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Chapter 1

Introduction

1.1 Background

Slag is the main by-product generated during iron and steel production. The nature and composition of slag depends on the type of steel made and the raw-materials used for steel making. Over the past decades, both the types of steel and the quantity of steel produced have increased. Consequently slag, more diversified in composition and nature and higher in volumes, are being generated. Slag is being produced since the production of iron and steel started but became a source of concern only after it was identified as an industrial waste in early 90s. Investigations have been directed to reduce the quantity of slag generation, recover value materials contained in it and to find suitable applications of this slag. The reuse of slag can reduce CO_2 emissions. Especially in densely populated countries like Bangladesh, the sustainable use of slag can contribute to natural resources saving, reduction of energy consumption and CO_2 emissions. This will help the promotion of the steel industry sustainability.

Bangladesh consumes more than 4 million tons of steel per annum and per capita steel consumption is around 25 kilograms. Around 400 steel mills, of different categories and sizes, currently produce steel in Bangladesh. With the progress of economy, the per capita consumption of steel and hence the production of steel in Bangladesh will increase leading to generation of higher volumes of slag. About 250,000 tons of steelmaking slag is generated in Bangladesh. There is no comprehensive industry statistics on slag produced versus slag utilized in Bangladesh. In most cases landfill is the main solution for the disposal of slag generated in the steel plants. In the developed countries like USA, Japan, Germany and France, the rates of utilization of slag generated is close to 100%. In these countries, 50% of slag is used for the road project directly, the remaining part is reused within the plant. Therefore, improving the utilization of steel slag in Bangladesh is a necessity to realize sustainable development in the steel sector.

1.2 Objective

This study aims to examine the nature of slag generated in the steel plants in Bangladesh in the process of its possible utilization for manufacture of some useful products primarily for the construction sector. When completed the outcome will help utilization of this industrial waste that is being generated in an ever-increasing volume in the rapidly growing steel sector and help maintain a healthy environment. This might also help save a natural resource like top soil and thus benefit the agriculture sector. Reuse of a by-product (slag) that is now being considered as a waste will also be financially rewarding for the steel sector.

1.3 Scope of Works

The ingredients of slag are similar to those of natural aggregates, the exact composition is however different and varied. Moreover, slag contains some valuable ingredients that could be extracted and reused. Brick aggregates, now used in road and building construction, are produced from burnt bricks. The production of bricks by burning clay mixes produces a significant quantity of CO_2 and is a major source of pollution in Bangladesh. There is enough indication that such slag can be converted into or incorporated in building materials and thus help manage such slag generated in steel plants in Bangladesh and help establish a cleaner environment in the steel sector.

Steel slag, due to its high strength and durability, can be processed in to aggregates of high quality comparable with those of natural aggregates. The high bulk density, the high level of strength and abrasion as well as the rough texture qualify steel slag as a construction material for hydraulic engineering purposes. In Germany, about 400,000 tons per year is used as aggregate for the stabilization of river bankers and river beds against erosion. Nippon Slag Association in Japan has, since 1993, been involved in application technology research for the use of steelmaking slag as a material for ground improvement in port and harbor construction.

This study aims to examine the nature of slag generated in the steel plants in Bangladesh in the process of its possible utilization in some useful products primarily used in the construction sector.

1.4 Outputs and Deliverables

According to the scope of work described in the ToR, the outputs and deliverables are mainly a report containing relevant data and recommendations. The content of the report will include:

1. Data generated through a survey on the quantity of slag generated in selected steel plants located in different steel making regions of Bangladesh.
2. The complete analysis of chemical composition and phases present in slag generated in these steel plants.
3. The nature and variation in composition of slag from different plants will be related to the practice of making steel in a plant
4. The physical and mechanical properties of the slag samples.
5. Possibility of using slag generated in steel plants in Bangladesh in road surfacing and also in concrete blocks.
6. The suitability of such blocks made using slag and additives (if required) in pavement surfacing and to contain river erosion.
7. Health hazards, if any, of using of such slag.
8. Recommendations on the use/destination of steel slags generated in Bangladesh.
9. Quantum of reduction in CO_2 emission due to reuse of such slag and
10. An extensive literature survey on the nature and use of similar slag in other countries.

1.5 Study Area

Technosum Steel Limited

Technosum Steel Ltd. is a steel mill in Dhaka, Bangladesh. It was founded in 2006. It produces steel through the induction furnace route. The plant is undergoing a massive program to enhance both quantity of steel produced and its quality.

Bandar Steel Industries Limited

Bandar Steel Industries Limited is one of the leading company in steel sector of Bangladesh. It is in operation since 2002. Key product manufactured by them is MS billets and deformed MS bars which are used for constructional purposes.

Anwar Ispat Limited

Anwar Ispat Ltd. is among the leading steel manufacturers in Bangladesh. Anwar Ispat currently produces 500W and grade 60 steel bars. Having been in the steel industry since 1978, Anwar Ispat has constantly set itself apart in the industry through resourceful and cutting-edge approaches.


Salam Steel Concast Re-Rolling Mills (pvt) Ltd (SCRM)

SCRM, located in Kadamtoli Industrial Area in Shyampur, Dhaka, has been in production for about 25 years. SCRM uses the induction furnace route for steel production and is equipped with modern facilities.

Kabir Steel Re-rolling Mills Ltd (KSRM)

KSRM is a steel manufacturing organization belonging to Kabir Group of Industries. Since its inception in 1984, KSRM has been driven to earn the trust and respect of the public by focusing on consistent quality, accurate weight and timely deliveries and producing world-class deformed bars. KSRM is meeting the increasing demands of the country head-on by producing and supplying international grade deformed bars emblazoned with the KSRM seal of quality. One of the largest steel plants in Bangladesh; this state-of-the-art facility has the ability to produce 8 lac metric tons a year. KSRM produces steel through the Induction furnace route.

Ratanpur Steel Re-Rolling Mills Ltd. (RSRM)

Ratanpur Steel Re-Rolling Mills Ltd. (RSRM) was established in January 1984 to meet the growing demand for high quality M.S. deformed bars in the country. The mill is situated in the heart of the progressive BaizidBostami Industrial Area, Chittagong.

Today, RSRM is widely recognized as one of the leading steel manufactures in the country and has embarked upon a series of initiatives aimed at increasing its production capacity to 1000 tons per day and yearly capacity of 300000 tons of world class products.

The facilities of RSRM include induction melting furnaces a ladle refining furnace, a continuous casting plant and rolling mills with the latest automated features.

GPH Ispat Limited

GPH Ispat Ltd. One of the leaders of Bangladesh in manufacturing steel promises a super strong future and economy with its world–class products. Not only structural bar, GPH Ispat Ltd. is also one of the producers of low and medium carbon and low alloy steel billets in Bangladesh, the main ingredient of manufacturing graded steel bar.

AbulKhair Steel

AbulKhair Steel of Bangladesh is a steel company catering to the steel demand of the country and abroad for almost a decade now. It is the only steel making plant in Bangladesh that uses the Electric Arc Furnace route for making reinforcing steel bars. Abul Khair Steels vision is to become a complete integrated steel plant with the ability to produce 100% refined steel.

Abul Khair Steels re-rolling mill is the single largest facility capable of producing 12 lakh tons of high quality hot rolled steel bars per anum.

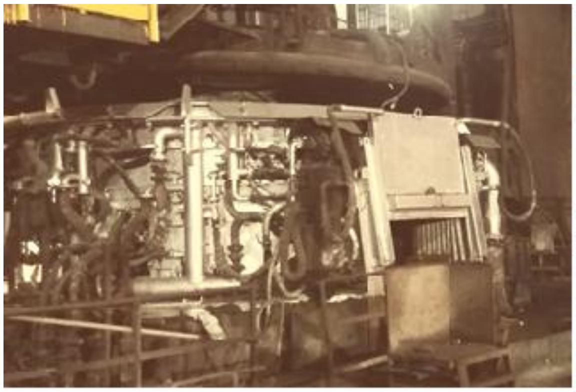


Table 1.1: Steels Mills with Location and Steel Production Route

Name of Mill	**Location**	**Steel Production Route**
Technosum Steel Limited	Dhaka	Induction furnace
Bandar Steel Industries (BSI)	Bandar, Narayangonj	Induction furnace
Anwar Ispat Limited	Tongi, Dhaka	Induction furnace
Salam Steel Contrast Re-Rolling Mills (pvt) Ltd (SCRM)	Abdullahpur, Dhaka	Induction furnace
Kabir Steel Re-rolling Mills Ltd (KSRM)	Agrabad, Chittagong	Induction furnace
Ratanpur Steel Re-Rolling Mills Ltd. (RSRM)	BaizidBostami Industrial Area, Chittagong.	Induction furnace
GPH Ispat	Asadgonj, Chittagong	Induction furnace
AbulKhair Steel (AKS)	Sonaichhari, Chittagong	Electric arc furnace

Chapter 2

Literature Review

2.1 Steel

Steels are alloys of iron and carbon containing up to about 1.7 per cent carbon. Most widely used steels however, contain much less carbon. In addition to carbon, steel also contains a number of other elements like manganese, silicon, sulphur, phosphorous, etc. Steel by itself is one of the most environment friendly products used in our daily life. Over the years, steel has played an important role in the development of human civilization. Steel has been a material of choice for innumerable applications all along in the past, and it is likely to continue to be an important material for use in the foreseeable future.

2.1.1 Global Steel Production

The world steel production has been increasing from year to year and has crossed the 1 billion tonnes mark for the first time in 2004. During the intervening period, steel production has grown very fast, and in 2010, global steel production has exceeded 1.4 billion tonnes. The rapid increase has been led by China accounting for more than 45% of world steel production. China is not only the largest producer of steel, it is also the largest consumer of steel followed by the United States and India.

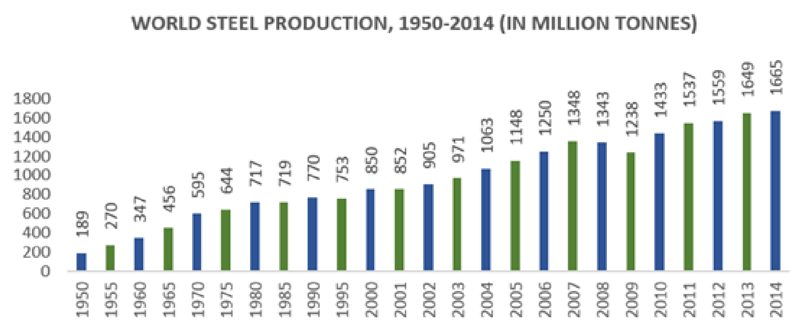


Figure 2.1: Changing global scenario of steel (Source: WORLD STEEL)

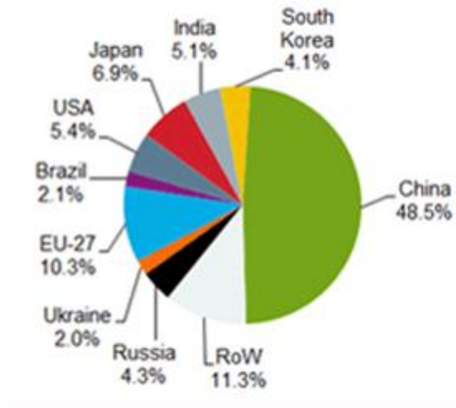


Figure 2.2: Global steel production in 2013 (Source: Internet)

2.1.2 Evolution of Steel Making Technology

Over the years, the world has seen considerable reforms in the technology of steel manufacture. In the 18th and 19th century the bulk of steel was produced by blowing air at high pressure through the bottom of the Bessemer converter that contained liquid iron. The oxygen in air oxidized excess carbon in the liquid iron as well as the impurities like manganese, silicon etc. It was noted that this technique could not remove all impurities. German scientist Siemen developed Open Hearth Furnace where the furnace was a rectangular shallow bath and the hot gases, produced from coal gas producer, were made to impinge on the hearth for ½ hour from one side and then for ½ hour from the other side. It took around 6 hours to produce good quality steel. The pig iron which contained high silicon, carbon etc. was refined by oxidizing these elements. The Siemen Open Hearth Furnaces of high capacities were installed all over the world. For over 100 years Siemen's process of making steel in Open Hearth Furnaces was the main technology used for making steel.

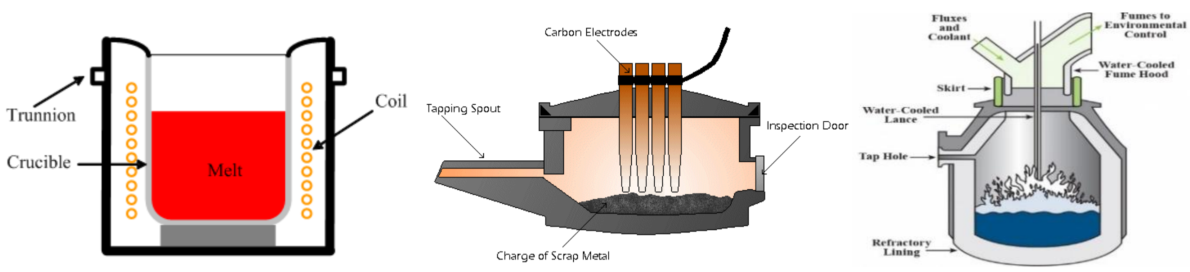
Subsequently in early 1950's L.D. process was developed in the cities of Linz of Germany and Donawitz of Austria to make steel. Oxygen, instead of air, was blown through the bottom of the L.D. converter as in the Bessemer converter. Very violent exothermic reactions took place. The process was faster. The chemistry of bath could be adjusted. This process, known as Basic Oxygen steel making (BOS) has now become the mainstay of making steel

The first attempt to melt steel electrically dates back to 1878 when Siemens conducted his initial experiments with arc melting. The first successful commercial arc furnace for melting steel went into operation in 1899. The capital cost of electric arc melting furnaces is much higher than that of fuel fired furnaces. Even then electric arc furnaces are now universally used for steel making and other purposes because the electric arc furnace system proved itself to be one of the most efficient and economic system to recycle scrap. The rapid growth of electric steelmaking may be attributed to the availability of a large volume of iron and steel scrap. The early developments in electric steelmaking were concerned with the production of alloy and special steels. Subsequently the arc furnaces have been used to produce those steels that were produced in open hearth furnaces and in Bessemer converters. Expansion into the carbon steels coincided with the demise of open-hearth and Bessemer processes. The growth of the electric arc furnace steel making has not been wholly related to the replacement plants, but in part has been due to emergence of new steelmaking areas. Now Electric Arc Furnaces of bigger capacities say 150 tonnes/charge have been developed. The recent developments in EAF technology are the increased oxygen consumption, reducing tap to tap time and the increased hot metal proportion to reduce power consumption and control ‘Cu’ content which comes from steel melting scrap to produce higher grades of steel. At present, nearly 30% of steel is produced by EAF route in the world.

Steelmaking by the Induction Furnaces technology came in early 80’s. The growth of the EAF industry has been adversely affected by the mushrooming of Induction Furnaces in India and Bangladesh and this trend is expected to continue. The Induction furnaces in India have taken to using DRI to the extent of 70% which improves their quality slightly in terms of controlling phosphorous and sulphur within acceptable limits for ordinary structural steel. Some of the bigger Induction Furnace units are in the process of installing Ladle Furnaces as a part-refining and heating equipment, coupled with Continuous Casting Machines. In Bangladesh, most of the steel produced is used for reinforcement of concrete and are now produced by melting iron and steel scrap in induction furnaces. Lower power requirements, lower capital investment, and easier mode of operation of induction furnaces were the major reasons for the adoption of this route of steel production.

An analysis of the Technology Profile of World Steel Industry shows that 70% steel is produced through the Basic Oxygen Furnace (BOF)/LD Convertor route, 28.8% through Electric Steel Making route and the balance 1.2% through the open hearth (OH). The open hearth route of production is almost extinct from the world map except in some of the erstwhile CIS countries like Russia, Ukraine etc. Another technical feature of the world steel industry is its increasing output of continuously cast steel thereby phasing out the obsolete ingot-casting route. In several countries, the continuous casting ratio is as high as 100% and in most of the technologically advanced countries, the ratio varies in the range of 90-95%, global average being 95% approximately.

In induction furnace steelmaking the composition of the liquid steel has to be controlled by controlling the selection and proportioning of raw materials. Because of the nature of induction heating, the melt in these furnaces is continuously stirred and complete separation of inclusions cannot take place. Attempts are being made to overcome these shortcomings by using what are known as Ladle Refining Furnaces (LRF). These are arc furnaces and are used to affect some refining of molten steel produced in induction furnaces. Molten steel from the induction furnaces are transferred to these ladle furnaces, the temperature of molten metal is maintained by arcing and refining is effected by the addition of required additions. Finally, the molten bath is homogenised by blowing argon/nitrogen through porous plugs fitted at the bottom of the refining ladles. Blowing of gas through also helps to remove inclusions from the molten metal.



(a) (b) (c)

Figure 2.3: Schematic of different types of furnaces; (a) Induction furnace, (b) Electric arc furnace, (c) Basic oxygen furnace.

All these efforts have enhanced quality of molten steel. The need to transfer molten steel to and from ladle refining furnaces has led to significant mechanization of the plants. By providing the refining outside the induction furnace, LRF provides many benefits including reduced alloy consumption, uniform temperature and composition, reduced holding time at the time of sequential casting, reduced tap to tap time of melting furnace which improve the lining life of furnace and productivity of the plant and finally decrease the overhead cost of the factory. So, the initial sense of increasing production cost by LRF is now changing and a strong belief is now growing in the mind of management that by efficient operation of LRF it is possible to produce steel billet in lower cost and maintaining reasonably high quality.

