3) the grade (activity) of the slag, and 4) the characteristics of the cement or activator. GGBFS has been commonly used for cement replacement to reduce the maximum temperature rise in mass concrete. When Grade 120 (highest activity) slag is used, at least a 70% replacement may be needed to meet specification requirements. Most of the ready-mix concrete producers use 50% replacement with highly reactive slag during warm weather (ACI Committee 233R 1995).

During the early hydration of the slag cement, the portland cement releases alkali metal ions and calcium hydroxides (CH). The glassy slag structure is broken down and dissolved by the hydroxyl ions. Initially, the reaction of the slag is with alkali hydroxide; later, the reaction is primarily with calcium hydroxide (ACI Committee 233R 1995). As hydration continues long term, the PC continues to precipitate calcium hydroxide and grow rings of calcium silicate hydrate (CSH) inward from the original grain surface. Slag, on the other hand, develops more CSH, contributing to strength, density, and chemical resistance (Roy and Idorn 1983). The filling of pores with additional CSH is called pore size refinement, while the replacement of CH with CSH (a denser structure) is termed grain size refinement (Bush et al 2000). Thus because of the pozzolanic reaction, slag pastes contain less calcium hydroxide than OPC pastes. It has been shown, in at least one study (Regourd 1980), that for slag-OPC mixes containing 80% slag, the CH is depleted. Higher CH contents tend to produce inferior concrete because of the
following: 1) production of an inhomogeneous body with poor bonding between CSH and CH, 2) a greater likelihood of cracks propagating from the interface of CSH and CH, and 3) CH is weaker than CSH (Feldman 1983). The slag retains the alkali and calcium hydroxides in its hydration products (i.e. CSH). This results in a hardened cement paste that has a greater density and smaller pore sizes than an equivalent OPC paste, thus permeability and ionic diffusivity is reduced (ACI Committee 233R, 1995).

The primary factors that affect the slag-cement reaction are as follows: 1) chemical composition, fineness, glass content, and age of the slag, 2) fineness of the cement, 3) alkali concentration of the reacting system and 4) temperature (Metso and Kajaus 1983). Glass content (degree of vitrification) is considered a primary factor, and the structure of the glass is also significant (8). In general, increasing glass content results in greater pozzolanic activity (Malhotra 1983 and Hooton and Emery 1983).

2.3.2.1 Effect of GGBFS on workability

It has been reported that water demand for a given slump is about 1 to 10% lower than plain concrete (ACI Committee 233R, 1995, Kosmatka et al 2003). Numerous authors have reported improved workability with slag mixes. This is thought to be because the surface of the slag, which is smooth and dense, creates smooth slip planes and low absorption of water as opposed to Portland cement. Also, when substituted on a mass basis, due to the lower specific gravity of GGBGS, more paste is present which would aid in workability. Because of greater workability, coarse aggregate content can be increased and the resulting decrease in paste will often render the paste less sticky (ACI Committee 233R, 1995). However, Bush et al (2000) found a moderate slump reduction with the introduction of 25% Grade 120 GGBFS. For most of the mixes tested by Sanjayan and Sioulas (2000), the slag mixes exhibited 20 to 50% greater slumps at constant w/c (water to cementitious
material ratio by weight) indicating that the w/c could have been lowered with consequent enhancement of hardened properties. Even more pronounced results were seen by Lane and Ozyildirum (1999). Bleszynski et al (2002) found that rheological properties were enhanced. However, in the Duos and Eggers (1999) study, at 23°C (73°F), slump decreased with increasing slag content.

### 2.3.2.2 Effect of GGBFS on setting time

In general, the use of GGBFS will retard setting time (Kosmatka, et al 2003). However, experiences have been mixed in regard to setting time. Duos and Eggers (1999) found that setting time was a function of the amount of cementitious material and mixing/curing temperatures. In general, setting time of richer mixes at 23°C (73°F) was not significantly affected by increasing amounts of slag. However, leaner mixes at 40°F exhibited slower setting as slag content increased. Bush et al (2000) found little change in setting times with 25 and 50% GGBFS contents. Saika et al (1992) found that although initial setting times were not impacted much by slag replacement, final setting times increased. Hogan and Meusal (1981) found that both initial and final set times were not affected appreciably. ACI 2334 states that slag mixes tend to have longer initial setting times by one half to one hour.

