CHAPTER 1

INTRODUCTION

1.1 GENERAL

This chapter emphasize the necessity of alternative sources for natural aggregates, types of industrial waste aggregates, role of aggregates and admixtures in high performance concrete and the need for the present investigation. The objectives and methodology of the work are also presented.

1.2 CONCRETE AND AGGREGATE

Concrete is the most widely used man-made construction material in the world today. The popularity of concrete is due to the abundance of raw materials, excellence in strength and durability, low manufacturing and maintenance cost, versatility in forming various shapes and its unlimited structural applications in combination with steel reinforcement. The aggregates typically account for 70–80% of the concrete volume and play a substantial role in different concrete properties such as workability, strength, dimensional stability and durability. Conventional concrete consists of sand as fine aggregate and gravel / limestone / granite in various sizes and shapes as coarse aggregate. The usage of enormous quantities of these natural aggregates results in destruction of natural resources (like river beds and hills) causing geological and environmental imbalance. Increase in demand and decrease in
supply of aggregates for the production of concrete results in the need to identify new sources of aggregates.

Construction materials are increasingly judged by their ecological characteristics. Moreover, the concrete industry faces a big challenge as cement is its vital component. The production of cement is an energy-intensive process, and the emission of Carbon dioxide (CO$_2$) during the cement production raises environmental concerns. There are increasing incidents where cement leads to distress in concrete in hostile environmental conditions. These factors have led to the thought of identifying alternatives to natural aggregates and reduction of cement consumption. The intensification of research in exploring the possibility of enhancing strength, durability and structural properties of concrete through the use of alternate materials and admixtures.

The construction industry recognizes considerable improvements are essential in productivity, product performance, energy efficiency and environmental performance. The industry needs to face and overcome a number of institutional, competitive and technical challenges. Throughout the industrial sector, including the concrete industry, the cost of environmental compliance is high. Use of industrial by-products such as fly ash, silica fume and slag can result in significant improvements in overall industry energy efficiency and environmental performance. The consumption of all types of aggregates has been increasing in recent years. Artificially manufactured aggregates are more expensive to produce and the available source of natural aggregates may be at a considerable distance from the point of use, in which case, the cost of transportation is a disadvantage. The other factors to be considered are the continued and expanding extraction of natural aggregates accompanied by serious environmental problems. Often, it leads to
irremediable deterioration of the countryside. Quarrying of aggregates leads to disturbed surface area but the aggregates from industrial wastes are adding extra aggregate sources to the natural and artificial aggregate. The use of industrial wastes as concrete aggregate prevents the environmental pollution also.

1.3 INDUSTRIAL WASTE

There is a growing interest in using industrial waste materials as alternative to natural aggregates. Significant research is made on the use of different materials as natural aggregate substitutes, such as coal ash, blast furnace slag, fibre glass waste materials, waste plastics, rubber waste and sintered sludge pellets.

The consumption of waste materials increases manifold if they are used as aggregate into cement mortar and concrete. This type of using waste materials can solve problems in lack of aggregate in various construction sites. It reduces environmental problems related to aggregate mining and waste disposal. The use of waste aggregates also reduces the cost of the concrete production. As the aggregates significantly control the properties of concrete, the properties of the aggregates have a great importance. Therefore, a thorough evaluation is necessary before using any waste material as aggregate in concrete.

1.3.1 Types of industrial waste

In this section, various types of industrial waste materials are explained. The types of industrial wastes available are,
1. Plastic wastes
2. Coal ash
3. Rubber tyre
4. Slags
5. Waste from food and agricultural industries
6. Pulp and paper mill waste
7. Leather waste
8. Industrial sludge
9. Mining industry waste

Depending on the generation, wastes can be separated into two types. They are the wastes that directly result from industry as industrial by-products and that which can be recycled. The first type includes coal ash, various slags from metal industries, industrial sludge, waste from industries like pulp and paper mills, mine tailings, food and agriculture, and leather. The second type includes different plastic and rubber wastes.