2.1.3 Steelmaking - Bangladesh Scenario

Steel making in Bangladesh started in late nineteen sixties in Chittagong Steel Mills Limited. The plant produced steel in open hearth furnace using pig iron and steel scrap as raw materials. The mill was closed in the 1980s.

Since then, the bulk of the total requirement of steel, particularly those suitable for use as reinforcement of concretes in Bangladesh, is being produced by melting steel scrap. Initially steel was made by melting steel scrap in Electric arc furnaces. Prevailing electrical power situation in Bangladesh in the 1980s obstructed the growth of the electric arc furnace route of steel making. Consequently, the producers of steel in Bangladesh resorted to making steel by melting steel scrap in electric induction furnaces. In recent days, the power generation and distribution situation in Bangladesh has improved significantly and a new technology of stabilizing arcs in electric arc furnaces has been developed. These have led to the re-introduction of electric arc furnace route for melting steel for use as reinforcement of concrete in Bangladesh.

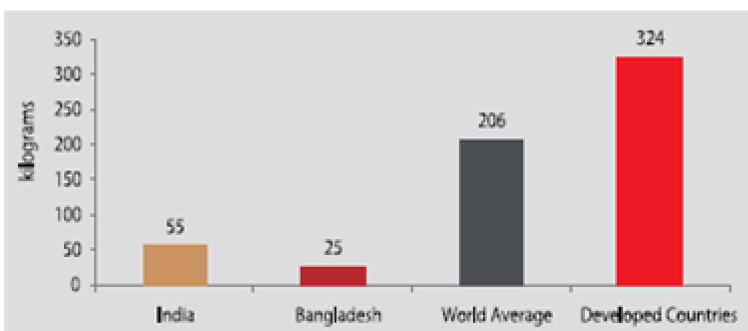


Figure 2.4: Per capita steel consumption (Source: World Steel Association)

In Bangladesh,current steel production capacity is approximately 4 milliontonnes per annum includingboth public and private producers. Theaverage per capita consumption of steel in Bangladeshis about 25 kg. By 2022 it is expected to increase to40Kg.

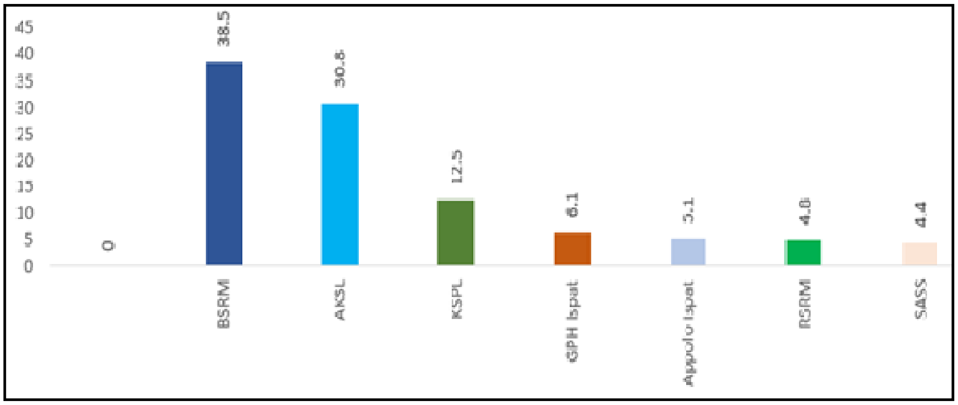


Figure 2.5: Gross sales of steel in 2014 (In billion BDT)

This growth is driven mostly by government spending on infrastructure projects, which accounts for 40% of steel consumption in Bangladesh. Although there are currently about 400 active firms in the industry, the top 20 companies serve more than half of the demand.

Business arenas

Factories of steel and re-rolling mills are mainly located at the following areas of Bangladesh:

Zone	Area
Dhaka	Demra, Shampur, Matuail, Gazipur
Narayanganj	Rupganj, Modonganj
Chittagong	Bhatiari, Fouzdarhat, Kumira, Baizid Bostami, Nasirabad

2.2 Steel Slag

Steel slag [Figure 2.4] is a byproduct obtained either from conversion of iron to steel in a Basic Oxygen Furnace (BOF), or from the melting of scrap to make steel in the electric furnaces. The slag is a molten liquid when formed and is a complex solution of silicates and oxides that solidifies on cooling and forms steel slag. Steel slag is defined by the American Society for Testing and Materials (ASTM) as a non-metallic product, consisting essentially of calcium silicates and ferrites combined with fused oxides of iron, aluminum, manganese, calcium and magnesium that are developed simultaneously with steel in basic oxygen, electric arc, or open hearth furnaces. The chemical composition and cooling of molten steel slag have a great effect on the physical and chemical properties of solidified steel slag.

Figure 2.6: Steel slag

The main constituents of iron and steel slags are iron oxide, silica, alumina, calcium, and magnesia, which together make about 95% of the total composition. Minor elements included are manganese, iron, sulfur compounds and traces of several other elements (Kalyoncu, 2001). Physical characteristics such as porosity, density, particle gradation of slag, are affected by the rate of cooling of the slag and its chemical composition.

2.2.1 Production of Slag in Iron and Steel Industries

Globally about 70 percent of the total quantity of steel is produced through the blast furnace-basic oxygen furnace (BF-BOS) route. Iron ores, primarily compounds of iron and oxygen, are the major raw-material for making iron. Natural deposits of iron oxides also contain various other compounds (primarily SiO_2 and compounds of manganese, sulphur, phosphorous etc.) with it. Making of iron is the first step in the production of steel. Iron is produced by the reduction of iron oxide (in iron ores) by coke. Reactions in which oxygen is removed are called reduction reactions. A blast furnace is commonly used to chemically reduce and physically convert iron oxides into liquid iron called "hot metal". The blast furnace is a huge steel stack lined with refractory brick, where iron ore, coke and limestone are dumped into the top, and preheated air is blown through the bottom. The raw materials require 6 to 8 hours to descend to the bottom of the furnace where they become the final product of liquid slag and liquid iron. The slag is produced through reactions between the various compounds contained in iron ore and coke. Various compounds like lime stone ($CaCO_3$), dolomite (Ca-Mg-CO_3) are added in the blast furnace to facilitate the effective separation of the unwanted materials in the form of slag.

Figure 2.7: Molten Slag

The intimate contact of coke and liquid iron at a high temperature within the blast furnace causes the reduced iron to absorb significant quantity of carbon (3 – 4 percent). Other elements like silicon, manganese, sulphur and phosphorous are also picked up by the liquid iron from the raw materials. This iron is very brittle and of little use in this form. To impart suitable properties, the impurities in pig iron are removed (or reduced in quantity) through oxidation of the unwanted elements. This process of removal of the undesirable elements in pig iron through a process of oxidation is called steel making.

The Basic Oxygen Steelmaking (BOS) process is the major modern process for steel making. Solid scrap steel is first charged into the vessel, followed by hot metal (liquid iron) from the blast furnace. A water-cooled lance is lowered into the vessel through which very pure oxygen is blown at high pressure. The oxygen, through a process known as oxidation, combines with the carbon, and with other unwanted elements, separating them from the metal, leaving steel. Lime-based fluxes (materials that help the chemical process) are charged, and they combine with the "impurities" to form slag.

A careful balance between the amounts of hot metal and solid scrap charged into the converter is maintained as a means of controlling the temperature and to ensure that steel of the required specification is produced. When the chemical content of the molten steel sample is found correct, the vessel is again tilted to allow the molten steel to flow out. This is known as tapping. The steel is tapped into a ladle, in which secondary steelmaking frequently takes place. During tapping small quantities of other metals and fluxes are often added to control the state of oxidation and to meet customer requirements for particular grades of steel.

Direct Reduced Iron (DRI), also known as Sponge Iron, offers an alternative steel production route to Blast Furnace-Basic Oxygen Furnace route. To produce DRI, iron ore is reduced in its solid state – unlike blast furnace process where a liquid metal is formed during reduction. DRI is then transformed in to steel in Electric Arc Furnace (EAF). DRI route offers an attractive option due to its small scale, low capital investments and its suitability to local market situations. Consequently, production has been expanding over the past three decades. However, the small scale of DRI operations also act as a barter for energy efficient investments.

Types of Slag

There are many grades of steel that can be produced, and the properties of the steel slag can change significantly with each grade. Grades of steel can be classified as high, medium, and low, depending on the carbon content of the steel. High-grade steels have high carbon content. To reduce the amount of carbon in the steel, greater oxygen levels are required in the steel-making process. This also requires the addition of increased levels of lime and dolomite (flux) for the removal of impurities from the steel and increased slag formation.

There are several different types of steel slag produced during the steel-making process. These different types are referred to as furnace or tap slag, synthetic or ladle slags, and pit or cleanout slag. The steel slag produced during the primary stage of steel production is referred to as furnace slag or tap slag. This is the major source of steel slag aggregate. After being tapped from the furnace, the molten steel is transferred in a ladle for further refining to remove additional impurities still contained within the steel. This operation is called ladle refining because it is completed within the transfer ladle. During ladle refining, additional steel slags are generated by again adding fluxes to the ladle to melt. These slags are combined with any carryover of furnace slag and assist in absorbing deoxidation products (inclusions), heat insulation, and protection of ladle refractories. The steel slags produced at this stage of steel making are generally referred to as raker and ladle slags.

Pit slag and clean out slag are other types of slag commonly found in steel-making operations. They usually consist of the steel slag that falls on the floor of the plant at various stages of operation, or slag that is removed from the ladle after tapping.

Because the ladle refining stage usually involves comparatively high flux additions, the properties of these synthetic slags are quite different from those of the furnace slag and are generally unsuitable for processing as steel slag aggregates. These different slags are usually segregated from furnace slag to avoid contamination of the slag aggregate produced.

2.2.1.1 Steelmaking in Induction Furnaces

While producing steel in induction furnaces, the chemistry of the end product is controlled. Steel scrap (and lesser quantity of cast iron scrap and sponge iron) is used as raw material. The chemical analysis of all the input materials is done to have a decision on the charge mix. After completing 50% charging of the input materials, a bath sample is analyzed for chemical composition. Based on the chemical analysis of the bath sample at this stage calculations are made for further additions of the metallics. If the bath sample at this stage shows high percentage of carbon, sulphur and phosphorus then the sponge iron content of the charge is increased. Final bath sample is taken when 80% melting is completed. Based on the analysis of this sample there is another adjustment in the charge. The lower content of carbon in the sample is corrected by increasing the quantity of pig iron/charge iron in the charge. Silicon and manganese in the metal is oxidized by the iron oxide of the sponge iron. Sulphur and phosphorus is also diluted by the sponge iron. Because of use of sponge iron the trace elements in the steel made in the IF remains under control.

The melting is done in an oxidizing environment. Thus, various oxides, those of iron, silicon and manganese are formed. These oxides (silica, iron oxide from steel scrap, other oxidation by products from melting, and those with refractory linings) react with each other to form what is known as slag. Once the melting is complete, the slag is skimmed off. This is one of the major solid wastes generated in the steel plants.

Figure 2.8: Induction Furnace Slag

2.2.1.2 Steelmaking in Electric Arc Furnaces

In Electric Arc Furnace (EAF) steelmaking, steel scrap, hot briquetted iron and pig iron is charged as raw materials. The heat for melting the charge is supplied through the creation of electric arc between two or more electrodes. After charging, the electrodes are lowered onto the scrap, and an arc is struck. Oxygen is also blown into the scrap and extra chemical heat is provided by wall-mounted oxygen-fuel burners. Both processes accelerate scrap melt-down.

For a furnace with basic refractories, which includes most carbon steel-producing furnaces, the usual slag formers are calcium oxide (CaO, in the form of burnt lime) and magnesium oxide (MgO, in the form of dolomite and magnesite). These slag formers are either charged with the scrap, or blown into the furnace during meltdown. Another major component of EAF slag is iron oxide from steel combusting with the injected oxygen. Later in the heat, carbon (in the form of coke or coal) is injected into this slag layer, reacting with the iron oxide to form metallic iron and carbon monoxide gas, which then causes the slag to foam, allowing greater thermal efficiency, and better arc stability and electrical efficiency. The slag blanket also covers the arcs, preventing damage to the furnace roof and sidewalls from radiant heat.

During melting and refining operations, some of the undesirable materials within the bath are oxidized and enter the slag phase. The slag is poured out of the furnace through the slag door.

Figure 2.9: Electric Arc Furnace Slag

2.2.2 History of use of iron and steel slag

The history of the use of iron and steel slag dates long back and European Slag Association noted that the earliest reports (European Slag Association, 2006) on the use of slag refer to Aristotle, who used slag as a medicament as early as in 350 B.C. Application of iron slag in road building has a long history and dates back to the time of the Roman Empire, some 2000 years ago, when slag from the iron-making forging were used in base construction.

Throughout history, the use of blast furnace slag has ranged from the novel to the usual including: cast cannon balls in Germany (1589), wharf buildings in England (1652), slag cement in Germany (1852), slag wool in Wales (1840), reinforced concrete in Germany (1892), and slag bricks made from granulated slag and lime in Japan (1901). Blast furnace slag has been utilized in concrete masonry for many years. The blast furnace slag can impart many desirable properties to the masonry units such as lighter weight and increased fire resistance. Blast furnace slag products have been used successfully for agricultural applications.

The physical and chemical properties of mineral wool insulation, also known as slag wool are major factors in their utility as residential and commercial insulation, pipe and process insulation, insulation for ships, mobile homes, domestic cooking appliances, and a wide variety of other applications.

In contrast, the application of steel slag was not attractive because vast volumes of blast furnace slag were available. Steelmaking slag has been used commercially since at least the mid-19th century. It is currently used in all industrialized countries, wherever steel is produced. Beginning in the 20th century, many new uses for steelmaking slag were developed in a variety of industries. Steel mills and slag processors work closely together to ensure that the steelmaking slag remains a high-quality product for current and future applications. The application of steel slag from steel mills was not very popular until the late 1990s, for there were vast amounts of blast-furnace slag available, while the steel slag from steel mills was used for the manufacture of chemical fertilizers, where only the so-called Thomas steel slag, a by-product of steel production from phosphorous raw iron, was used.

Through awareness of environmental considerations and more recently the concept of sustainable development, extensive research and development has removed slag from industrial waste into modern industrial material which is effectively and profitably used for many industrial purposes, especially as raw materials in cement production, in landfill cover material, and in the numerous construction and agricultural applications.

2.2.3 Utilization of Steel Slag

It has been estimated that each year fifty million tons of steel slag is generated throughout the world. Only in Europe, around twelve million tonnes of steel slag is generated every year. Steel slag is a residual material that is generated in the liquid form during the production of steel. Towards the end of the steel making process, the floating steel slag is separated from the surface of molten steel which subsequently solidifies to a solid product.

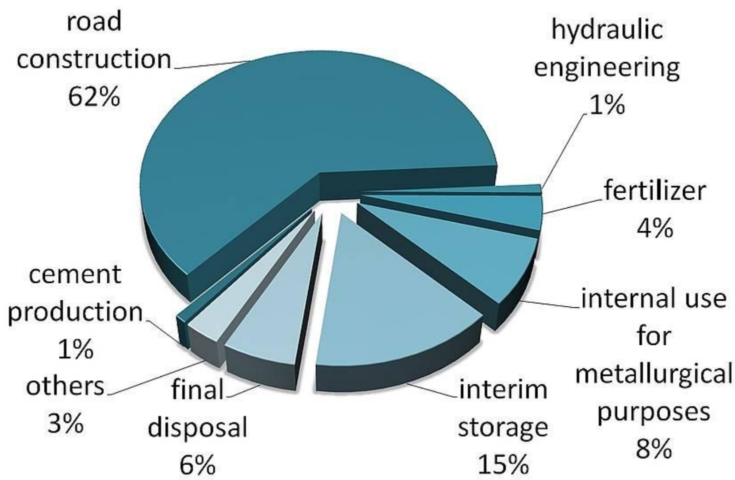


Figure 2.10: Use of slag for different purposes (Source: Euroslag)

The solidified slag is then crushed with the help of a large steel ball or a solid steel cylinder by dropping it on to the slags. The process for crushing and grading is repeated until the required size of aggregates is obtained. Recovery of metallic iron particles is carried out electromagnetically. The slag is then supplied in the form of construction aggregate to the construction agencies. It is competing with natural aggregate, where high performance aggregate is limited. This indicates the importance of alternative aggregates like steel slag. These are thus valuable products not wastes, and can provide environmental benefits. Utilization of steel slag is an involved process which includes several stages from production of steel slag to end products. Successful utilization is not expected to be fulfilled in one stage. The overall process can be expressed as in Figure 2.11.