### 2.3.2.3 Effect of GGBFS heat of hydration

Because slag cement reacts more slowly than Portland cement, it is used for mass concreting situations (Virtanen 1983). Replacement levels range from 50 to 85%. In a study of adiabatic temperature rise, it was shown that as slag replacement level increased up to 70%, temperature rise was reduced, although the reduction was only significant at the 70% replacement level.
2.3.2.4 Effect of GGBFS compressive strength

ASTM C 98928 divides GGBFS into three strength grades in accordance with their Slag Activity Index (SAI) values: Grade 80, 100, and 120, with Grade 120 being the most active. The SAI is the ratio of the strength of a 50-50 blend of slag and PC to the strength of a plain PC mix at 7 and 28 days. The SAI is considered the best criterion for assessing the relative cementitious potential of slag (ACI Committee 233R 1995). However, the PC used as a reference material must meet minimum requirements of compressive strength and alkali content. The PC used in a particular project may be less reactive. In general, the early strengths of Grade 120 slag mixes are lower than OPC mixes, but usually catch up and then surpass at 7 days and beyond. It is commonly believed that the other two grades typically exhibit lower strengths than 100% OPC concrete at all ages.

Factors which affect slag mix performance are as follows: 1) proportions of cementitious materials, 2) physical and chemical characteristics of the slag, 3) curing conditions, 4) presence and dosage rate of admixtures, 5) characteristics of the aggregate, and 6) characteristics of the Portland cement.

2.3.2.5 Effect of GGBFS proportions of cementitious materials

In most cases, replacement of portland cement with slag ultimately lead to increases in strength. Unfortunately, the grade of slag was usually not reported. Using superplasticized constant w/cm mixes, Lim and Wee (2000) used GGBFS replacement at 30, 50, 65, and 80% levels. By 7 days, the 50 and 65% mixes had surpassed the control mix, and by 91 days all slag mixes were stronger. At 91 days, the optimum replacement (Duos and Eggers 1999) amount was 50%. Lane and Ozyildirum (2005) investigated constant w/cm Grade 120 GGBFSPC binary mixes with 25, 35, 50, and 60% replacement. Early strengths of the replacement mixes were lower than the
control, but by 56 days, the 50 and 60% slag mixes exceeded the OPC mix, and at the one year mark all slag mixes were stronger than the OPC mix. From 28 days on, increasing slag percentage increased the strength. Blomberg (2003) varied GGBFS replacement levels at 25 and 50%.

Hogan and Meusal (1981) studied 40, 50, and 65% blends. In general, at ages from 28 days to one year, blends between 40 and 50% gave the highest strengths. Early rate of strength gain was inversely proportional to slag content. Mixes with slag contents above 40% were all superior in strength to the OPC mixes. Using GGBFS contents of 25 and 50%, a study by Bush et al (2000) exhibited 38 and 51% increases in strength, respectively, compared to the control. In at least one study, slag replacement did not result in an ultimate increase in strength; however, longer-term strengths were essentially equal to OPC concrete. Thus, strength of slag mixes was initially lower than the OPC mix, but eventually caught up by 91 days at all slag replacement levels (Jin and Yazdani 2003). In several cases, slag replacement resulted in lower strengths compared to OPC control mixes. Bleszinski et al (2002) varied slag replacement levels at 35 and 50%. As the replacement level increased from zero to 50%, strength at 28 days was reduced significantly. Working with high slag replacement values, Tomisawa and Fujii (1995) found that as slag percentage increased from 50 to 90%, strengths dropped. Using a Grade 80 slag, for a 55% slag mix, Zhang et al (1999), in comparison to OPC concrete, saw strength losses of 13% and 25% at 28 and 91 days, respectively.