A broad classification of industrial waste aggregate is made depending on the chemical nature of wastes. Some waste aggregates come from production and use of organic materials. Plastics, rubber, leather and wastes from some food industries are organic wastes. On the other hand, industrial slags, mining wastes, coal industry wastes are inorganic wastes. Glass reinforced plastics and some industrial sludge contain both organic and inorganic materials. Another classification of industrial waste aggregate is done depending on the weight of waste aggregates. Some aggregates are lightweight by nature. Plastics, rubber, wastes of food and agricultural industries and coal bottom ash are of this kind. On the other hand, most of the industrial slags are heavier than the conventional aggregates.
1.4 INDUSTRIAL SLAG

Slag is a partially vitreous by-product of smelting ore due to separation of the metal fraction from the worthless fraction. It is considered as a mixture of metal oxides. However, slags also contain metal sulphides and metal atoms in the elemental form.

Ferrous slag is produced during the production of iron using blast furnace (blast furnace slag) as well as in the separation of the molten steel from impurities in steel-making furnaces (steel slag). Non-ferrous metallurgical slags are generated during refining of various metals such as Cu, Cr and Zn. The main types of slags that are generated from the iron and steel making industries are classified as Blast-furnace slag (BFS) and Steel-furnace slag (SFS).

1.4.1 Steel slag

Steel slag is produced during the separation of molten steel from impurities in steel furnaces. The slag occurs as a molten liquid and is a complex solution of silicates and oxides that solidifies upon cooling. There are several different types of steel slag produced during the steel-making process. Out of which basic oxygen furnace slag, electric arc furnace slag, electric induction furnace slag and ladle furnace slag are important. Steel slag is considered as potential alternative to natural aggregates.

An electric arc/induction furnace produces steel by melting recycled steel scrap, using heat generated by an arc/induction, created by a large electric current. The slag is formed through the addition of fluxing agents (such as lime or dolomite), which are used to remove impurities from the
molten steel. The impurities combine with the fluxing agents at high temperature forming a by-product known as steel slag. The temperature at the steel slag forming stage is up to 1700°C. Under this temperature, the liquid reaction occurs. Liquid steel slag contains appreciable amount of CaO and SiO₂. In the process of steel making, basicity keeps increasing due to the continuous addition of lime and mineral composition also changes with change in basicity. The following replacement reactions occur (Wang 1992).

\[
2(CaO\cdot RO\cdot SiO_2) + CaO = 3CaO\cdot RO\cdot 2SiO_2 + RO
\]

\[
3CaO\cdot RO\cdot 2SiO_2 + CaO = 2(2CaO\cdot SiO_2) + RO
\]

\[
2CaO\cdot SiO_2 + CaO = 3CaO\cdot SiO_2
\]

The resultant products in the right hand side contained in set, solid slag. Steel slag has a lower density than steel and therefore floats on top of the molten bath of steel. Then the molten steel and slag are removed separately from the furnace.

In the basic oxygen process, hot liquid blast furnace metal, scrap and fluxes, consisting of lime and dolomitic lime, are charged into the furnace. The oxygen, injected into the furnace, combines with and removes the impurities in the charge. These impurities consist of carbon as gaseous carbon monoxide, silicon, manganese, phosphorus and some iron as liquid oxides, which combine with lime and dolomitic lime to form the BOF slag. After being tapped from the furnace, molten steel is transferred in a ladle for further refining to remove additional impurities that still remain within the steel. This operation is called ladle refining because it is completed within the transfer ladle. During ladle refining, additional slags are generated by further adding fluxes to the ladle for melting. Steel mill scale is produced during the processing of iron in steel mills.
During the processing of steel in steel mill, iron oxides, known as mill scale are formed on the surface of the metal during the continuous casting, reheating and hot rolling operations. The steel mill scale is removed by water sprays. The steel mill scale is somewhat similar to steel slag and therefore, like steel slag, it can be used in concrete production. A flow chart showing the production process of various types of slag is given in Figure 1.1.