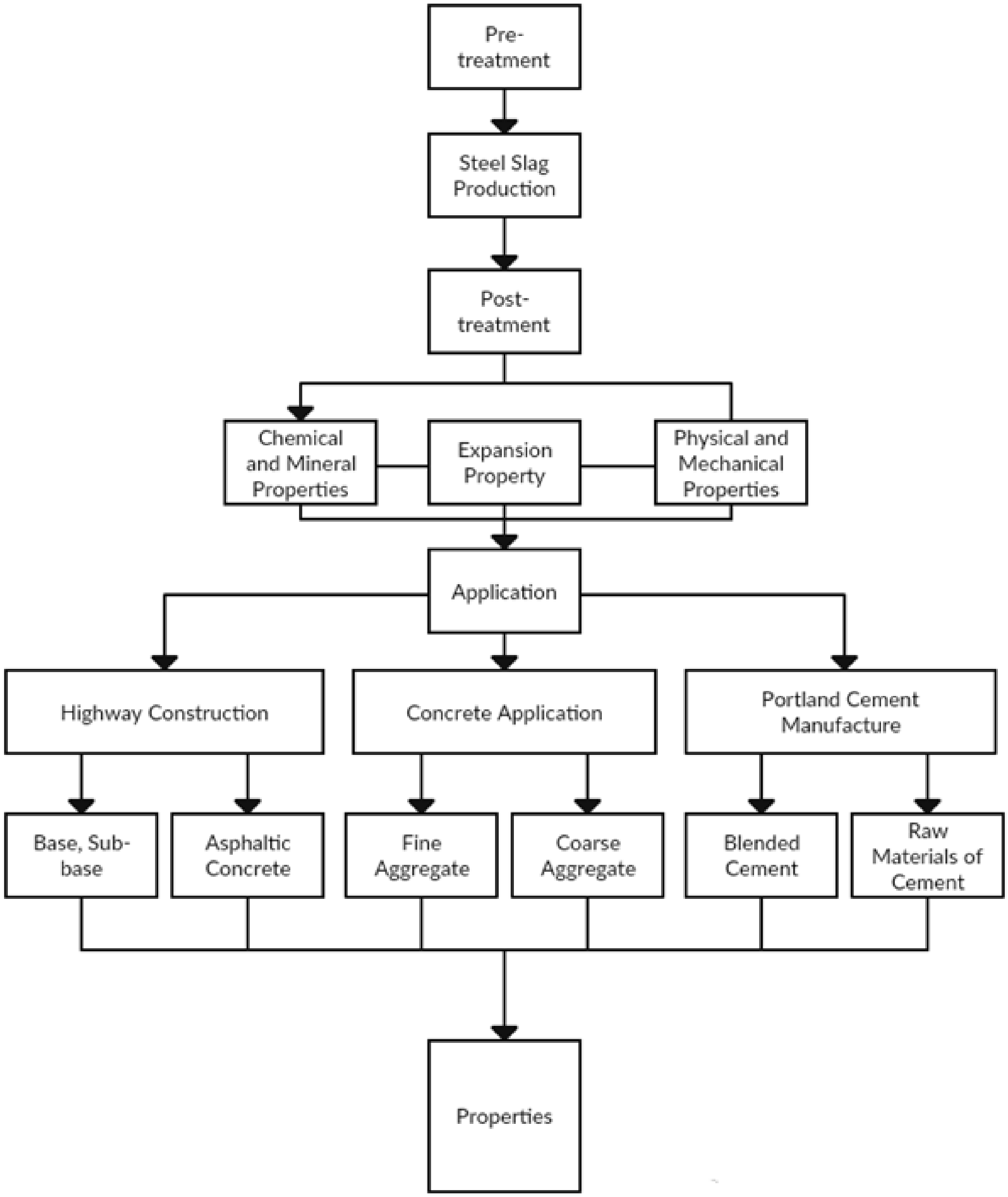


Figure 2.11: Steel slag utilization

There are eight links or areas in this whole process. Any individual link in the process might affect the final use of the slag in engineering practice. These links or areas include: the pre-, and post-treatment of slag; chemical, physical and expansion properties and their affecting factors; the evaluation and measurement of the expansion. The comprehensive utilization can be related to three main stages: treating and processing, intrinsic properties of steel slag and properties of end products. The utilization of slag for different purposes are shown in Figure 2.9. the major use is in road engineering, in concreting and in cement manufacture. Other utilizations include use in agriculture as fertilizer or soil addition. Any use is different from any other use and is specified by its own specific properties.

The comprehensive utilization of steel slag is a topic which requires a knowledge of materials and a sound understanding of the properties of both steel slag and the target usage is essential. That means, on the one hand, the intrinsic properties of steel slag must be investigated before finding out its potential use, while on the other hand, the requirement of the target use should be well understood. Without the study of both aspects, “utilization” will be blind, inactive or low grade. Usually, in the utilization, steel slag comprises a composite with other materials or matrix and therefore, it is necessary to understand the matrix properties. The principle is also suitable for other waste materials utilizations.

2.2.4 Production and Current Management of Slag in Bangladesh

In Bangladesh bulk of steel is made by re-melting steel scrap. Most of the steel plants melt scrap in induction furnaces. Only one plant now melts scrap in EAF and raw-materials like pig iron and lime are also used in limited quantities. In the Induction furnaces, very small quantity of slag (about 6-8 percent) is generated. A higher quantity of slag is generated in electric arc furnace steel making.

The main by-products resulting in steelmaking are slags (90% of the total by-products), dusts and sludges. Around 140 mills use their induction furnaces for scrap melting purpose which give us steel slag [BRMA, 2014]. About 200 kg of by-products per ton of steel result from the steel production through electric arc furnace, while about 400 kg of by-products per ton of steel production through BF/BOF (World Steel Association).

Table 2.1 Typical Composition of Bangladesh Slag (Weight Percent)

	FeO	**SiO_2**	**MnO**	**Al_2O_3**	**CaO**
Induction Melting	5 – 12	55	23	4	-
EAF Melting	27	25	2.3	4	35
Ladle Furnace	0.72	26.50	1.0	13.85	55.23

Figure 2.12: Disposal of steel slag

In Bangladesh, most of the steel making plants dump these solid wastes only for landfill purpose (Figure 2.10). Due to land scarcity, land-fill will not be available for slag disposal in the near future. Only in recent years there has been some concern in the steel sector regarding the management of the ever-increasing amount of slag. Less scientific utilization of such slag in concrete structures is being attempted.

2.2.5 Properties of Steel Slag

The United States Department of Transportation and the Federal Highway administration along with the Turner Fairbank Highway Research Center (TFHRC) have listed some of the properties of steel slag:

2.2.5.1 Physical Properties

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 gives a greater surface area than smoother aggregates of equal volume; this feature provides an excellent bond with Portland cement (NSA accessed Nov 2008).

Steel slag has a high degree of internal friction and high shear strength. The rough texture and shape ensure little breakdown in handling and construction (NSA accessed Nov 2008). Steel slag has high bulk specific gravity and less than 3% water absorption. Steel slag aggregates have high density. Apart from this feature most of the physical properties of steel slag are better than hard traditional rock aggregates. Below are listed some of the positive features of steel slag. (GeoPave, 1993):

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.

Table 2.2: Typical physical properties of steel slag

Properties	**Values**
Specific Gravity	> 3.2 - 3.6
Approximate Dry rodded Unit Weight, kg/m^3 (lb/ft^3)	1600 – 1920, (100-120)
Water Absorption	up to 3%

2.2.5.2 Chemical Properties

The major oxides usually contained in slag are iron oxide, lime, magnesia, silica and alumina. Minor elements include sulfur, iron, manganese, alkalis and trace amount of several others. The chemical composition of slag is generally expressed in terms of simple oxides calculated from elementary analysis determined from x-ray fluorescence. Table 2.3 shows the list of various ranges of compounds presents in steel slag:

Table 2.3: Typical Compositions of Steelmaking Slag (Weight Percent)

Constituents ⇩	Furnace type ⇨	IF*	EAF	BOF
CaO		2-4	30-35	35
SiO_2		35-45	10-12	14
Fe_2O_3		20-40	22-29	29
MgO		0.5-1.6	5-8	7.7
Mn_2O_3		10-25	4-7	5.7
Al_2O_3		4-12	4.5 - 5.5	5.5

*the slag samples were collected from local steel plants

The predominant compounds in steel slag are di-calcium silicate, tri-calcium silicate, di-calcium ferrite, merwinite, calcium aluminate, calcium-magnesium iron oxides, some free lime and magnesia. Steel slag is mildly alkaline, with a solution pH generally in range of 8 to 10. However, the pH of leachate from steel slag can exceed 11, a level that can be corrosive to aluminum or galvanized steel pipes placed in direct contact with the slag.

According to Department of Transportation (DOT) and Federal Highway Administration (FHA), the amount of free calcium and magnesium oxides is not completely consumed in steel slag. The hydration of unslaked lime and magnesia in contact with moisture is largely responsible for the expansive nature of most steel slag. The free lime hydrates very rapidly and can cause large changes in volume over a relatively short period of time, i.e. weeks, while magnesia hydrates much more slowly and contributes to long term expansion which may continue for many years.

2.2.5.3 Mechanical Properties

Table 2.4: Typical mechanical properties of steel slag. (TFHRC accessed 2008)

Property	**Value**
Los Angeles Abrasion (ASTM C131), %	20-25
Sodium Sulfate Soundness Loss (ASTM C88), %	12
Angle of Internal Friction	40° - 50°
Hardness (measured by Moh's scale of mineral hardness) *	6-7
California Bearing Ratio (CBR), % top size 19 mm (3/4 inch) **	Upto 300

* Hardness of dolomite measured on same scale is 3 to 4.

** Typical CBR value for crushed limestone is 100%.

According to TFHRC (www.tfhrc.gov) the processed steel slag has favorable mechanical properties for use as aggregates in construction; these include good abrasion resistance, good soundness characteristics, and high bearing strength.

2.2.5.4 Effect on the Environment and Health

A Steel Slag Coalition (SSC) was formed in 1995 to provide a comprehensive study of steel slag. This coalition consisted of iron and steel manufacturers, slag processors, chemical laboratories and risk assessment teams, environmental scientists and toxicologists to conduct an industry-wide Human Health and Ecological Risk Assessment (HERA) on iron and steel slag. (NSA accessed Nov 2008).

The result of this study confirmed that the iron and steel slag have no threats to human health or the environment when used in residential, agricultural, industrial and construction applications. Slag has also been effectively used to treat acid mine drainage discharge and is also useful in the removal of excess phosphorous from waste water discharges, thus rendering the waste water more ecologically beneficial (Wagaman and Stanley, 2005).

2.3 Use of Steel Slag

2.3.1 Steel Slag in Concrete

Concrete

Concrete is a composite material which is composed of coarse granular materials called aggregates or filler embedded together in the form of a matrix with the help of the cement or binding material that fills the space between the aggregates particles and glues them together. Aggregates are usually obtained from natural rocks, either crushed stones or natural gravels. Other material like fly ash or ground granulated blast furnace slag may also be used as binding material.

Aggregates are divided into two parts: fine aggregates and coarse aggregates. Fine aggregates are considered to be the material passing through 4.75mm (No 4) sieve (0.187 in. square opening) and are predominately retained on a No. 200 sieve. Natural coarse aggregates are generally crushed stones or gravels which are retained on the No.4 sieve. Finally, water is added to initiate the binding process. This makes the mix stiffer and forms the material called concrete, which can be used in construction and forms a basis of our modern society.

Aggregates

Aggregates provide dimensional stability and wear resistance to concretes. Not only they provide strength and durability to concrete, they also influence the mechanical and physical properties of concrete. Aggregates act as a filler material and lower the cost 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 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 because they can influence the workability of fresh concrete and its hardened strength. The porosity of aggregates and their absorption capacity affects the resistance of concrete to freezing and thawing.

Steel slag to replace natural aggregate in concrete

Using steel slag to replace natural aggregate in concrete is initially based on the consideration of the availability of natural resources and good characteristics of steel slag. In Japan, the portion of natural mineral aggregate content used in concrete diminishes each year and is being replaced by artificial aggregate and industrial by-product aggregate. In recent years, shortages of high quality natural aggregates have been experienced in several areas of the United States. On the other hand, steel slag possesses good physical properties which can be utilized to provide strength when used as an aggregate in concrete.

The application of steel as an aggregate in cement concrete has previously been considered a forbidden zone. However, in more recent years, extensive research into this use have been carried out. In japan, several patents have been taken out regarding the use of steel slag to replace crushed stone or sand as coarse and fine aggregate in cement concrete. The concern of people over using steel slag in cement concrete as coarse or fine aggregate results from the expansion of steel slag. However, some recent experimental results prompt a reconsideration of this question.

Two types of steel slag, being slag immediately after supply from the iron works and that naturally weathered, were used for making concrete. Dimensional changes in the concrete made with slags weathered for three months and with the natural aggregate showed expansion from 36-70 microstrain after 17 weeks of immersion in water, but symptoms such as pop-outs and cracks were not found on the surface of the concrete specimens. Also, no symptoms were found indicating unsoundness of the slag in the concrete up to the age of six months.

George and Sorrentino used BOS slag produced from a process in which aluminium slagging flux (CAMFlux) was added (called Alag). The content of free lime in this slag was about 2%. The results showed that, for both flexural strength and compressive strength, the steel slag coarse aggregate concrete samples at ages from 2 days to 90 days. Instant Chilled Steel (ICS) slag was used as a coarse aggregate in cement concrete in laboratory trials to investigate compressive strength and mechanical properties. The concrete made with ICS slag was treated under 173^0C (8 atm) treating and strength properties were higher than those of crushed limestone coarse aggregate concrete.

Concrete in which ordinary fine aggregate was replaced by fine steel slag (0-5mm) was made for the determination of mechanical properties. The slag used was exposed to air for three months. Results showed that the characteristic roughness and polygonal porous surface structure of the slag sand give the concrete or mortar a satisfactory weatherability, frost resistance and heat-stability. Other physical and mechanical properties were also satisfactory.

2.3.2 Problems associated with Steel Slag aggregates

Steel slag aggregates have two main features which are of concern to their use in construction, namely, volume expansion and high particle density. During the making of steel there is a small percentage of calcium and magnesium oxides which is left undissolved in the slag. These non-hydrated calcium and magnesium oxides later come in contact with moisture which leads to hydration process. The volume expansion is primarily caused by the reaction between the free lime in slag and water during the hydration process to produce calcium hydroxide. As a result, there is a great increase in volume due to the difference of specific density of the hydration product. These changes in volume can occur either in a few weeks after production of slag or may occur many years later if the slag is initially protected from contact with water. A general method usually used to overcome the expansion problem is to store the slag for aging in stockpiles for some four to six months before using it.

Density of steel slag is also an important issue to be considered. Steel slag is a heavier material than natural rock types such as basalt, granite, or limestone. Thus, any given volume would require about 15 to 25% greater tonnage of steel slag than traditional natural aggregates which may create an economic disadvantage for steel slag in some applications where transportation costs are significant.

Chapter 3
Resources for Project Implementation

3.1 Human Resources

A well-defined team composition was developed considering (i) the time frame, and (ii) the estimated work load. The team had 4 (four) regular members and requisite number of work charged workers (these persons workedon a daily basis, as and when required). The designated team members were:

Principal Investigator 1: (A Metallurgical/Materials Engineering Expert)
Principal Investigator 2: (A Metallurgical/materials Engineering Expert)
Two metallurgical/materials engineering graduates

Principal Investor 1 acted as the team leader and the contact person.

Organization of the team is shown in the organogram in Figure 3.1:

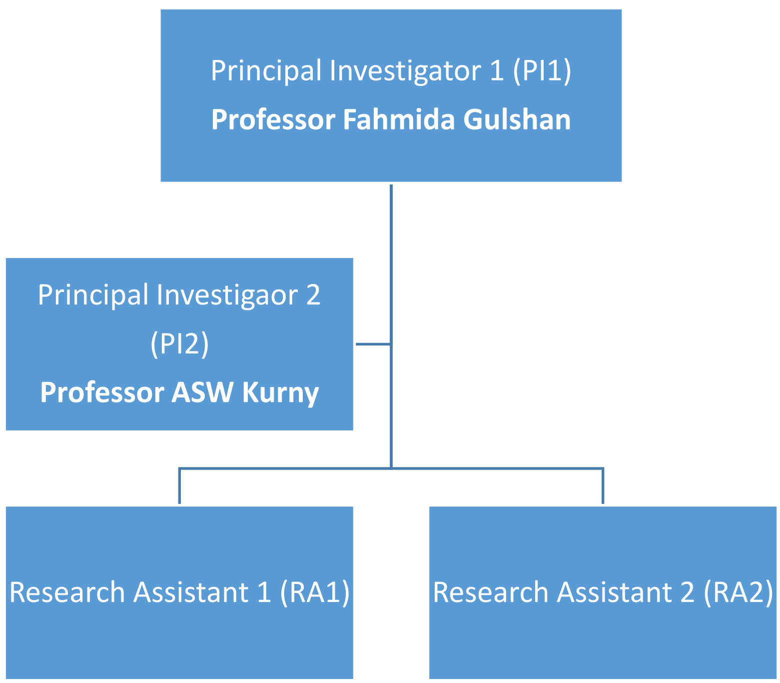


Figure 3.1: Proposed organization of the study plan

3.2 Project Management

The following major activities was included in the project management plan:

(i) Activity management
(ii) Team management
(iii) Monitoring and execution of field activities
(iv) Delivery of the products

Principal investigator 1 was the key person. S/he was responsible for the overall management and execution of the project. The project was implemented with team working approaches and each of the team members cooperated with the Principal Investigator 1 for performing their well-defined responsibility.

A brief description of the individual members is given below:

Principal Investigator 1:

She is an expert in Metallurgical engineering and has successfully supervised a number of research projects financed by BUET and the Ministry of Science and Technology, Government of the People's Republic of Bangladesh. She was intensely involved in designating the mills from where the samples were collected, the characterization of the samples collected, design of experiments based on findings of the literature search, analysis of the experimental results and in the formulation of the recommendations. She was responsible for the preparation and the submission of the Final report.