Sivasundarum and Malhotra (1992) varied slag replacement at 65% to 75%. Strengths were reduced at all replacement values compared to the OPC control mix at ages up to 91 days. Li et al (1998) varied slag replacements from zero to 70%. They observed a slight loss in strength at 50%, but a more significant loss at 70%. Using a 60% slag replacement mix
which featured a w/cm of 0.45, Grade 120 slag, and 155 kg/m3 OPC, Peterson and Hale (2004) were able to achieve 48 MPa, but the slag mix strength fell somewhat below the OPC mix; 28 day and 90 day results were 88% and 98% of the control strengths, respectively.

2.3.2.6 Effect of GGBFS on permeability

Use of GGBFS as a partial replacement of portland cement has been found to reduce permeability (Manmohan and Mehta 1981) and has shown to result in good resistance to chloride penetration (Mehta et al 1980). The pore structure of the paste is changed through the reaction of the slag with the calcium hydroxide and alkalis released during hydration of the PC7. The pores are filled with calcium silicate hydrates instead of calcium hydroxide. Additionally, because workability is enhanced, the w/cm can be lowered, thus resulting in a denser paste structure. It has been postulated that slag replacement of portland cement will decrease the permeability by producing a finer pore size distribution even though the total porosity may increase (Mehta 1980). Bakker and Malhotra (1983) has theorized that the reason the permeability of slag-PC mixes is less than that of OPC mixes is that the precipitation of CH in OPC mixes will not necessarily result in a total blocking of pores, whereas in slag-PC mixes, the Al2O4 and SiO3 set free by the hydration of slag will meet the released CH from the PC clinker and the resulting precipitation of CSH and C4AH13 will tend to fully block the pores, for the same porosity. Lane and Ozyildirim (1999) used ASTM C 120247 electrical resistance as an indicator of ionic transport properties. Mixes with slag replacement levels from 25% to 60% were investigated. The 25% replacement mix had comparable values to the OPC mix, while all other slag mixes had superior properties. The 60% mix resulted in an electrical resistance of about half of that of the OPC mix. Rose (1987) used slag contents of 0, 40, 50, and 65% and found that as slag content increased, Rapid
Chloride Ion Penetration (RCIP) significantly decreased. Additionally, a chloride soaking test was performed and it was determined that increases in $w/cm$ had less effect on RCIP for the slag mixes than on the OPC control. Using somewhat higher slag contents (50% to 75%), Sivasundarum and Malhotra (1992) found similar results. Zhang et al (1999) saw a significant reduction in chloride permeability using 55% slag replacement. Duos and Eggers (1999) noted that chloride permeability decreased with increasing slag contents. Blomberg (2003) found that as slag content increased from zero to 90%, chloride permeability dropped significantly at 90 days. Bleszinski et al (2002) found that the 35% and 50% slag mixes significantly reduced chloride permeability, with the 50% blend somewhat lower than the 35% blend. Bush et al (2000), using a 25% replacement with GGBFS, saw RCIP values reduced by half. Additionally, saltwater ponding test results at 90 days had about 50% lower chloride penetration in the top 0.5 in. than the OPC control. Using a 60% slag replacement, Peterson and Hale (2004) measured a reduction in RCIP by about two-thirds.

Durability of concrete mixes is commonly evaluated by use of ASTM C 666-49 (AASHTO T 161) AASHTO1997 in which concrete prisms are subjected to freezing and thawing cycles, then periodically tested for loss in weight, increase in length, or reduction of relative dynamic modulus. The relative dynamic modulus is expressed as the Durability Factor (DF), which also takes into consideration the relative number of cycles that the specimen survives. Using mixes with 377 kg/m3 total cementitious material at a $w/cm$ of 0.45 and an air content of 6.5±0.5%, Lane and Ozyildirim(1999) found excellent results for OPC and 60% slag mixes (Durability Factors all in excess of 100), with all slag mixes somewhat higher than the OPC mix. The highest Durability Factor occurred with the 50% slag mix. Pigeon and Regourd (1983) compared OPC and 66% slag mortar mixes (0.5 w/cm) and found good durability characteristics for both mixes as determined by a method similar to
ASTM C 666 Method. One possible problem is that slag delays the setting of concrete, therefore increasing the period of bleeding. If the bleed water is finished into the surface of the concrete, the durability of the surface could be lowered. In their study, Bleszinski et al (2002) found that slag mixes showed increased salt scaling with the 50% blend exhibiting the most severe damage in both the lab and field studies. Malhotra (1983, 1987) reported that with slag replacements of 65% and 75%, both strength and durability decreased.