(Source: De Brito & Saikia 2013)

Figure 1.1 Production process of different types of slag
1.4.2 Properties of steel slag

Generally, the slag produced is very angular and porous with a rough surface texture. The chemical properties of the slag vary depending on the furnace, raw materials and slag formers (fluxing agents) used to produce the steel. Steel slag has rough vesicular nature with many non-interconnected cells which gives a greater surface area than smoother aggregates of equal volume. This feature provides an excellent bond with cement paste. Steel slag has high bulk specific gravity and moderate water absorption. Steel slag aggregate have high density, but apart from this feature most of the physical properties of steel slag are better than hard traditional rock aggregates. Processed steel slag has favourable mechanical properties for aggregate use, including good abrasion resistance, good soundness characteristics, and high bearing strength. In summary, SSA is angular and porous, has a high specific gravity, is more resistant to abrasion and impact, is highly stable due to high angles of internal friction, has high load carrying capacity as measured by the CBR, and has hardness that approaches quartz. The aggregate formed from the slag mainly comprises of calcium oxide (CaO), silicon oxide (SiO$_2$), iron oxide (Fe$_2$O$_3$), magnesium oxide (MgO), manganese oxide (MnO), and aluminum oxide (Al$_2$O$_3$). Due to their high heat capacity, steel slag aggregate are observed to retain heat considerably longer than conventional natural aggregates. The heat retention characteristics of steel slag aggregate is advantageous in hot mix asphalt repair works in cold weather.
1.5 **FLY ASH**

Burning of coal generates two types of waste materials namely fly ash and bottom ash. There are two types of bottom ashes, wet bottom boiler slag and dry bottom ash depending on both the boiler type and its design. Coal fly ash, also known as pulverised fuel ash, is the finest fraction of these ashes, which are released from combustion chamber and transported by flue gases. Fly ash contains the non-combustible matter in coal along with a small amount of carbon that remains due to incomplete coal combustion. Fly ash consists mostly of silt-sized and clay-sized glassy spheres. When pulverised coal is burned in a dry bottom boiler about 80 per cent of the unburned material or ash is entrained in the flue gas and is captured and recovered as fly ash. The remaining 20 percent ash that is collected from the bottom of furnaces is called coal bottom ash. This is a coarse, incombustible by-product with grain sized similar to that of fine and coarse sized natural aggregates.

Bottom ash is produced as a granular material and removed from the bottom of dry boilers. Boiler slag, a coarse grained product is produced from two types of wet bottom boilers, slag-tap and cyclone boilers. The slag-tap boiler burns pulverised coal while the cyclone boiler burns crushed coal. Both boiler types have a solid base with an orifice that is opened to allow molten ash to flow into a hopper, which contains quenching water. When the molten slag comes in contact with the quenching water, the ash fractures instantly, crystallises, and forms pellets. High pressure water jets wash the boiler slag from the hopper into a sluiceway, which then transmits the ash to the collection basins for dewatering and further processing. Boiler slag is a coarse, angular, glassy, black material. When pulverised coal is burned in a slag-tap furnace, as much as 50% of the ash is retained in the furnace as boiler
slag. In a cyclone furnace, which burns crushed coal, 70–85 % of the ash is retained as boiler slag. Properties of coal ash depend on coal type, pulverising system, combustion conditions, temperature, type of furnace, minerals in coals and milling system.

The use of fly ash (FA) as partial replacement of normal Portland cement in concrete is very common nowadays. Around 15–30 % of cement is generally replaced by FA in normal structural concrete mixes. However, the overall percentage of utilisation remains very low in many countries, and most of the fly ash is dumped at landfills. Much higher quantities of FA can be used in concrete if fly ash can partially replace the fine sand fraction in concrete mix. This replacement can be made by low quality fly ash too, which has low pozzolanic properties. American Society for Testing and Materials (ASTM) classifies fly ash into two categories - Class F (low calcium) and Class C (high calcium) fly ash. Combustion of bituminous or anthracite coal normally produces Class F fly ash and combustion of lignite or sub-bituminous coal normally produces Class C fly ash.