Principal Investigator 2:

He is an expert in Metallurgical engineering and has successfully supervised several research projects financed by BUET, UGC, Third World Academy of Sciences (TWAS, Italy) and the Ministry of Science and Technology, Government of the People's Republic of Bangladesh. He was involved in sample collection and characterization, design of experiment, analysis of the results and in the formulation of the recommendations. Heassisted PI 1 in the preparation of the Final report.

Research Assistants:

Two Research assistants, both graduates in Materials and Metallurgical Engineering, worked as Research Assistants. They collected the samples from the designated steel mills, prepared samples for characterization, record the results and process them to presentable formats, supervise the preparation and testing of the experimental blocks. They also carried out other tasks assigned by the principal investigator(s).

Table 3.1: Team Composition and Task Assignment

Name of Staff	Firm/ Organization	Area of Expertise	Position Assigned	Task Assigned
ProfessorFahmidaGulshan	BUET	Materials and Metallurgical Engineering with specialization in environment friendly materials, industrial waste recycling	Principal Investigator 1 (PI1)	- Lead and assist the team in all respects - Coordination with DoE - Project management - Data analysis - Prepare reports
Professor Abu Syed WaisKurny	Retired from BUET	Materials and Metallurgical Engineering with specialization in environment friendly materials, industrial waste recycling	Principal Investigator 2 (PI 2)	- Assist the Team Leader in project management and coordination with DoE - Design experiments - Analyze data - Prepare reports
RaihanAtahar	BUET	Materials and Metallurgical Engineering	Research Assistant 1 (RA 1)	- Slag collection, characterization [XRD, XRF etc] and sample preparation - laboratory testing [compressive strength etc] - Assist in report preparation - Other necessary tasks as required
Riad Morshed Rezaul	BUET	Materials and Metallurgical Engineering	Research Assistant 2 (RA 2)	- Slag collection, characterization [XRD, XRF etc] and sample preparation - laboratory testing [compressive strength etc] - Assist in report preparation - Other necessary tasks as required

Chapter 4
Project Implementation

The project was proposed for 5 months of which 4 months was the core time for carrying major activities. The major activity of the project was to review the literature; identification and collection of information and policy documents from secondary sources and review them; collection of primary data from field through community consultation; assessment of existing slag disposal procedure; testing of properties of slag; development of sample collection protocol; prepare the technical report and share the study findings through national validation workshop.

The work schedule and staff month inputs are described in the following tables:

Table 4.1: Work Schedule

No.	**Activity**	**Months**									
		1		**2**		**3**		**4**		**5**	
1	Steel slag collection from 6 – 8 steelmaking industries. Literature search and Experiment design	■	■								
2	Characterization of the samples: Chemical analysis, x-ray diffraction analysis and x-ray fluorescence analysis.		■	■							
3	Experimental investigation and data collection				■	■	■	■			
4	Preparation and submission of Midterm Report							■			
5	Analysis of Data and preparation of report							■	■	■	
6	Preparation and submission of Draft Final Report										■

Table 4.2: Staff Month Inputs

No.	**Position** **Name of Staff**	**Staff-month input by month**					**Total staff-month input**		
		1	**2**	**3**	**4**	**5**	**Field**	**Home**	**Total**
1	Principal Investigator 1 **ProfessorFahmidaGulshan**	●	●	●	●	●	0	3.5	3.5
2	Principal Investigator 2 **Professor ASW Kurny**	●	●	●	●	●	0	3.5	3.5
3	Research Assistant 1 **RaihanAtahar**	■	■	■	■	■	0	5	5
4	Research Assistant 2 **Riad Morshed Rezaul**	■	■	■	■	■	0	5	5
Total							**0**	**17**	**17**

● Intermittent input

■ Continuous input

Chapter 5
Materials, Methods andExperimental Design

5.1 Scope of Research on Slag

The production of slag is inevitable in the process of production of both iron and steel. Earlier this slag was considered as a solid waste generated in the process of iron and steelmaking and thus a potential environmental problem. The major use was in land filling. In recent years, research on slags generated during the production of iron and steels through the BF-BOS route or the DRI-EAF route, has shown that this material can have useful environment friendly applications. They are now used in cement manufacture, road surfacing materials and in concrete blocks.

In Bangladesh, steel is produced by melting what is already steel and thus require minor refinement in chemistry of the charge materials. A lesser quantity of slag than those produced in conventional steelmaking processes are produced. There is no comprehensive industry statistics on the quantity of slag produced versus slag utilized in Bangladesh. The composition of the slag produced in Bangladesh is also likely to be different from those generated in conventional integrated steel plants that operate globally. Slags produced in induction furnaces and in electric arc furnaces are also likely to be different. Moreover, induction furnaces are not globally used for structural steelmaking and therefore, not much literature is available on the use of slags generated during steelmaking in the Induction furnaces.

There is thus enough scope to undertake research on the nature and possible applications of slag produced in the steel plants in Bangladesh.

5.2 Selection of Plants for Collection of Samples of Slag

Steelmaking Industries in Bangladesh are concentrated in Dhaka (Narayanganj, Demra, Kadamtali, Shyampur, etc) and Chittagong (Nasirabad Industrial Area and Mir Sarai, etc). Induction steel slag was collected from the following 4 industries in Dhaka and 3 industries in Chittagong. It was expected that samples of steel slag collected from these plants will represent the overall nature of slag produced in the plants that use **induction furnaces**for the production of steel in Bangladesh.

Induction Furnace Slag

Dhaka

Bandar Steel Industries Limited (BSI)
Anwar Ispat Limited
Technosum
Salam Steel Contrast Re-Rolling Mills Limited (SCRM)

Chittagong

Kabir Steel Re-rolling Mills Ltd (KSRM)
Ratanpur Steel Rerolling Mills Limited (RSRM)
GPH Ispat Limited

Electric Arc Furnace Slag

In Bangladesh, only AbulKhair Steel uses Electric Arc Furnace to produce steel for reinforcing bars. The composition and nature of Electric Arc Furnace (EAF) slag is different. Representative ~~of~~ samples of EAF slag was collected from AbulKhair Steel Industries (4th Industry from Chittagong).

5.3 Preparation of the Samples of Slags

The steel slags were obtained in the form of boulders. Samples of slag from a particular industry were crushed. The crushed samples were sieved to obtain required size fractions for further study. The steel slag used in this research was provided by seven steel industries.

Technosum

Slag: Before Chemical Addition

Slag: After Chemical Addition

Tundish Slag

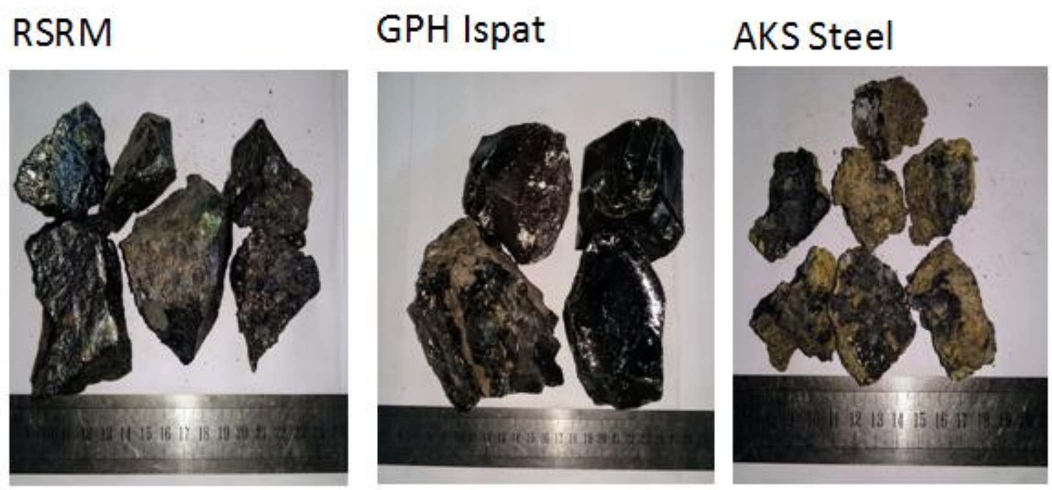
Ladle Slag

Bandar Steel Industries

Slag prodı **dle Slag**

Anwar Ispat

Salam Steel



Different Size Fractions of Slag

The samples of induction furnace slag collected from seven different industries in Dhaka and Chittagong showed similar chemical composition. These samples were mixed together and subsequently used for further studies. A general view of crushed slag samples is shown in Figure 5.1.

Figure 5.1: Coarse slag sample in saturated surface dry (SSD) condition

Figure 5.2: (a) Fine aggregate (sand) sample in saturated surface dry (SSD) condition (b) Coarse aggregate (stone chips) sample in saturated surface dry (SSD) condition

5.4 Other Materials Used in the Study

5.4.1 Ordinary Portland Cement (OPC)

The cement used in this project was collected from Fresh Cement. This is Type IPortland cement as classified by ASTM C150. The cement properties and its chemical composition is shown in Table 5.1.

Table 5.1: Cement Composition

Chemical	Percentage (%)

SiO_2	24.09
Fe_2O_3	3.56
Al_2O_3	6.68
CaO	56.70
MgO	1.56
SO_3	4.91
K_2O	0.97
Na_2O	0.15
TiO_2	0.99
P2O5	0.13
MnO	0.11

5.4.2 Fine Aggregates

The fine aggregate used for the research was Sylhet natural sand (Figure 5,2(a). This Aggregate has absorption of 1.61%. The Bulk Specific Gravity of the fine aggregate was 2.54 while its SSD Specific Gravity was 2.58.

5.4.3 Coarse Aggregates

The coarse aggregates used in this research were obtained from Bolagonj (Figure 5.2(b). The absorption of these coarse aggregates was 0.83%. The Bulk Specific Gravity was 2.60 with an SSD Specific Gravity of 2.62.

5.5 Experimental Design

5.5.1 Chemical and Mineralogical Characterization of Slags

The steel slag was obtained in form of boulders. Samples of slag from a particular industry was crushed with a jaw crusher followed by milling to obtain powdered samples. The powdered samples were sieved to obtain required size fractions for further study. Sampling of powdered slag was carried out by 'coning and quartering' technique of sampling.

a) The chemical compositions of the slags were determined using X-ray fluorescence spectroscopy.
b) Mineralogical composition was studied at room temperature (25^{o}C) using X-ray diffractometer.
c)The pH of the slag samples was determined using a pH meter.
d)Granulometric analysis (mesh grid) was performed to determine size distribution in the slag samples investigated.

5.5.2 Reclamation of waste steel

Steel slag contains approximately 10% waste steel, which can be reclaimed through crushing, sorting, magnetic separation and screening process. Research on recycling waste steel contained in steel slag has been carried out in developed countries. For example, USA reclaimed approximately 3.5 Million tons steel scrap from 1970 to 1972 and Nippon Magnetic Dressing Co., Ltd in Japan has annual slag treatment capacity of 2 Million tons, reclaiming 0.18 Million tons iron particles with more than 95% Fe content yearly.

In China, Anshan Iron and Steel Company recycles 0.28 Million tons of grained steel with 60%-65% Fe content and 0.4 Million tons of iron concentrate with approximately 50% Fe content yearly from steel slag through the combination of sorting, magnetic separation and gravity concentration processes. Attempts were made to reclaim waste steel from slag through the combination of sorting, magnetic separation and gravity concentration processes. Quantitative estimation of waste steel in slag produced through the two different routes of steel production now in use in Bangladesh was performed.

5.5.3 Classification of Slag

a) The nature and variation in composition of slag from different plants (particularly between those produced in Induction Furnace and in Electric Arc Furnace) was identified and related to the practice of making steel in a plant (nature of raw materials, additives used etc.).
b) The slag produced in different steel plants in Bangladesh was classified, on the basis of composition and phases present, in two types.

5.5.4 The Physical and Mechanical Properties of Slag

5.5.4.1 Unit Weight Calculation

Unit weight values of aggregates are necessary for selecting proportion of ingredients in the concrete mixtures. They may also be used for determining mass/volume relationships for conversions and calculating the percentages of voids in aggregates. The unit weight is measured in accordance to ASTM specification C29-97 R03. The Rodding procedure was used for the determination of unit weight.

5.5.4.2 Determination of Specific Gravity and Absorption of Fine and Coarse aggregate

The measured water absorption rate and specific gravity of aggregate is routinely used in design and construction of pavement materials and structures worldwide. Most of the aggregates are porous in which some pores are permeable and some impermeable. The presence of these pores is very important for defining specific gravity of aggregates. The absorption capacity in aggregate is important in determining the net water-cement ratio in the concrete mix.

The specific gravity and absorption of coarse and fine aggregate were determined according to the specification ASTM C128-01.

5.5.4.2 Leachability Test

Toxic Characteristic Leaching Procedure (TCLP) is a test method used to determine whether a waste is a toxic hazardous waste or not. TCLP comprises four fundamental procedures:

- Sample preparation for leaching
- Sample leaching
- Preparation of leachate for analysis
- Leachate analysis

Particle size below 10 mm were brought into contact with 10 times the weight of water under continuous stirring for 24 hours. The corresponding elements were passed through 45 micrometer membrane filters for subsequent analysis. The leachates were analyzed by Flame Atomic Absorption Spectroscopy (FAAS). Special attention will be focused on the possible health hazards of using of such slag.

5.6 Tests for Incorporation of slag in Construction Materials

Attempts were made to prepare and investigate the properties of two types of construction material, concrete blocks and structural bricks.

5.6.1 Concrete blocks

The work on concrete blocks aimed at replacing a certain percentage of the volume of natural aggregates, normally used in the manufacture of concrete, with steel slag in increments of 25% until all the natural aggregates were replaced by the steel slag.

All concrete mixing was performed in the Concrete Research Laboratory in Bangladesh University of Engineering and Technology. Before mixing commenced, the gradation of steel slag samples was determined and compared with the natural aggregates. The experimental program consisted of first testing the fresh concrete properties, then forming specimens for the following tests: ASTM C 143: slump value, ASTM C 39: compressive Strength, ASTM C 496: splitting tensile strength, ASTM C 469: modulus of elasticity, ASTM C 1202: chloride penetration, DIN 1048: water permeability, ASTM C 157: drying shrinkage of Concrete Specimens.

Table 5.2 shows the testing program for the research. ASTM specifications for different test methods to be employed and number of samples to be prepared are also shown.

Table 5.2: List of tests, corresponding standards and sample size

SI No.	Property of concrete	ASTM standard	Sample description	No. of sample
Fresh concrete				
1	Slump value	C 143	Fresh concrete	
Hardened concrete (mechanical properties)				
2	Compressive strength	C 39	4”X8” cylinder	9
3	Splitting tensile strength	C 496	4”X8” cylinder	9
4	Modulus of elasticity	C 469	4”X8” cylinder	3
5	Absorption, unit weight and void ratio		4”X4” cube	3
Hardened concrete (durability properties)				
6	Chloride penetration	C 1202	4”X8” cylinder	6
7	Water permeability	DIN 1048	6”X6” cube	3
8	Drying shrinkage	C 157	4”X4”X12” samples	3

5.6.2 Concrete Mix Design

The slag aggregates were tested for fineness modulus, specific gravity, absorption capacity and unit weight. Coarse aggregates of EAF and IF slag and fine aggregate of IF slag were used. Concrete specimens were made with a constant Water/Cement (W/C) ratio of 0.45. A volumetric ratio of Cement: Sand: Aggregate = 1:1.5:3 was used. The natural aggregate was replaced by coarse slag by 0%, 25% 50%, 75% and 100%. After mixing, the Workability of the concrete was measured by Slump test. The concrete specimens were cured under water and tested at 7 days and 14 days for compressive strength and splitting tensile strength. The results were analyzed to determine practical applications.

Figure 5.3: Concrete cylindrical specimen after casting

5.6.3 Gradations

The steel slag aggregate for this investigation was provided by seven renowned steel industries. The initial visual examination of the steel slag samples suggested that they consisted of a mixture of both fine and coarse aggregates. Sieve analysis was done according to ASTM C 136. The results of the percentage passing each screen for the steel slag were compared to the curves of the natural aggregates it was to replace.

Figure 5.4: (a) and (b) show sieve analyses conducted to determine gradation.

5.6.4 Properties of Concrete

The properties of concrete are classified into two categories: fresh and hardened. The durability of concrete depends upon the mix design and durability of aggregates. The water-cement ratio and addition of admixtures greatly affect the durability of concrete. The properties which affect the strength and durability of a concrete structure change over the life of structure, increasing with time.

5.6.4.1 Fresh Concrete Properties

Fresh concrete properties include slump, unit weight. The slump of the concrete was tested following ASTM C143: Slump of Cement Concrete. The slump test is empirical in nature, and it does not directly measure the workability of concrete mixture. Instead, it is used to ensure the uniformity between the different concrete batches for a given job. The unit weight test is a more reliable test and provides more valuable information than the slump test. The unit weight test also gives information related to air content, water content and changes in the aggregate proportion in the mixture.

The unit weight of the mixture was tested according to ASTM C29-97 R03. The specific gravity and absorption of coarse and fine aggregate were determined according to the specification ASTM C128-01 (for fine aggregate) and ASTM C127-01 (for coarse aggregate).

Figure 5.5: Slump test being conducted on the concrete sample.

5.6.4.2 Hardened Concrete Properties

To determine the hardened properties of concrete, the Compression test (ASTM C 39) and Splitting tensile test (ASTM C 496) were conducted. Concrete is much stronger in compression than in tension and so the compressive strength of concrete is an important property of the concrete. It is very difficult to directly measure the tensile strength of concrete; therefore, the splitting tensile test, an indirect method, was adopted.