2.4 INHIBITORS

Addition of corrosion inhibitor is another effective method of corrosion protection. Ping Gu et al (1997) have reported that, corrosion inhibitors are becoming an accepted method of improving durability of reinforced concrete in chloride laden environments. According to NACE (National Association of Corrosion Engineers) inhibitors are substances which, when added to an environment, decrease the rate of attack on a metal. David Bone (1989) and Luo De Schutter (2008) have concluded that corrosion inhibitors function by reinforcing a passive layer or by forming oxide layer and prevent outside agents and reduce the corrosion current. Based on the mode of application, corrosion inhibitors can be classified into two types, integral inhibitors (cast -in) and migrating inhibitors. Integral inhibitors are liquids or solids that are batched and mixed with the other concrete ingredients as a preventive measure for new construction work or repair work. Migrating inhibitors are used in mature reinforced concrete structures that are showing signs of reinforcement corrosion.

Violetta Munteanu and Frederick Kinney (2000) and Luo De Schutter (2008) have investigated the mechanism of inhibitors and reported that inhibitors can act as anodic inhibitors that block the corrosion reaction of the chloride-ions by chemically reinforcing and stabilizing the passive protective film on the steel (e.g. Nitrites); cathodic inhibitors react with the
steel surface to interfere with the reduction of oxygen (e.g. Zinc oxide) and ambidic or mixed inhibitors suppressing both anodic and cathodic sites by forming an adsorptive film on the metal surface (e.g. amines and fatty acids).

Luo De Schutter (2008) have reported that organic corrosion inhibitors consist of amines and fatty-acid act by adsorption on the metal surface forming an organic layer that may inhibit both the anodic and cathodic processes and they are considered as mixed inhibitors. These adsorption type inhibitors are typically organic compounds (e.g. amines and fatty acids). Research on corrosion inhibitors has increased substantially during the last 20 years and various chemicals have been investigated, including benzoates of amines and morpholine. Amines and alkanolamines and salts thereof have been described and patented for different applications such as for the protection of steel in cementitious matrices (Hope 1989). Alkanolamines such as diethanolamine, dimethylpropanolamine, monoethanolamine, dimethylethanolamine, methylidietanolamine, and triethanolamine have been tested as corrosion inhibitors and their effect on the concrete mechanical properties was evaluated (Ha-Won Song and Velu Saraswathi 2007). An inhibitive effect was noted for triethanolamine, monoethanolamine, and methylidietanolamine. Alkanolamine salts of organic and inorganic salts were also found to reduce steel corrosion rates and to be compatible with the concrete matrix. Alkanolamines are the active agent in many proprietary inhibitive formulations.

Calcium nitrite-based inorganic corrosion inhibitors have been widely used since the mid-1970s. A prominent inhibiting effect has been reported in the majority of previous studies (Nagla et al 2002, Pedro Montes et al 2004), showing an increase in the chloride threshold level and in the corrosion-free life of concrete structures. Notably, calcium nitrite is preferred over other corrosion inhibitors (sodium nitrite, sodium benzoate), because of
its compatibility with concrete properties. When added to concrete, sodium nitrite and sodium benzoate lower concrete strength (Monticelli et al 2000), while the inhibition effect of stannous chloride is marginal. In determining the minimal dosage of calcium nitrite to prevent corrosion, the preferred concentration ratio of nitrite to chloride ions is regarded as being 0.5-1.0 (Neal Berke and Maria Hicks 2004). Besides calcium nitrite, the traditional commercial inhibitor used for application in reinforced concrete structures, numerous substances have been tested as inhibitors against the corrosion of reinforcing steel rebars (Monticelli et al 2000). Sodium monofluorophosphate has been widely studied and applied in the field to prevent the onset of corrosion or to reduce corrosion rates, both in the presence of chlorides (Soylev Richardson 2008) and in the presence of carbonation. It is used by penetration from the concrete surface because, as an admixture, it induces strong retardation of the concrete setting and can be transformed into insoluble compounds.