1.6 SILICA FUME

Silica fume is a by-product in the reduction of high-purity quartz with coke in electric arc furnaces in the production of silicon and ferrosilicon alloys. Silica fume consists of fine particles with a surface area on the order of 20,000 m²/kg with particles approximately one hundredth the size of the average cement particle. Because of extreme fineness and high silica content, silica fume is a very effective pozzolanic material. Silica fume is added to Portland cement concrete to improve its properties, in particular its compressive strength, bond strength, and abrasion resistance. These improvements result from the addition of a very fine powder to the cement
paste mix as well as from the pozzolanic reactions between the silica fume and free calcium hydroxide in the paste. Addition of silica fume also reduces the permeability of concrete to chloride ions. It also protects the reinforcing steel of concrete from corrosion, especially in chloride-rich environments such as coastal regions. When silica fume is incorporated, the rate of cement hydration increases at the early age. During the last decade, considerable attention has been given to the use of silica fume as a partial replacement of cement to produce high-performance concrete.

1.7 HIGH PERFORMANCE CONCRETE

The American Concrete Institute (ACI) defines high performance concrete as concrete meeting special combination of performance and uniformity requirements that cannot be achieved routinely when using conventional constituents and normal mixing, placing and curing practices. A commentary to the definition states that a high-performance concrete is one in which certain characteristics are developed for a particular applications and environment. The performance requirements of concrete cannot be the same for different applications. Hence, the specific definition of HPC requirement for each industrial application is likely to vary. In general the high performance concrete is defined as that concrete which has the highest durability for any given strength class. The comparison between the concrete of different strength classes is not appropriate. This means that, with the available knowledge, one can always strive to achieve a better (most durable) concrete required for a particular application. A HPC using only cement as a binder requires high paste volume, which often leads to excessive shrinkage and large evolution of heat of hydration, besides increased cost. A partial replacement of cement by mineral admixtures such as, fly ash, silica fume, and ground granulated blast furnace slag in concrete mixes would help to
overcome these problems and lead to improvement in the durability of concrete. This would also lead to additional benefits in terms of reduction in cost, energy saving, promoting ecological balance and conservation of natural resources.

1.7.1 Role of aggregates in HPC

Aggregates provide dimensional stability and wear resistance for concrete. Not only do they provide strength and durability to concrete, but also influence the mechanical and physical properties of concrete. Aggregates should be hard, strong, free from undesirable impurities and chemically stable. They should not interfere with the cement or any of the materials incorporated into concrete. They should be free from impurities and organic matters which may affect the hydration process of the cement. The workability, strength, durability and moisture susceptibility of concrete are greatly influenced by the characteristics of aggregates. The size and grading of aggregates are important parameters in the design of a mix for a particular project as they can influence the workability of fresh concrete and its hardened strength. Most of the aggregates used are naturally occurring aggregates, but some artificial aggregates can be introduced in concrete. These artificial and processed aggregates react with the cement paste and chemically combine to improve the mechanical properties of concrete.

Steel slag aggregates are fairly angular, roughly cubical pieces having flat or elongated shapes. They have rough vesicular nature with many non-interconnected cells which give a greater surface area than smoother aggregates of equal volume; this feature provides an excellent bond with cement paste. Steel slag has a high degree of internal friction and high shear strength. Most of the physical properties of steel slag are better than hard
traditional rock aggregates. Some of the positive features of steel slag are listed below.

1. They are strong and durable.
2. They have excellent angular shape which helps to develop very strong interlocking properties.
3. They have high resistance to abrasion and impact.

### 1.7.2 Role of mineral admixtures in HPC

When mineral admixtures are incorporated to concrete, the silica present in these materials react with the calcium hydroxide (CH), released during the hydration of cement. It also forms additional calcium silicate hydrate (C-S-H), which improves the durability and the mechanical properties of concrete. The use of mineral admixtures such as fly ash, silica fume and metakaolin is to overcome the adverse effects of calcium hydroxide produced during hydration of cement in concrete. These mineral admixtures produce less percentage of CH when compared to ordinary portland cement. The pozzolanic reaction of these mineral admixtures involves only the consumption and not the production of CH. The consumption of CH improves the durability of cement paste by making the paste dense and impervious. Hence, the mineral admixtures when used in optimum proportion, improve the quality of concrete by

- Lowering the heat of hydration and thermal shrinkage
- Increasing water tightness
- Reducing the alkali-aggregate reaction
- Improving the chemical resistance and
- Improving the workability.
1.7.2.1 Role of fly ash in HPC

Fly ash, a principal by-product of the coal-fired power plants, is well accepted as a pozzolanic material that may be used either as a component of blended portland cement or as a mineral admixture in concrete. In commercial practice, the dosage of fly ash is limited to 15% - 30% by mass of the total cementitious material. Usually, this amount has a beneficial effect on the workability and cost economy of concrete. The influence of fly ash on the properties of fresh concrete depends upon the source and quality of the fly ash.