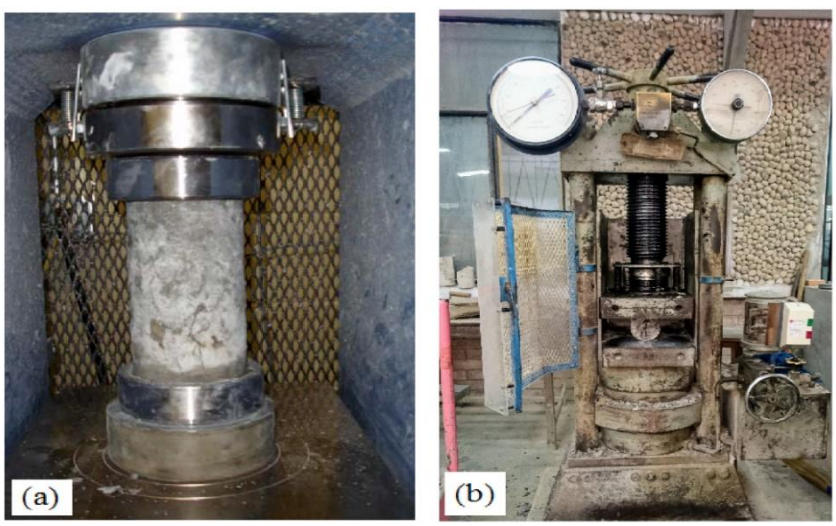


Figure 5.6: (a) Compression test conducted on a concrete specimen with steel slag aggregates (b) Splitting tensile Test conducted on concrete specimen.

5.6.4.3 Compressive Strength of Concrete

The concrete specimens were tested for compressive strength at 7, 14 and 28 days. Specimens were made following ASTM C192 and stored in the water curing tank following ASTM C511. The cylindrical specimens prepared for the research were made with a diameter of four inches (102 mm) and a height of eight inches (203 mm).

Figure 5.7: Concrete specimen after compressive strength test.

Three specimens were tested at each age, following ASTM C39, on a hydraulic loading machine. The compressive strength was determined by dividing the ultimate applied load by the cross-sectional area of the cylinder. The type of fracture of the specimen and the compressive strength was also recorded and compared with ASTM C39.

5.6.4.4 Splitting Tensile Strength of Concrete

The splitting tensile strength of the concrete specimens was tested at 7, 14 and 28 days. The four inches (102 mm) and eight inch (203 mm) cylindrical specimens were molded at the same time as compressive strength specimens. The specimens were tested on a hydraulic loading machine following ASTM C 496. The splitting tensile strength was obtained from the following equations:

$$\mathbf{T} = \frac{\mathbf{2P}}{\mathbf{\Pi L D}}$$

Where:

T = splitting tensile strength (psi)(MPa)

P = maximum applied load (lbf) (N)

l = length (in) (mm)

d = diameter (in) (mm)

For this research, the length (l) was equal to eight inches (203mm) and the diameter (d) of was taken as four inches (102 mm).

Figure 5.8: Concrete specimen after splitting tensile strength test.

5.6.5 Structural Bricks

5.6.5.1 Materials and Methods

Both Induction furnace steel slag and Electric arc furnace steel slag, sand and hydrated lime mixtures with gypsum as a binder were used to make bricks. Process variables like the composition of the mix and curing conditions were maintained constant. Only variable parameter was the forming pressure. Finally, the compressive strength of the bricks produced under these conditions were determined. The ingredients like hydrated lime and gypsum were collected from the local market.

Brick specimens were produced under the conditions given in Table 5.2. In total eighteen bricks were made for the testing purpose. Before making a brick, each ingredient of the raw materials was dried in a muffle furnace at 110℃ for 24 hours. Required amount of each ingredient was weighed, 14% moisture was added and the components were mixed thoroughly.

Table 5.3 Test parameters

Slag Type	**Bricks code**	**Sand wt%**	**Slag (IF) wt%**	**Lime wt%**	**Gypsum wt%**	**Forming Pressure(psi)**	**Curing process**	**Other Parameters**
IF	01	20	70	10	2	1000	Under water	14% moisture added Pressure applied for 15 sec
	02	20	70	10	2	1000		
	03	20	70	10	2	1000		
	01	20	70	10	2	2000		
	02	20	70	10	2	2000		
	03	20	70	10	2	2000		
	01	20	70	10	2	3000		
	02	20	70	10	2	3000		
	03	20	70	10	2	3000		
EAF	01	20	70	10	2	1000	Under water	14% moisture added Pressure applied for 15 sec
	02	20	70	10	2	1000		
	03	20	70	10	2	1000		
	01	20	70	10	2	2000		
	02	20	70	10	2	2000		
	03	20	70	10	2	2000		
	01	20	70	10	2	3000		
	02	20	70	10	2	3000		
	03	20	70	10	2	3000		

To ensure uniform size of the bricks a known weight of mixture was used each time to fill the mould cavity. Dimension of the mould cavity (Figure 5.9) was 6 X 3.5 cm. A hydraulic press (Fig 5.10) was used to apply pressure for a period of 15 Seconds. The bricks (Figure 5.11) were then ejected and finally cured. Curing was done by immersing the bricks in water (Figure 5.12).

Figure 5.9: (a) Brick samples in mould (b) Mould ready for pressing

Figure 5.10: Hydraulic Press

Figure 5.11 (a): Brick samples in the hydraulic press.

Figure 5.11 (b): Green Slag-Sand-Lime-Gypsum bricks.

Figure 5.12: Water curing of brick samples.

5.6.5.2 Test Methods

Compressive strength

Compressive strength was determined by applying load on the specimen using a Universal Testing Machine. Load was applied on an area measuring 6mm X 3.5 mm [The size of one face of the entire brick].

Chapter6
Results and Discussion

6.1 Overview

The chapter discusses the results obtained from various tests mentioned in the previous chapter. The results presented in this chapter are the average results when more than one sample of mixtures was tested.

6.2 X-Ray Fluorescence(XRF) Results

The samples of steel slag collected from different industries were analyzed by x-ray fluorescence analysis using XRF-1800 SHIMADZU, Japan. Table 6.2 shows the chemical compositions of the different steel slag samples.

The major components in the induction furnace slag samples collected from 7 different steel mills in Bangladesh were: Fe_3O_4 are SiO_2. Significant amounts of Al_2O_3,MnOand CaOwere also present. The composition of the samples of the induction furnace slag collected from seven different steel plants appeared similar. The minor difference in the actual content of oxides in the samples from different steel mills may be related to the difference in the quality and composition of the raw materials used and the practice of alloy addition during the process of making steel.

The samples of induction furnace slag were all mixed together and used as induction furnace slag for all subsequent studies. The typical composition of the mixed slag is given in Table 6.1.

Table 6.1: Comparison of the compositions of slag generated through the two different routes

	Fe_3O_4	SiO_2	MnO	Al_2O_3	CaO
IF Slag	37.31	35.20	10.02	3.70	3.71
EAF Slag	26.51	19.88	5.10	6.31	35.48

In contrast, the arc furnace slag contained a larger amount of CaO. A comparison of the major components of mixed induction furnace slag and arc furnace slag can be seen in Table 6.2. This variation in the CaO content of the two types of slag is due to the practice of making steel through these two different routes. In arc furnace steel making lime (CaO) is added as a slag formerand thus EAF slag contains a significant amount of CaO. The induction furnaces used for making steel in Bangladesh is generally silica lined. Silica is an acidic oxide and therefore care is taken so that during the process of making steel in induction furnaces the lining does not come in contact with any basic oxide. CaO is a strong base and is particularly harmful for the lining of induction furnaces. The addition of any lime in induction furnace steelmaking is effected later in ladle refining (LRF) furnaces. The lining of electric furnaces is different in chemical nature permitting additions of basic oxides during steel making process. This difference in furnace lining of electric arc furnaces offers some technical advantages to making of steel in electric arc furnaces.

Table 6.2: Results of XRF Analysis of Slag of Different Steel Mills

Company	**Major Components (%)**					**Minor Components (%)**						
	Fe_2O_3	SiO_2	Al_2O_3	MnO	CaO	TiO_2	MgO	Na_2O	K_2O	SO_3	ZnO	BaO
BSI-1	15.38	60.91	4.66	11.56	2.73	1.48	0.70	-	0.73	0.13	0.58	0.22
BSI-2	23.29	40.01	7.85	9.73	12.80	1.61	1.61	0.81	0.95	-	0.96	0.28
Technosum	7.95	45.37	4.00	35.11	3.25	1.85	0.72	0.55	0.75	-	0.11	0.33
Salam	34.97	36.42	6.74	11.49	3.66	1.54	0.50	1.01	0.72	-	2.57	0.37
Anwar Ispat	39.66	35.3944	12.10	6.42	2.82	1.77	0.81	-	0.29	0.19	0.22	0.13
RSRM	40.42	32.41	4.08	15.09	2.71	1.80	1.34	0.72	0.49	-	0.72	0.22
GPH	18.15	37.02	13.51	23.32	4.04	1.52	1.30	0.40	0.49	-	0.05	0.211
AKS	26.51	19.88	6.31	5.10	35.48	1.09	4.44	0.22	0.10	-	0.04	0.21

6.3 X-Ray Diffractometric Analysis of Slag Samples

The x-ray diffraction patterns of the different types of slag by using EMPYREAN PANalytical, Netherlands are shown in Figure 6.1. It is evident that spinelloid phase (Fe_3O_4-Fe_2SiO_4) is predominant in the x-ray diffraction pattern of induction furnace slag. This is in good agreement with the x-ray fluorescence analysis results. Free lime or a phase containing lime could not be identified in the diffraction patterns of induction furnace slag. This is because either these phases are not present or the quantity of any such phase is below the detection limit of x-ray diffractometry.

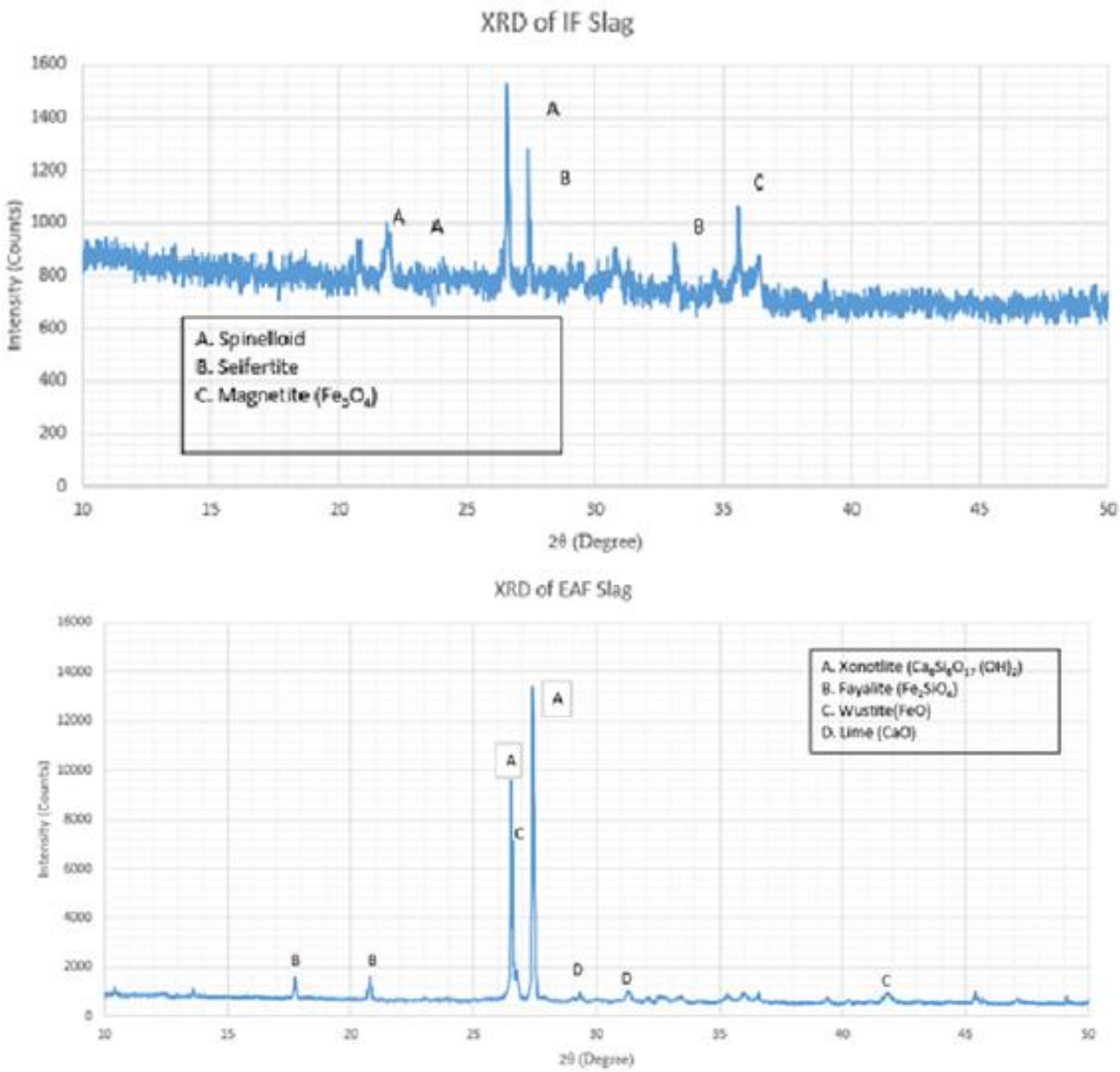


Figure 6.1: X-ray diffraction patterns of Slags.
Upper pattern – IF slag, Lower pattern - EAF Slag

On the other hand, the diffraction pattern of electric arc furnace slag showed, instead, a predominant phase containing CaO. A weak diffraction line of free CaO could also be identified. Moreover, the spinelloid phase (Fe_3O_4-Fe_2SiO_4) predominant in the x-ray diffraction pattern of induction furnace slag was absent in the pattern of EAF slag. This makes electric furnace slag qualitatively different from induction furnace slag.

6.4 Unit Weight

Unit weight or density of the fresh concrete was determined by weighing a known volume of concrete. The sample is generally weighed immediately before the air content is determined. The presence of entrained air affects the unit weight, since air contributes volume, but not weight. The unit weight also gives an approximate indication of air content for concrete made with different materials. Unit weight is a function of initial ingredients of concrete, mix proportions, initial and final water content, air content, volume changes, and degree of consolidation. The unit weight is shown in Table 6.3. The unit weight of electric arc furnace slag was higher than that of induction furnace slag.

Table 6.3: Unit weight of concrete ingredients

Sample	Unit Weight (kg/cft)	Unit Weight (kg/m^{3})
Cement	29.70	1050
sand	40.18	1420
stone	39.63	1400
EAF (Coarse aggregate)	46.29	1635
EAF (Fine aggregate)	43.52	1537
IF (Coarse aggregate)	28.16	995
IF (Fine aggregate)	30.81	1095

6.5 Specific Gravity and AbsorptionCapacity

The measured water absorption rate and specific gravity of aggregates is routinely used in design and construction of pavement materials and structures worldwide. The specific gravity and absorption of coarse and fine aggregate were determined (Table 6.4) according to the specification ASTM C128-01 (for fine aggregate) and ASTM C127-01 (for coarse aggregate).

Table 6.4: Specific Gravity and Absorption Capacity of concrete materials

Properties	Fine aggregate (Sand)	Coarse aggregate (Stone chips)	EAF coarse aggregate	EAF fine aggregate	IF coarse aggregate	IF fine aggregate
Apparent specific gravity	2.65	2.66	3.62	3.96	2.91	3.05
Bulk specific gravity (OD basis)	2.54	2.6	3.47	3.53	2.77	2.7
Bulk specific gravity (SSD basis)	2.58	2.62	3.51	3.64	2.81	2.82
Absorption capacity (%)	1.61	0.83	1.17	3.09	1.67	4.17

6.6 Gradations

The sieve analysis of the steel slag samples revealed that the material was a combination of both fine aggregates and coarse aggregates.