The performance of inorganic inhibitors has been studied by Prabhakar et al (2009) and found out that addition of 4% Sodium Nitrate in concrete enhances the durability properties in addition to mechanical properties of concrete. Abdullah et al (2000) have reported that Calcium nitrite has been used as a corrosion inhibitor against chloride attack and as a set accelerator in concrete for more than 20 years. Considerable data are available concerning its effects on corrosion inhibition, setting times, freeze-thaw resistance, strength, and other properties. Justness (2001) reported that both calcium nitrate and calcium nitrite may act as anodic inhibitors against chloride induced corrosion of rebars in concrete through a similar mechanism, although the kinetics of reaction may be different.

Steel reinforced concrete is one of the most durable and cost effective construction materials, but it can suffer in high chloride
environments from corrosion due to chloride induced breakdown of the normal passive layer protecting the steel. One way of protecting embedded steel reinforcement from chloride induced corrosion is by the addition of corrosion inhibiting admixtures. The most widely used corrosion inhibiting admixture is calcium nitrite, due to its excellent inhibitor properties and its benign effect on concrete properties. One advantage to calcium nitrite is that its protection mechanism is well defined.

Saricimen et al (2002) have evaluated the effect of inhibitors on the corrosion of steel reinforcements in concrete by using anodic polarization, electron spectroscopy for chemical analysis (ESCA) and Auger electron spectroscopy (AES). The reinforcement corrosion in uncontaminated concrete specimens was evaluated by impressing +4 V anodic potential for accelerated corrosion of the steel bar and measuring the time-to-cracking of the concrete specimens. The effectiveness of the inhibitors in retarding reinforcement corrosion in the contaminated concrete specimens was evaluated by measuring the corrosion potentials and corrosion–current density. Results indicated that the time-to-cracking in uncontaminated concrete specimens incorporating alkanolamine based inhibitor(M2) and water based inorganic inhibitor R2 was higher than that in the control concrete specimens. The electrochemical test results and surface analysis results showed the better performance of inhibitor R2 compared to inhibitor M2 in retarding corrosion of steel in an environment of saturated calcium hydroxide in the presence of chloride ions.

Omar et al 2003 have investigated the effect of four types of corrosion inhibitors (calcium nitrite at two dosages, calcium nitrate at three dosages and two organic inhibitors at their recommended dosages) at five different levels of contamination, i.e., 0.8% chloride; 0.8% chloride plus 1.5% SO₃; seawater; brackish water; and unwashed aggregates. Concrete specimens
were used to assess the effect of corrosion inhibitors on the compressive strength of concrete and reinforcement corrosion. The results indicated that the corrosion inhibitors investigated in this study did not adversely affect the compressive strength of concrete. Furthermore, calcium nitrite was efficient in delaying the initiation of reinforcement corrosion in the concrete specimens contaminated with chloride, while both calcium nitrite and calcium nitrate mitigated the corrosive effects of chloride plus sulfate salts or sea water. In the concrete specimens prepared with brackish water or unwashed aggregates, all the inhibitors were effective in reducing the rate of reinforcement corrosion. The type and dosage of corrosion inhibitor were observed to be dependent on the nature and level of contamination.

Ngala et al 2002 have conducted laboratory investigations were performed to assess the efficacy of calcium nitrite as an inhibitor when used in surface treatments applied to reinforced concrete specimens that were chloride contaminated to varying extents in the presence or absence of carbonation. The corrosion responses of embedded steel bars at various depths of cover were monitored electrochemically during a controlled programme of cyclic wetting and drying undertaken for several months prior to the inhibitor treatment and for approximately 18 months thereafter. On completion of the exposure tests, measurements of corrosion weight losses and their distribution on the steel surfaces were also made. In non-carbonated specimens with high levels of internal chloride and carbonated specimens with even low levels of internal chloride, the surface-applied inhibitor treatment appeared to be ineffective under the conditions of the experiments and enhancement of local corrosion rates was observed in some specimens.