A concrete mix containing fly ash is cohesive and has a reduced bleeding capacity. The action of fly ash is similar to that of superplasticizer with respect to water demand. The fly ash disperses and absorbs the particles of portland cement. Fly ash in the mix has a retarding effect, typically of about 1 hour, caused by the release of sulphur trioxide ions present at the surface of the fly ash particles. Because of this retarding effect, initial setting gets delayed. However, the time interval between initial setting and final setting remains unaffected. It is proved that the addition of fly ash improves the dispersion of the portland cement particles, improving their reactivity. The reaction takes place within the pores of the cement paste and on the surface of fly ash particles. Using fly ash in concrete will increase the setting time compared with an equivalent grade of normal concrete.

1.7.2.2 Role of silica fume in HPC

The presence of silica fume in the concrete mix improves workability and makes the mix more mobile, yet cohesive. This is the consequence of a better dispersion of the cementitious particles. Due to the surface characteristics of the silica fume particles which are smooth and
absorbs little water during mixing. The workability of concrete containing silica fume is more sensitive to variations in the water content of the mix than ordinary mix, as the fineness of silica fume reduces bleeding of concrete. The mix containing silica fume has very low penetrability and good resistance to penetration by chloride ions and thereby reducing freeze and thaw effect.

1.7.3 Role of chemical admixtures in HPC

The use of mineral admixtures in concrete, requires the addition of chemical admixtures or superplasticizers. The action of chemical admixture or superplasticizer is mainly to fluidify the mix and improve the workability of concrete. Addition of superplasticizer to a concrete mix causes a repulsion leading to deflocculating and consequent increase in the fluidity of the mix.

1.8 NEED FOR THE PRESENT STUDY

At present, many steel plants which are set up across the world causes a huge production of solid waste materials like slag. The 2012 world output of SFS was in the order of 150 to 230 million tons, while in the United States the amount of iron and steel-making slag was around 17 to 22 million tons (Van Oss 2013). Production of iron and steel is associated with the generation of solid waste materials like slag. Big steel plants in India generate about 29 million tonnes of waste materials annually. In addition, there are several medium and small plants all over the country (Khan & Shinde 2013a). Steel production in India is about 72.20 million tons and steel slag waste generated annually is around 18 million tons, but hardly 25% is being used in cement production (Nadeem & Pofale 2012). However, steel slag is not used efficiently and thoroughly for long, which causes its great accumulation, waste of land, and serious air and water pollution.
The aggregates are vital elements in concrete to improve the bulk shape of the concrete. The usage of enormous quantities of aggregates results in destruction of hills causing geological and environmental imbalance. The negative environmental impacts of extracting river sand and crushed stone aggregate become a major problem in most parts of the country. Pollution hazards, noise, dust, blasting vibrations, loss of forests and spoiling of natural environment are the bad impacts caused due to extraction of aggregates. Landslides of weak and steep hill slopes are induced due to unplanned exploitation of rocks (Behra et al. 2004).

Government restrictions on extraction of natural aggregates have resulted in scarcity and significant increase in its cost. With increasing concern over the excessive exploitation of natural aggregates and environmental pollution, there is a need to look for an alternative aggregate which is economically viable and suitable for the construction industry. Steel slag aggregate is a viable source of concrete aggregates. Usage of steel slag aggregate in concrete is the best disposal route of steel slag which can also solve the environmental pollution problems. In view of the above, an attempt is made in the present work to develop high performance concrete with complete replacement of natural coarse aggregate by steel slag aggregate. This fulfils the need of alternative aggregates for concrete, improves the properties of concrete and prevents the environmental pollution due to the disposal of steel slag.