Table 6.5 (a): Sieve analysis for fine aggregate (Sand)

Sieve no.	Sieve opening (mm)	material retained (gm)	% material retained	Cumulative % retined	% finer	Grain diameters	Coefficient of uniformity (Cu)	Fineness Modulus (FM)
No. 4	4.75	0	0	0	100	D10= 0.11 D60= 0.185	1.68	2.626
No. 8	2.36	26.2	5.25	5.25	94.75			
No. 16	1.18	96.4	19.31	24.56	75.44			
No. 30	0.6	169.5	33.95	58.51	41.49			
No. 50	0.3	111.7	22.38	80.89	19.11			
No. 100	0.15	62.6	12.54	93.43	6.57			
No. 200	0.075	24.6	4.93	98.36	1.64			
Pan	0.01	8.3	1.67	100	0			
Total		499.3	100					

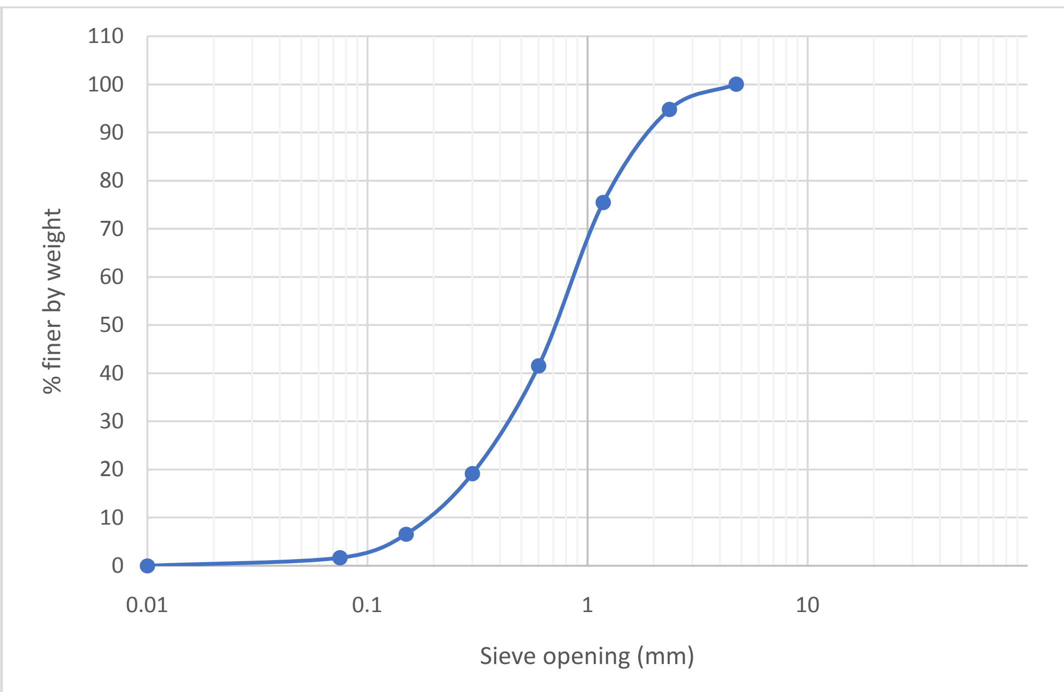


Figure 6.2 (a): Sieve analysis for fine aggregate (sand)

Table 6.5 (b): Sieve analysis for fine aggregate (IF)

Sieve no.	Sieve opening (mm)	material retained (gm)	% material retained	Cumulative % retained	% finer	Grain diameters	Coefficient of uniformity (Cu)	Fineness Modulus (FM)
No. 4	4.75	4.5	0.91	0.91	99.09	D10= .132 D60=2.4	18.18	3.89
No. 8	2.36	191	38.78	39.69	60.31			
No. 16	1.18	161.5	32.79	72.48	27.52			
No. 30	0.6	71	14.41	86.89	13.11			
No. 50	0.3	28	5.68	92.57	7.43			
No. 100	0.15	19	3.85	96.42	3.58			
No. 200	0.075	12	2.43	98.85	1.15			
Pan	0.01	5.5	1.11	100	0			
Total		492.5	100					

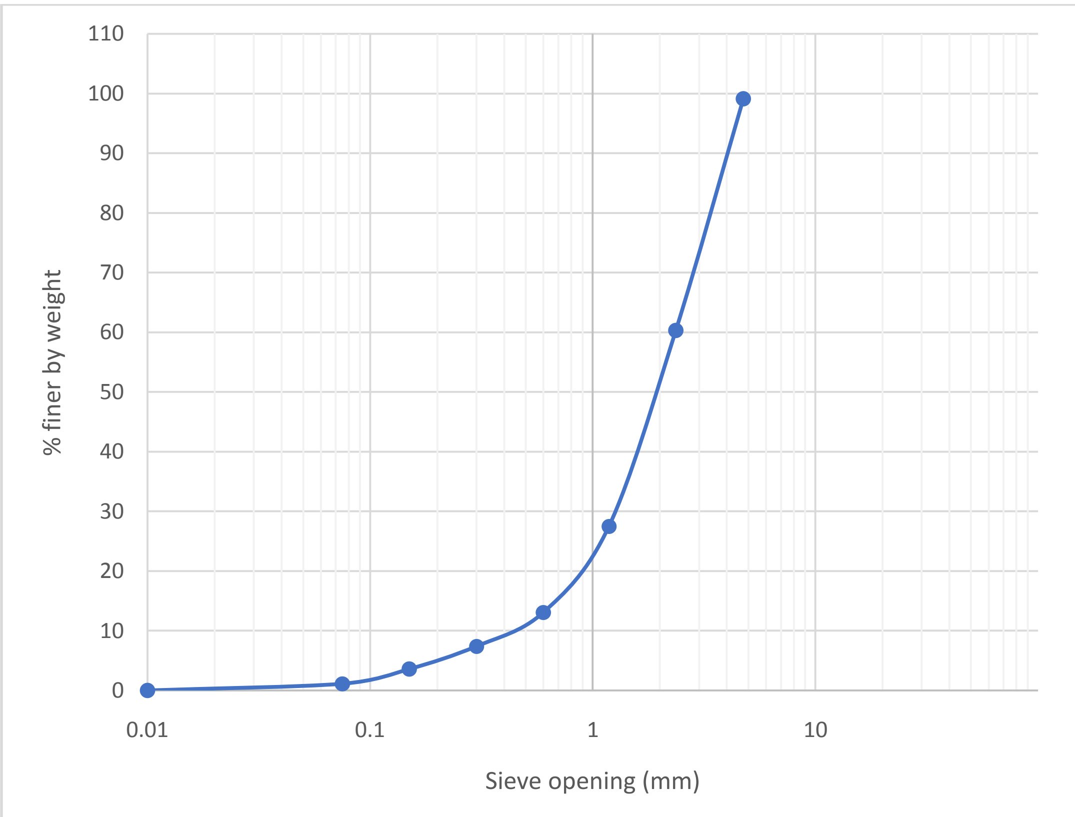


Figure 6.2 (b): Sieve analysis for IF fine aggregate

Table 6.5 (c): Sieve analysis for fine aggregate (EAF)

Sieve no.	Sieve opening (mm)	material retained (gm)	% material retained	Cumulative % retained	% finer	Grain diameters	Coefficient of uniformity (Cu)	Fineness Modulus (FM)
No. 4	4.75	0	0	0	100	D10=0.15 D60= 2.36	15.73	3.698
No. 8	2.36	198.1	39.78	39.78	60.22			
No. 16	1.18	148.7	29.86	69.64	30.36			
No. 30	0.6	65.2	13.09	82.73	17.27			
No. 50	0.3	23.5	4.72	87.45	12.55			
No. 100	0.15	14	2.82	90.27	9.73			
No. 200	0.075	21.4	4.3	94.57	5.43			
Pan	0.01	27.2	5.47	100	0			
Total		498.1	100					

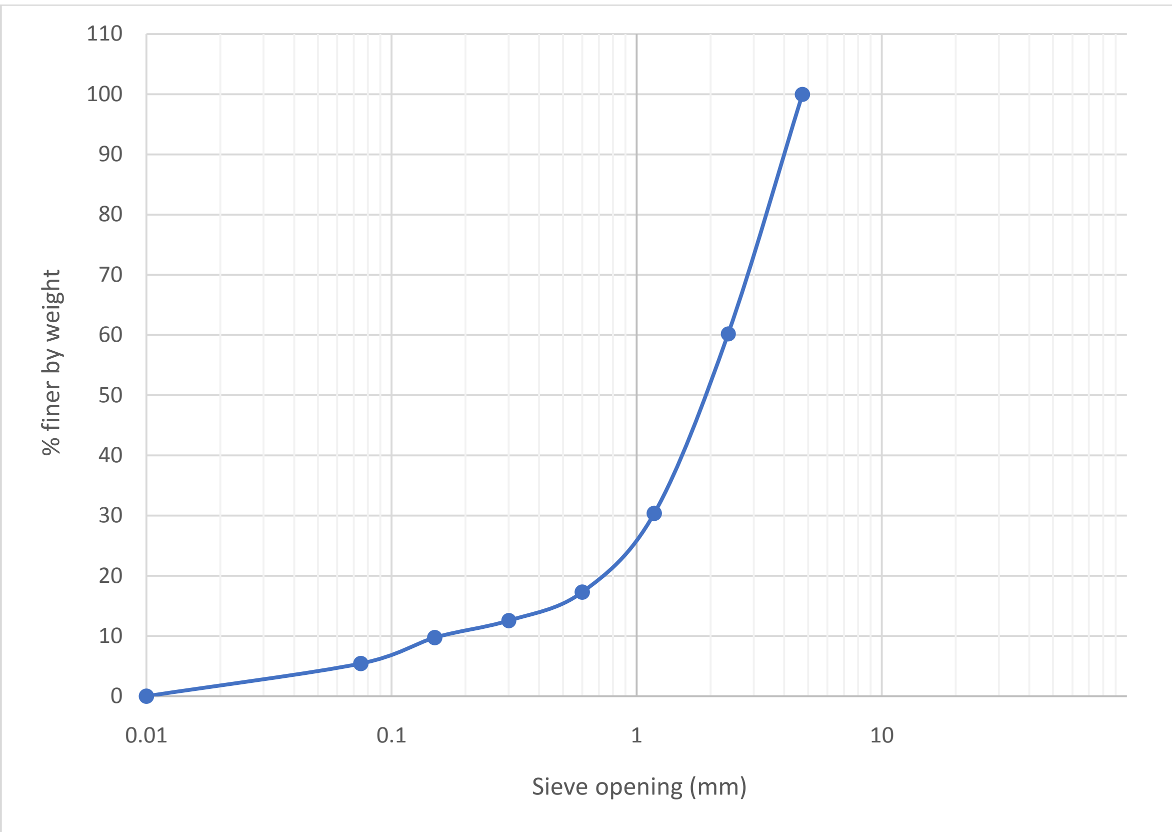


Figure 6.2 (c): Sieve analysis for EAF fine aggregate

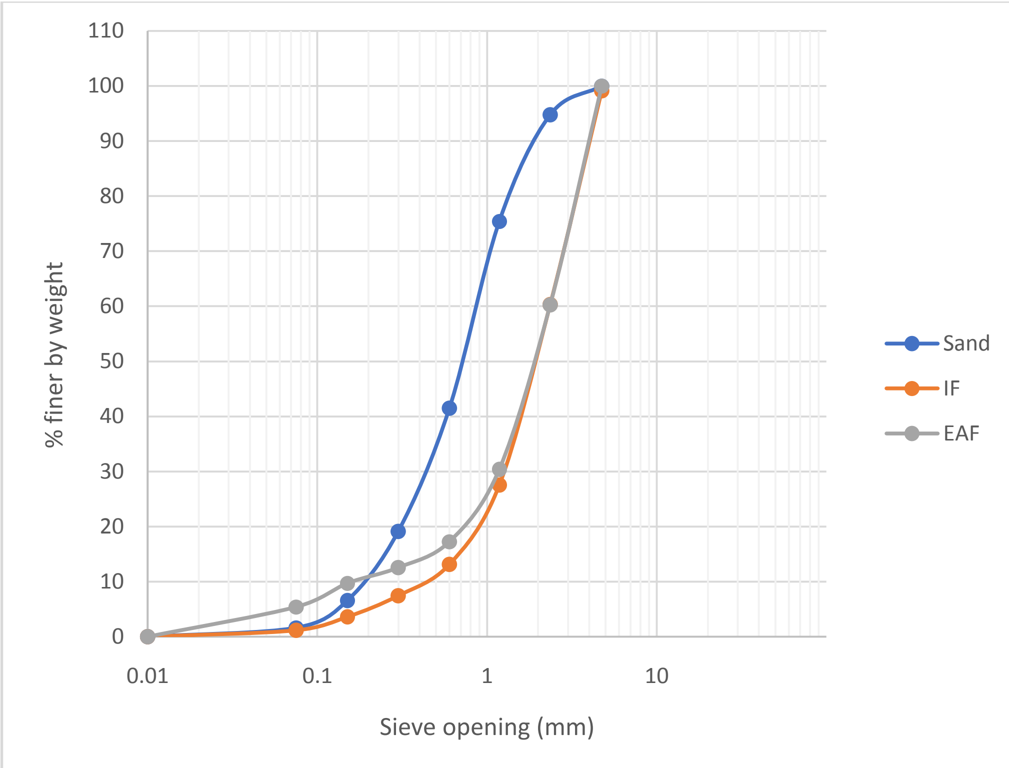


Figure 6.3: Comparison of sieve analysis for fine aggregates

Table 6.5 (d): Sieve analysis for coarse aggregate (Stone chips)

Sieve no.	Sieve opening (mm)	material retained (kg)	% material retained	Cumulative % retined	% finer	Grain diameters	Coefficient of uniformity (Cu)	Fineness Modulus (FM)
No. 3/4"	19	3.8	38.14	38.14	61.86	D10= 12 D60= 19	1.58	3.17
No. 1/2"	12.5	4.3	43.16	81.3	18.7			
No. 3/8"	9.5	1.345	13.5	94.8	5.2			
No. 4	4.7	0.52	5.22	100	0			
Total		9.965	100					

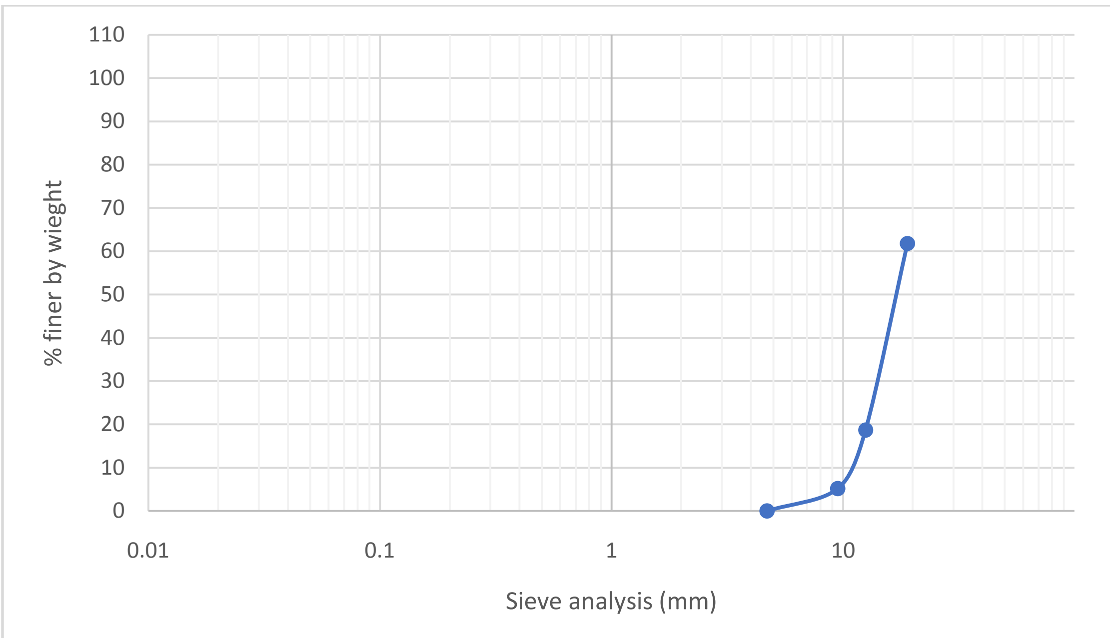


Figure 6.4 (a): Sieve analysis for coarse aggregate (Stone chips)

Table 6.5 (e): Sieve analysis for coarse aggregate (IF)

Sieve no.	Sieve opening (mm)	material retained (gm)	% material retained	Cumulative % retined	% finer	Grain diameters	Coefficient of uniformity (Cu)	Fineness Modulus (FM)
No. 3/4"	19	0.65	6.61	6.61	93.39	D10= 6.8 D60=14	2.058	2.32
No. 1/2"	12.5	4.06	41.27	47.88	52.12			
No. 3/8"	9.5	2.88	29.27	77.15	22.85			
No. 4	4.7	2.25	22.87	100	0			
Total		9.84	100					

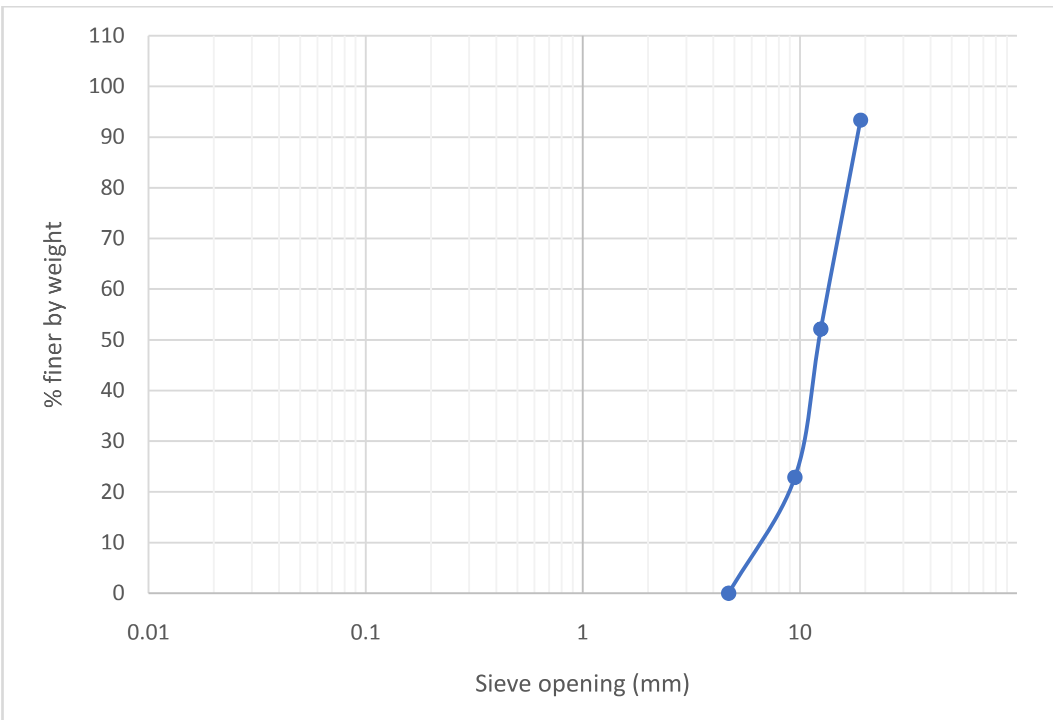


Figure 6.4 (b): Sieve analysis for coarse aggregate (IF)