Sawada (2005) introduced two organic based (ethanolamine and guanidine) inhibitors into saturated specimens of carbonated and non-carbonated concrete from external electrolytes under the influence of an
electrical field applied between embedded steel cathodes and external anodes. The cathodic current density was galvanostatically controlled at values in the range 1–5 A/m² for periods of 3–14 days. Control experiments, in which the corrosion inhibitors were applied to similar saturated concrete surfaces from external electrolyte without current, were also conducted. After treatment, the specimens were sectioned and analysed to determine the concentration profiles of the corrosion inhibitors within the concrete. It was found that the efficiency of injection of both ethanolamine and guanidine under the applied field was far higher in carbonated concrete than in non-carbonated concrete and that, in the carbonated specimens, the inhibitors became concentrated near the embedded steel. In non-carbonated concrete, guanidine penetration was accelerated to a modest extent by the applied field but ethanolamine penetration was not significantly enhanced by the field. These findings were explicable in terms of the influence of the pH values of the pore solutions in the various specimens on the degrees of ionization of the organic bases concerned and hence on their tendencies to migrate and neutralize cathodically-generated hydroxyl ions.

Soylev and Richardson (2008) have published a state of art report on corrosion inhibitors for steel in concrete. Emphasis was given to the most commonly used inhibitors such as aminoalcohols (AMAs), calcium nitrites (CN) and sodium monofluorophosphates (MFPs). The report presents information related to (a) basic mechanism study, which gives information about the mechanism of protection provided by inhibitors, (b) effectiveness of inhibitors against corrosion in chloride contaminated and carbonated concrete, which deals with the preventive and curing effect of the inhibitors in different environments, (c) penetrability of the inhibitor, which underlines some difficulties of penetration into concrete for migrating corrosion inhibitors (MCIs), (d) influence on fresh and hardened concrete properties, which compares fresh concrete properties, mechanical performance and durability
with and without inhibitor, (e) field trials, which gives the limited data on the long-term performance of the inhibitors in real structures

Jamil et al (2003) performed laboratory investigations in order to assess the effectiveness and the inhibition mechanism of an amino alcohol-based inhibitor currently used as admixture to prevent corrosion of steel in concrete. The investigation was performed in the presence of chloride ions, using solutions simulating the concrete interstitial solution. Electrochemical measurements show that, an inhibitor film is formed on the surface hindering the anodic activity. Furthermore, the analytical investigation through the use of X-ray photoelectron spectroscopy (XPS) shows that the inhibitor film is able to complex with the chloride ion.

Ann and Song (2006) studied the effect of calcium nitrite-based corrosion inhibitor using a polarisation method and its influence on the chloride transport, compressive strength and setting time of concrete. The calcium nitrite-based corrosion inhibitor significantly reduced the corrosion rate of steel in chloride contaminated mortar and raised the chloride threshold level, ranging from 0.22% to 1.95% by weight of cement, while nitrite-free specimen produced the threshold level ranging from 0.18% to 0.33%. It was observed that concrete specimens containing the corrosion inhibitor produced the higher total charge passed in a rapid test for chloride ion permeability. An increase in the dosage of corrosion inhibitor resulted in a decrease in the concrete setting time. In addition, the compressive strength at early ages was increased by corrosion inhibitor, but in a long term (900 days), decreased to the level for 28 days.

Velu Saraswathy and Ha-Won Song (2007) analysed the corrosion characteristics of three kinds of cements, namely ordinary Portland cement (OPC), pozzolana Portland cement (PPC) and 25% fly ash replaced in ordinary Portland cement (FA) by designing two grades of concrete, M20 and
M40 mixes under accelerated exposure conditions. Reinforced concrete slabs of size 900 mm × 180 mm × 100 mm were cast, cured and pre-cracked to crack width of 0.10 mm, exposed to accelerated testing conditions in 3% NaCl environments and evaluated for their corrosion resistance using various electrochemical tests like open circuit potential, linear polarization technique, free chloride, alkalinity and weight loss measurements and the results obtained were discussed in detail. It was concluded that compared to OPC and FA, PPC performed better under chloride and sulphate environment and it will enhance the service life of concrete structures in marine environment.