1.9 SCOPE AND OBJECTIVES OF THE WORK

The basic aim of this research is to evaluate the feasibility of locally available steel slag to use as concrete aggregate in order to find an alternate source to natural aggregates. From literatures, it is observed that
steel slag is considered as potential alternative to natural aggregates and steel slag must be allowed to aging, before it is used as aggregates. There are different opinions about the aging period of steel slag. The research papers on the effect of aging period of steel slag on the properties of concrete are also quite rare. Hence, a detailed study is made to evaluate the effects of different aging periods of steel slag on the properties of concrete. The scope of the work is to investigate the strength and durability properties of High Performance Concrete (M60 grade) with steel slag aggregate after different aging periods (every six months) of steel slag. Based on the strength and durability property test results, the feasibility of steel slag to use as concrete aggregate is evaluated and optimum aging period of steel slag is established. The following are the objectives of the present work.

(i) To determine the properties of locally available steel slag and to study the effect of steel slag aging.

(ii) To investigate the strength and durability properties of HPC with steel slag aggregate after different aging periods of steel slag.

(iii) To determine the load carrying capacity and deflection of HPC beams with SSA (after optimum aging period) and to validate the experimental results with numerical modeling using ANSYS software.

(iv) To study the economy of HPC with steel slag aggregate

1.10 RESEARCH METHODOLOGY

In order to meet the above objectives the following methodology is adopted. Research problem is identified after extensive literature survey. Materials required for the investigation are collected from nearest sources.
Experiments are conducted to determine the properties of materials. After finding the material properties mix design is carried out as per ACI 211.4R-93. An attempt is made to produce HPC with SSA and to find optimum aging period of SSA. The strength properties such as compressive strength, flexural strength, Young’s modulus, impact strength and bond strength of HPC (using SSA after different aging periods) are determined.

Durability of concrete is the primary criteria for the life of concrete structures even its performance in strength aspects are much better. Keeping the above in mind the durability tests such as water absorption, porosity, acid resistance, fire resistance, abrasion resistance and rapid chloride permeability tests are carried out for the different mixes.

From the strength and durability test results, optimum aging period of the steel slag aggregate is established. The relationship between aging period of SSA and compressive strength is developed by regression analysis. The relationship between the compressive strength and other strength properties such as flexural strength, Young’s modulus, impact strength and bond strength are developed. From these relations, it will be possible to predict the flexural strength, Young’s modulus, impact strength and bond strength of concrete without performing experiments, if the compressive strength of concrete is known. Similarly the relationship between the compressive strength and some of the durability properties are also developed.

After finding strength, durability properties and optimum aging period, reinforced HPC beams are cast and tested, to study their behaviour in flexure. The beam specimens of size 100 x 200 x 2000 mm are are used for their flexural behaviour study. Analytical (ANSYS) models are developed for
the beams in flexure. The basic steps involved in ANSYS include model generation, assigning material and model properties, meshing, application of boundary condition and loading, analysis and interpreting results. The load carrying capacity and deflection values obtained from experimental investigation are compared with the analytical results. By considering strength, durability and flexural behaviour test results suitable conclusions are drawn.

1.11 ORGANIZATION OF THE CHAPTERS

The present work “Effect of steel slag aging on strength and durability properties of high performance concrete” is organized in five chapters.

Chapter 1 provides a basic idea about the necessity of alternative sources for natural aggregates. The types of industrial waste aggregates, role of aggregates and admixtures in high performance concrete and need for the present investigation are also explained.

Chapter 2 deals with critical review of literature on high performance concrete, utilization of steel slag aggregate in concrete and aging of steel slag aggregate.

Chapter 3 presents the materials and methodology adopted in the present work. It includes methodology adopted to investigate the strength, durability and flexural behaviour of high performance concrete.

Chapter 4 summarises the test results and detailed discussion on strength, durability and flexural behaviour of high performance concrete. The relationship between aging period of SSA and compressive strength of
concrete is explained. Relationships between strength and durability properties are also presented. Flexural behaviour of concrete studied by experimental and analytical investigations are explained. Economy aspects of concrete with SSA are discussed.

Chapter 5 presents the conclusions arrived based on the results obtained from experimental and analytical investigations. Suggestions for further research work are also added at the end.