Table 6.5 (f): Sieve analysis for coarse aggregate (EAF)

Sieve no.	Sieve opening (mm)	material retained (kg)	% material retained	Cumulative % retined	% finer	Grain diameters	Coefficient of uniformity (Cu)	Fineness Modulus (FM)
No. 3/4"	19	0.435	4.38	4.38	95.62	D10= 8 D60= 15	1.875	2.448
No. 1/2"	12.5	5.09	51.24	55.62	44.38			
No. 3/8"	9.5	2.9	29.19	84.81	15.19			
No. 4	4.7	1.51	15.2	100	0			
Total		9.935	100					

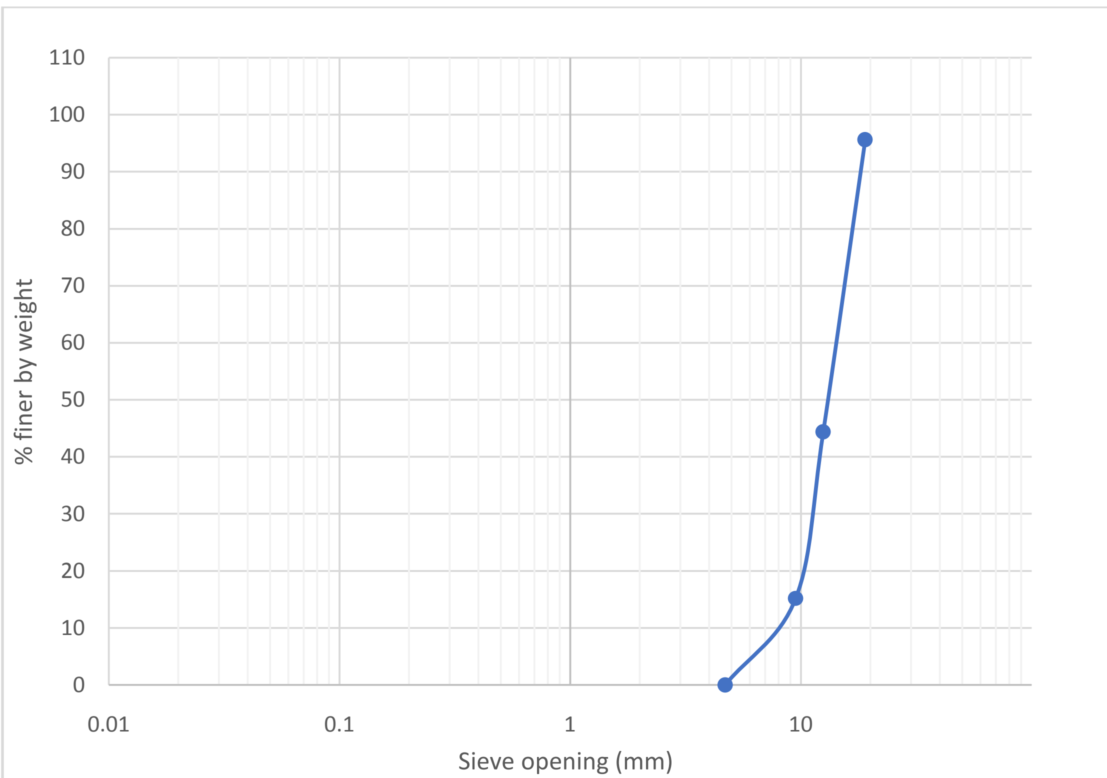


Figure 6.4 (c): Sieve analysis for coarse aggregate (EAF)

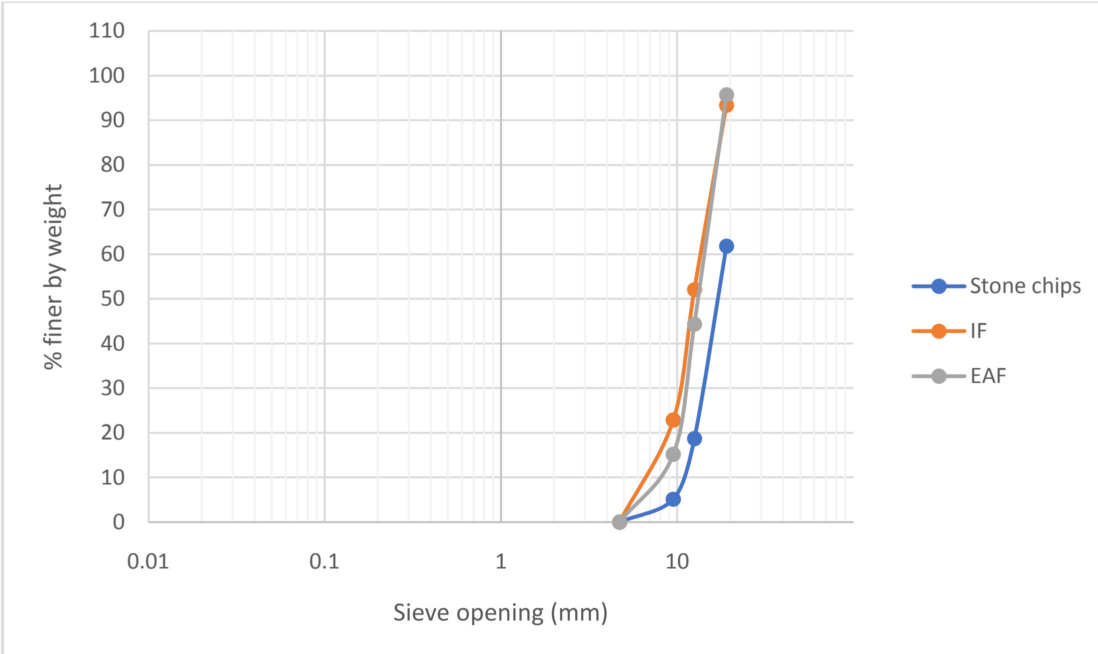


Figure 6.5: Comparison of sieve analysis for coarse aggregates

6.7 Fresh Concrete Properties

6.7.1 Workability

The workability of concrete (measured by slump) made with different types of slag is shown. EAF coarse slag shows better workability compared to the both IF coarse and fine slag. IF coarse shows the worst slump values.

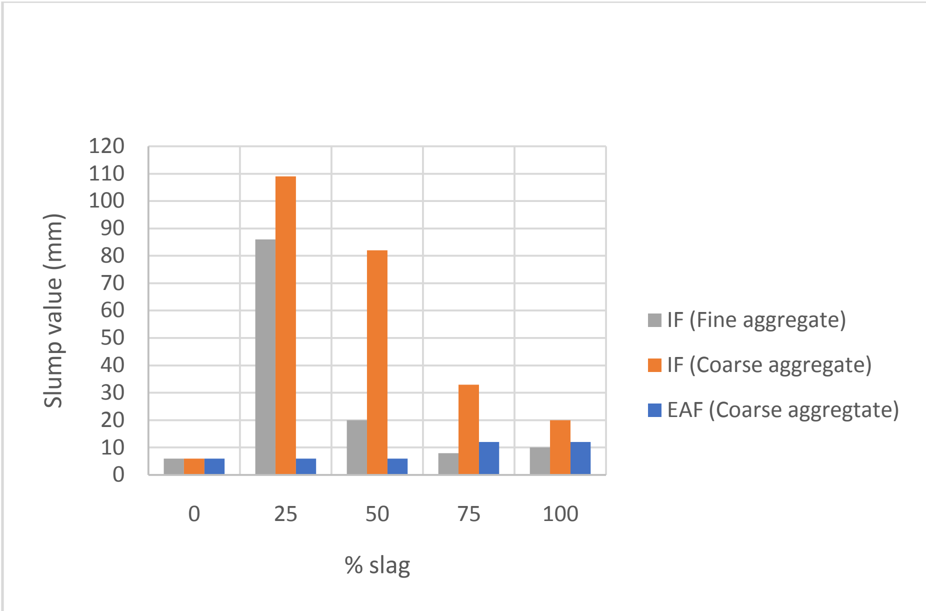


Figure 6.6: Workability of coarse aggregate replacement by different types of slag

6.8 Hardened Concrete Properties

6.8.1 Compressive Strength for Concrete Specimens

Most properties of concrete are directly related to its compressive strength. The compression test on the concrete specimens was carried out according to ASTM C39. Cylindrical samples, 4 inches in diameter and 8 inches in height, were properly molded and cured. The specimens were loaded at a control rate in the compression machine.

Tables 6.5 and Figures 6.7 and Figure 6.8 provide the compressive strength of concrete for 7, 14 and 28 days. In case of concrete with no slag replacement, the values of compressive strength for 7, 14 and 28 days are 4109 psi, 4448 psi and 4399 psi respectively. It is evident from the table and graph that, the compressive strength of concrete samples replaced with IF fine slag has lower values than the concrete samples with no slag replacement. However, there is an increasing trend in the strength values with the gradual replacement of slag especially for 28 days. The highest value attained is 3699 psi after 28 days with 100 percent slag replaced.

For IF coarse aggregate, the scenario is the same as the previous one. The strength of the concrete specimens was almost the same for the replacement of slag from 25% to 100% with the numerical values ranging from 3288 psi to 3578 psi.

In the case of EAF steel slag, it is evident that the compressive strength of samples replaced with slag in varied ratios by weight shows superior numerical values compared to the concrete with no slag in it. Again, it is evident that, increasing the amount of the ratios of slag increases the compressive strength of the concrete. The highest strength was attained for 75% slag replacement with a value of 5850 psi. Concrete samples with 100% slag replaced also showed a comparable value of 5705 psi. This higher strength might be due to the cement paste and the bond strength at the paste-aggregates boundary. This shows that concrete with steel slag aggregates achieves similar strength compared to conventional concrete.

6.8.2 Splitting Tensile Strength

The splitting tensile strength of the concrete specimens was determined at 7days, 14 days and 28 days following ASTM C 496. As previously mentioned the specimens were molded at the same time as the compressive strength specimens. Cylinders were molded with a diameter of 4 inches (102 mm) and a length of 8 inches (203 mm). Tables 6.6 and Figures 6.9 and 6.10 show the 7 days, 14 days and 28 days splitting tensile strength on concrete specimens.

The splitting tensile test is an indirect way of estimating the tensile strength of cylindrical concrete specimens. Since the concrete is much weaker in tension than in compression, the failure would be at a much lower load than in compression. The cylinders were tested according to ASTM C 496.

In case of EAF slag replaced, the maximum values were obtained for 50% slag replaced and 100% slag replaced in 7 days and 14 days respectively but all the slag replaced samples showed superior values than the concrete with no slag.

In IF coarse aggregate replacement, the maximum values were obtained for 100% slag replacement and no slag replacement in 7 days and 14 days respectively. For 7 days curing, the values were found to be more or less consistent. For 14 days, an increasing trend was observed for the gradual replacement of slag except for concrete with no slag replacement.

In IF fine aggregate replacement, the maximum values were obtained for 0% slag replacement and 50% slag replacement in 7 days and 14 days respectively. For 7 days curing, the values were found to be consistent. For 14 days, the strength values were observed in the range of 250-300 psi.

Overall, it was evident that, both the compressive and splitting tensile strength of the concrete specimen were found to be superior for EAF steel slag replacement than the IF steel slag replacement.

Table 6.6 (a): Compressive strength of concrete specimens (replacement with IF fine aggregate)

slag %	sample no.	Age in days	Average diameter (mm)	Area (sq. mm)	Max load (KN)	Calibrated max load (KN)	Compressive strength (MPa)	Compressive strength (psi)	Average Compressive Strength (MPa)	Average Compressive Strength (psi)	Type of failure
0%	1	7	101	8011.87	217.3	222	28	4061	28	4109	Combined
	2		101	8011.87	201.8	206	26	3771			Combined
	3		101	8011.87	240	245	31	4496			Combined
	1	14	101.5	8091.39	225.9	231	29	4206	31	4448	Combined
	2		101.5	8091.39	258.4	263	33	4786			Combined
	3		101.5	8091.39	238.8	244	30	4351			Combined
	1	28	101	8011.87	271.1	276	34	4931	30	4399	Combined
	2		101	8011.87	218.8	224	28	4061			Combined
	3		101	8011.87	231.6	236	29	4206			Combined
25%	1	7	102	8171.31	132	136	17	2466	17	2466	Combined
	2		102	8171.31	110	114	14	2031			Combined
	3		101.75	8131.3	154.4	159	20	2901			Combined
	1	14	101	8011.87	173.1	178	22	3191	22	3119	Combined
	2		102	8171.31	165.8	170	21	3046			Combined
											Combined
	1	28	101.5	8091.39	150.3	155	19	2756	19	2708	Combined
	2		101	8011.87	148	152	19	2756			Combined
	3		101.5	8091.39	140.2	144	18	2611			Combined
50%	1	7	101.75	8131.3	162.4	167	21	3046	20	2901	Combined
	2		102	8171.31	157.3	162	20	2901			Combined
	3		101.5	8091.39	150.1	154	19	2756			Combined
	1	14	102	8171.31	139.6	144	18	2611	21	3094	Combined
	2		102	8171.31	183.1	188	23	3336			Combined
	3		101.5	8091.39	184.7	189	23	3336			Combined
	1	28	101	8011.87	301.7	307	38	5511	24	3409	Combined
	2		101.5	8091.39	193.6	198	24	3481			Combined
	3		101.5	8091.39	181.1	186	23	3336			Combined

Table 6.6 (a): Compressive strength of concrete specimens (replacement with IF fine aggregate, contd.)

slag %	sample no.	Age in days	Average diameter (mm)	Area (sq. mm)	Max load (KN)	Calibrated max load (KN)	Compressive strength (MPa)	Compressive strength (psi)	Average Compressive Strength (MPa)	Average Compressive Strength (psi)	Type of failure
75%	1	7	102	8171.31	184.3	189	23	3336	19	2708	Combined
	2		102	8171.31	146.6	151	18	2611			Combined
	3		102	8171.31	118	122	15	2176			Combined
	1	14	102	8171.31	143.3	148	18	2611	21	3046	Combined
	2		102	8171.31	186.7	191	23	3336			Combined
	3		102	8171.31	174.8	179	22	3191			Combined
	1	28	101.5	8091.39	201.9	207	26	3771	24	3481	Combined
	2		101.5	8091.39	269.6	275	34	4931			Combined
	3		101.5	8091.39	170.8	175	22	3191			Combined
100%	1	7	101.5	8091.39	176	180	22	3191	23	3336	Combined
	2		101.75	8131.3	192.9	197	24	3481			Combined
	3		101.5	8091.39	178.1	183	23	3336			Combined
	1	14	101	8011.87	154.7	159	20	2901	22	3191	Combined
	2		102	8171.31	174.7	179	22	3191			Combined
	3		102	8171.31	189	194	24	3481			Combined
	1	28	102	8171.31	160.9	165	20	2901	26	3699	Combined
	2		101.5	8091.39	196.3	201	25	3626			Combined
	3		102	8171.31	210.7	215	26	3771			Combined