In the above mentioned study proprietary organic- and inorganic-based inhibitors were evaluated under accelerated and free corrosion conditions in laboratory by using electrochemical and surface analytical techniques. Assessment and monitoring of corrosion in steel reinforcement have been a prime concern for concrete structures. There have been a large number of investigations on the problems of deterioration of concrete and the consequent corrosion of steel in concrete. Properly monitoring the structures for corrosion performance and taking suitable measures at the appropriate time could effect enormous saving. Moreover, the repair operation themselves are quite complex and require special treatments of the cracked zone, and in most instances the life expectancy of the repair is limited. Quality control, maintenance and planning for the restoration of these structures need non-destructive inspections and monitoring techniques that detect the corrosion at an early stage.

Over the past two decades, various electrochemical and non-destructive techniques were implemented for measurement of the corrosion rate of reinforcing steel in concrete structures. Ha-Won Song and Velu Saraswathi (2007) briefly discussed all the electrochemical and nondestructive techniques such as Open circuit potential (OCP) measurements, Surface
potential (SP) measurements, Concrete resistivity measurement, Linear polarization resistance (LPR) measurement, Tafel extrapolation, Galvanostatic pulse transient method, Electrochemical impedance spectroscopy (EIS), Harmonic analysis, Noise Analysis, Embeddable corrosion monitoring sensor and Cover thickness measurements, Ultrasonic pulse velocity technique, X-ray, Gamma radiography measurement, Infrared thermograph Electrochemical and analysis Visual inspection from the point of view of corrosion assessment and their applications to bridges, buildings and other civil engineering structures. Electrochemical Impedance Spectroscopy (EIS) is a powerful, rapid and accurate non-destructive method for the evaluation of wide range of materials.

Ismail and Ohtsu (2005) conducted a study on the corrosion assessment of reinforcing steel in concrete cylinders exposed to chloride ions. Fifty-two concrete cylinders, each with a single embedded reinforcing steel rod, were subjected to sodium chloride solution with 0%, 1%, 3% and 5% concentrations. Specimens were also subjected to pre-conditioning and drying-wetting cycles. Concrete mix proportion was designed with 60% water-to-cement ratio, containing plain Portland cement. AC Impedance Spectroscopy Technique (IS) was employed to determine the corrosion rate (CR) of the reinforced concrete cylinders. Electrical Equivalent Circuit was used to interpret the AC impedance spectra. To study the reliability of IS, results were compared with those obtained by such corrosion assessment techniques as Tafel Plot (TP) and linear Polarization (LP). Results confirm that IS gives reliable results with respect to the effect of exposure conditioning on CR of steel reinforcement. They also show a good agreement with both of TP and LP techniques.

Paul Vrkljan et al (1997) have studied the performance of migrating type corrosion inhibitors (MCI). It was observed that vapor and migrating corrosion inhibitors can make use of the porosity of concrete. Conventional
inorganic contact inhibitors need a liquid carrier to reach the metal. MCIs reach the surface of reinforcing steel while moving through the porous structure of concrete. Electrochemistry and other methods were used to evaluate the effectiveness of the corrosion inhibiting ability of MCIs. Their usefulness and limitations are discussed. The results of laboratory and independent tests for a new generation of MCIs combined with field experience of their applications are also presented.

Oan-Chul Choi et al (2008) have evaluated the corrosion performance of epoxy-coated reinforcing bars in chloride contaminated Southern exposure concrete test specimens by electrochemical impedance spectroscopy method. The test specimens with conventional bars, epoxy-coated bars and corrosion inhibitors were subjected 48 weekly cycles of ponding with sodium chloride solution and drying. The polarization resistance obtained from the Nyquist plot was the key parameter to characterize the degree of reinforcement corrosion. The impedance spectra of specimens with epoxy-coated bars are mainly governed by the arc of the interfacial film and the resistance against the charge transfer through the coating is an order of magnitude higher than that of the reference steel bars. Test results show good performance of epoxy-coated bars, although the coatings had holes simulating partial damage, and the effectiveness of corrosion-inhibiting additives. The corrosion rate obtained from the impedance spectroscopy method is equivalent to those determined by the linear polarization method for estimating the rate of corrosion of reinforcing steel in concrete structures.

Electrochemical Impedance Spectroscopy (EIS) or ac impedance methods have seen tremendous increase in popularity in recent years. Initially applied to the determination of the double-layer capacitance and in ac polarography, they are now applied to the characterization of electrode processes and complex interfaces. Electrochemical studies, the popularity of
this technique cannot be denied. However, EIS is a very sensitive technique and it must be used with great care. It is a complementary technique and other methods must also be used to elucidate the interfacial processes. Lasia et al (1999) conducted studies on recent and old techniques of impedance test. The purpose of the study is to fill this gap by presenting a modern and relatively complete review of the subject of electrochemical impedance spectroscopy, containing mathematical development of the fundamental equations.

2.4 **NEED FOR THE PRESENT STUDY**

The use of quarry dust as fine aggregate in concrete will reduce not only the demand for natural sand but also the production cost of the concrete and environmental problems. Most of the studies on the usage of quarry dust in concrete were carried out to judge the properties of fresh concrete and strength properties. Corrosion of steel in concrete is one of the major causes of premature deterioration of reinforced concrete structures, leading to structural failure. Literature survey revealed that not much work was done on the corrosion resistance of quarry dust concrete. Hence, in the present investigation consideration is given to study both the strength and corrosion resistance performance of concrete having quarry dust as fine aggregate.

A number of remedies such as use of mineral admixtures, addition of inhibitors and rebar coating have been suggested to prevent corrosion of steel in concrete structures. Mineral admixtures are finely divided siliceous materials which are added to concrete in relatively large amounts, generally in the range of 20 to 50% by weight of Portland cement. The use of mineral admixtures like fly ash and ground granulated blast furnace slag (GGBFS) in quarry dust concrete as partial replacement of cement, appears to constitute a very satisfactory outlet for this industrial by-product and improves ease of pumping of the concrete, strength, durability and reduction of cement
consumption. In addition to the cost saving, it also reduces CO₂ emission during the manufacture of Portland cement and environmental pollution due to disposal. Hence the utilization of these industrial by products not only reduces the cost of the concrete but also ensure sustainable development against environmental pollution.

Numerous studies were carried out to investigate the use of mineral admixtures in enhancing the corrosion resistive properties of conventional concrete. The corrosion resistance performance of concrete having quarry dust as fine aggregate with mineral admixtures has not been discussed much. In order to enhance the strength and durability characteristics of the quarry dust concrete the cement was partially replaced with fly ash and ground granulated blast furnace slag and their influence was studied. Efforts were also taken to determine the optimum replacement level of these mineral admixtures in quarry dust concrete. In the present study, the effect of partial replacement of cement with fly ash and GGBFS at 10%, 20%, 30%, 40% and 50% percentages in concrete containing quarry dust as complete substitute for fine aggregate has been investigated and the optimal percentage is determined.

Concrete construction along the coastal areas is frequently reported to be unsatisfactory as the concrete in these areas are found to be deteriorating rapidly due to the effect of chloride. The use of corrosion inhibitors is found to be one of the effective method to control rebar corrosion. Therefore, an attempt has been made to study the performance of the organic inhibitors and inorganic inhibitors to control rebar corrosion. The organic inhibitors used in this study are triethanolamine, diethanolamine and diethylamine and the inorganic inhibitors used are calcium nitrite, calcium nitrate and sodium nitrate at the dosage of 1%, 2%, 3% and 4% by weight of cement in concrete containing quarry dust as fine aggregate in resisting corrosion. The optimal percentage addition of each inhibitor for getting maximum strength and corrosion resistance is also determined individually.