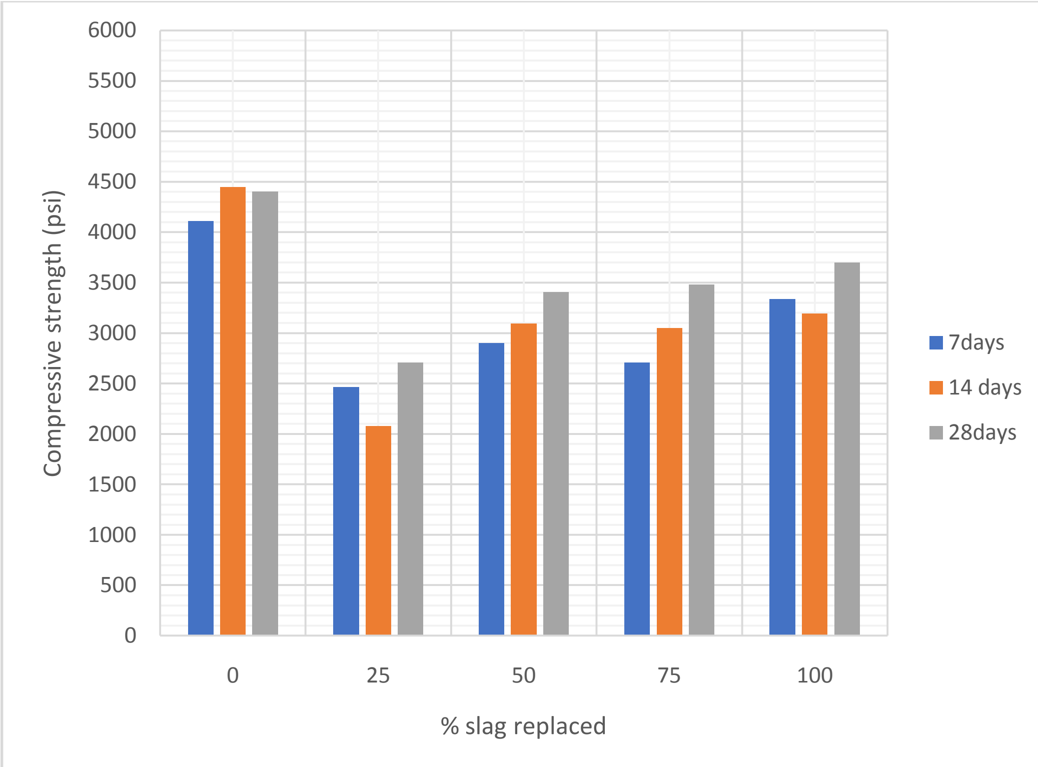


Figure 6.7 (a): Compressive strength of IF fine aggregate

Table 6.6 (b): Compressive strength of concrete specimens (replacement with IF coarse aggregate)

slag %	sample no.	Age in days	Average diameter (mm)	Area (sq. mm)	Max load (KN)	Calibrated max load (KN)	compressive strength (MPa)	compressive strength (psi)	Average compressive Strength (MPa)	Average compressive Strength (psi)	Type of failure
0%	1	7	101	8011.87	217.3	222	28	4061	28	4109	Combined
	2		101	8011.87	201.8	206	26	3771			Combined
	3		101	8011.87	240	245	31	4496			Combined
	1	14	101.5	8091.39	225.9	231	29	4206	31	4448	Combined
	2		101.5	8091.39	258.4	263	33	4786			Combined
	3		101.5	8091.39	238.8	244	30	4351			Combined
	1	28	101	8011.87	271.1	276	34	4931	30	4399	Combined
	2		101	8011.87	218.8	224	28	4061			Combined
	3		101	8011.87	231.6	236	29	4206			Combined
25%	1	7	101.5	8091.39	133.7	138	17	2466	17	2418	Combined
	2		101.75	8131.3	124.6	129	16	2321			Combined
	3		101	8011.87	134	138	17	2466			Combined
	1	14	101	8011.87	153.2	158	20	2901	19	2804	Combined
	2		102	8171.31	134.3	139	17	2466			Combined
	3		101	8011.87	161.8	166	21	3046			Combined
	1	28	102	8171.31	166.7	171	21	3046	23	3288	Combined
	2		102	8171.31	190.3	195	24	3481			Combined
	3		102	8171.31	180.9	185	23	3336			Combined
50%	1	7	101.25	8051.58	144.4	149	19	2756	17	2466	Combined
	2		102	8171.31	124.5	129	16	2321			Combined
	3		101	8011.87	123.9	128	16	2321			Combined
	1	14	101	8011.87	175.4	180	22	3191	23	3336	Combined
	2		101.5	8091.39	191.4	196	24	3481			Combined
	3		101	8011.87	177.1	182	23	3336			Combined
	1	28	102	8171.31	183.6	188	23	3336	24	3409	Combined
	2		102	8171.31	189.8	194	24	3481			Combined
	3		102	8171.31	157.6	162	20	2901			Combined

Table 6.6 (b): Compressive strength of concrete specimens (replacement with IF coarse aggregate, contd.)

slag %	sample no.	Age in days	Average diameter (mm)	Area (sq. mm)	Max load (KN)	Calibrated max load (KN)	compressive strength (MPa)	compressive strength (psi)	Average compressive Strength (MPa)	Average compressive Strength (psi)	Type of failure
75%	1	7	101	8011.87	146.3	151	19	2756	19	2804	Combined
	2		101.5	8091.39	143.6	148	18	2611			Combined
	3		101.5	8091.39	162.3	167	21	3046			Combined
	1	14	102	8171.31	193.2	198	24	3481	23	3336	Combined
	2		101	8011.87	181.4	186	23	3336			Combined
	3		101	8011.87	169.8	174	22	3191			Combined
	1	28	102	8171.31	188.7	193	24	3481	24	3481	Combined
	2		101	8011.87	189.9	194	24	3481			Combined
	3		101.5	8091.39	192.7	197	24	3481			Combined
100%	1	7	102	8171.31	195.4	200	24	3481	22	3143	Combined
	2		102	8171.31	145.6	150	18	2611			Combined
	3		101.5	8091.39	180.9	185	23	3336			Combined
	1	14	102	8171.31	211.5	216	26	3771	23	3336	Combined
	2		102	8171.31	155.9	160	20	2901			Combined
	3		102	8171.31	179.4	184	23	3336			Combined
	1	28	102	8171.31	189.8	194	24	3481	25	3578	Combined
	2		102	8171.31	194.7	199	24	3481			Combined
	3		102	8171.31	205.7	210	26	3771			Combined

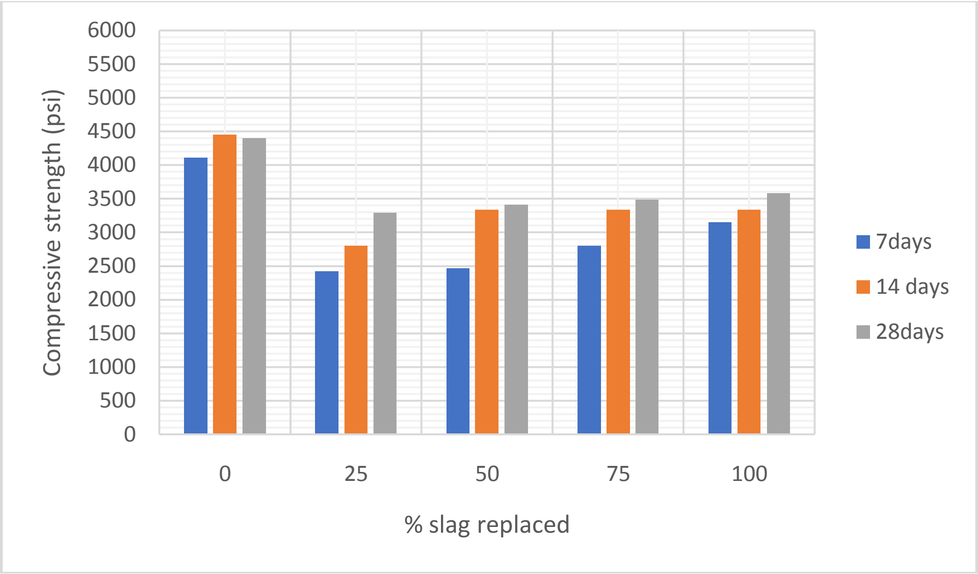


Figure 6.7 (b): Compressive strength of IF coarse aggregate

Table 6.6 (c): Compressive strength of concrete specimens (replacement with EAF coarse aggregate)

slag %	sample no.	Age in days	Average diameter (mm)	Area (sq. mm)	Max load (KN)	Calibrated max load (KN)	Compressive strength (MPa)	Compressive strength (psi)	Average compressive strength (MPa)	Average compressive Strength (psi)	Type of failure
0%	1	7	101	8011.87	217.3	222	28	4061	28	4109	combined
	2		101	8011.87	201.8	206	26	3771			combined
	3		101	8011.87	240	245	31	4496			combined
	1	14	101.5	8091.39	225.9	231	29	4206	31	4448	combined
	2		101.5	8091.39	258.4	263	33	4786			combined
	3		101.5	8091.39	238.8	244	30	4351			combined
	1	28	101	8011.87	271.1	276	34	4931	30	4399	combined
	2		101	8011.87	218.8	224	28	4061			combined
	3		101	8011.87	231.6	236	29	4206			combined
25%	1	7	101.5	8091.39	252.3	257	32	4641	32	4593	combined
	2		101	8011.87	235.4	240	30	4351			combined
	3		101	8011.87	258.7	264	33	4786			combined
	1	14	101.5	8091.39	270.7	276	34	4931	34	4979	combined
	2		102.25	8211.41	270.9	276	34	4931			combined
	3		101.5	8091.39	276.4	281	35	5076			combined
	1	28	101	8011.87	266.5	272	34	4931	35	5076	combined
	2		101	8011.87	283.6	289	36	5221			combined
	3		101	8011.87	274.8	280	35	5076			combined
50%	1	7	101	8011.87	249.6	255	32	4641	32	4641	combined
	2		101	8011.87	259.8	265	33	4786			combined
	3		101	8011.87	244.3	249	31	4496			combined
	1	14	101	8011.87	209.4	214	27	3916	33	4448	combined
	2		102	8171.31	260.8	266	33	4786			combined
	3		101.25	8051.58	256.5	261	32	4641			combined
	1	28	101	8011.87	305.6	311	39	5656	39	5608	combined
	2		101	8011.87	311.5	317	40	5802			combined
	3		101	8011.87	294.2	299	37	5366			combined

Table 6.6 (c): Compressive strength of concrete specimens (replacement with EAF coarse aggregate, contd.)

slag %	sample no.	Age in days	Average diameter (mm)	Area (sq. mm)	Max load (KN)	Calibrated max load (KN)	Compressive strength (MPa)	Compressive strength (psi)	Average compressive strength (MPa)	Average compressive Strength (psi)	Type of failure
75%	1	7	101	8011.87	254.1	259	32	4641	32	4641	combined
	2		101.5	8091.39	233.9	239	30	4351			combined
	3		101	8011.87	269.6	275	34	4931			combined
	1	14	101.25	8051.58	314.9	320	40	5802	37	5366	combined
	2		101.5	8091.39	283.5	289	36	5221			combined
	3		101	8011.87	278.5	284	35	5076			combined
	1	28	101	8011.87	314.3	320	40	5802	40	5850	combined
	2		101	8011.87	309.8	315	39	5656			combined
	3		101	8011.87	329.2	335	42	6092			combined
100%	1	7	102	8171.31	237.1	242	30	4351	34	4883	combined
	2		101	8011.87	284.4	290	36	5221			combined
	3		101.25	8051.58	279.2	284	35	5076			combined
	1	14	101	8011.87	296.9	302	38	5511	38	5511	combined
	2		101	8011.87	318.9	324	40	5802			combined
	3		101.5	8091.39	285.7	291	36	5221			combined
	1	28	102	8171.31	293.6	299	37	5366	39	5705	combined
	2		101	8011.87	313.5	319	40	5802			combined
	3		101	8011.87	323.9	329	41	5947			combined

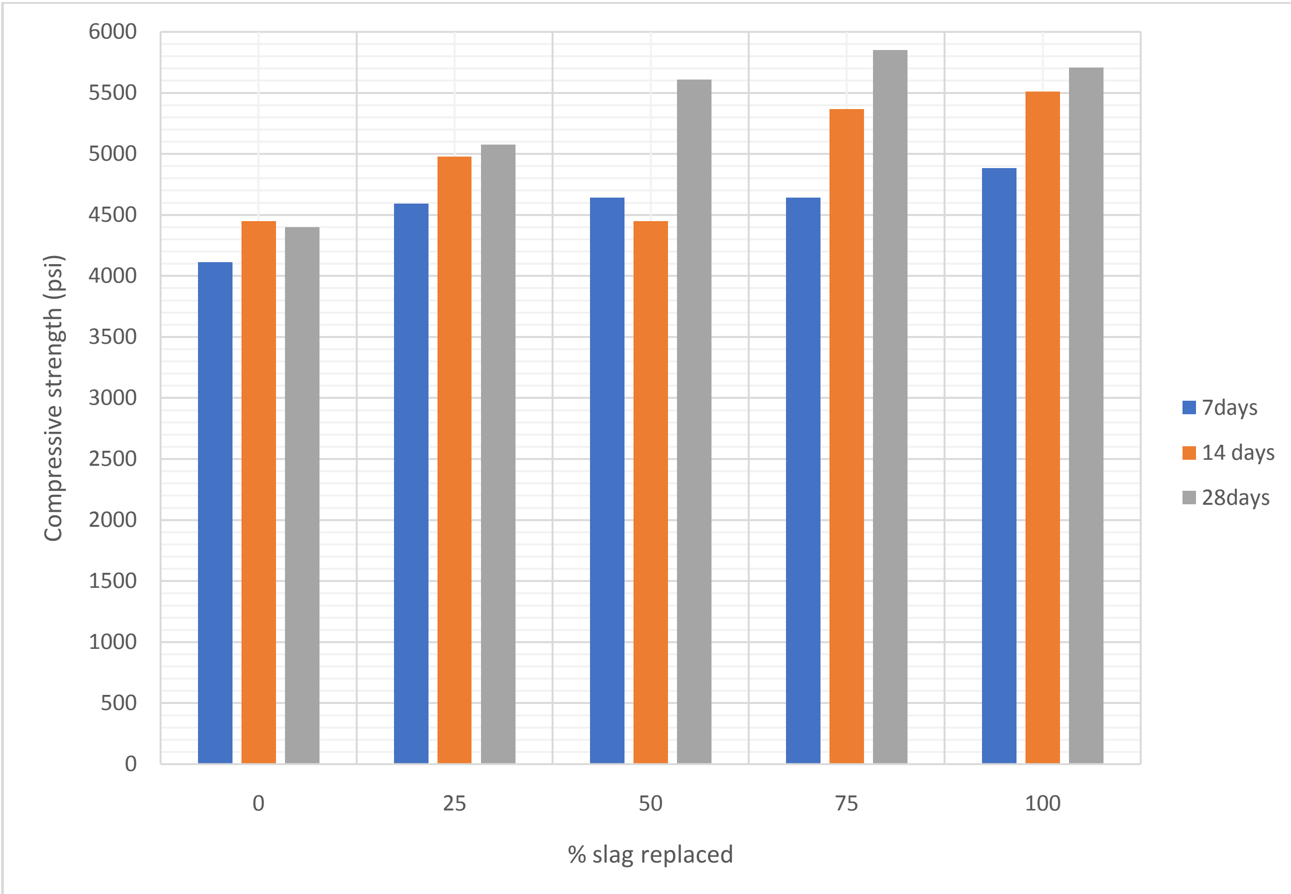


Figure 6.7 (c): Compressive strength of EAF coarse aggregate.

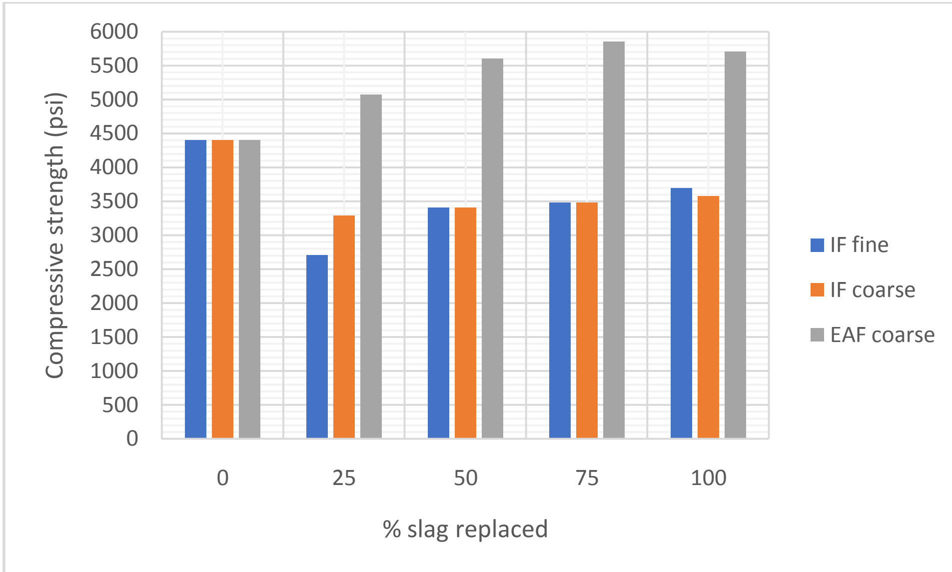


Figure 6.8: Comparison of compressive strength of the concrete specimen after 28 days.

Table 6.7 (a): Splitting tensile strength of concrete specimens (replacement with IF fine aggregate)

slag %	Sample no.	Age in days	Average diameter (mm)	Average length (mm)	Max load (KN)	Calibrated max load (KN)	splitting tensile strength (MPa)	splitting tensile strength (psi)	Average splitting tensile strength (MPa)	Average splitting tensile strength (psi)	Type of failure
0%	1	7	101.75	204	30	34	1.05	152	1.86	270	Combined
	2		101	204	50	53	1.64	238			Combined
	3		101	204	64	67	2.08	302			Combined
	1	14	101	204	84	87	2.69	390	2.3	333	Combined
	2		101.25	204	70	73	2.25	326			Combined
	3		101.25	204	60	63	1.95	283			Combined
	1	28	101	204	62	65	2.01	292	1.97	285	Combined
	2		101	204	60	63	1.95	283			Combined
	3		101.5	204	60	63	1.94	281			Combined
25%	1	7	101.75	205	42	45	1.38	200	1.47	213	Combined
	2		102	205	48	51	1.56	226			Combined
	3										Combined
	1	14	102	204	60	63	1.93	280	2.03	294	Combined
	2		102	204	40	43	1.32	191			Combined
	3		102	204	66	69	2.12	307			Combined
	1	28	101	205	34	37	1.14	165	2.06	299	Combined
	2		101	202	64	67	2.1	305			Combined
	3		101.5	202	62	65	2.02	293			Combined
50%	1	7	102	204	60	63	1.93	280	1.65	239	Combined
	2		101.75	204.5	42	45	1.38	200			Combined
	3		101.75	204	50	53	1.63	236			Combined
	1	14	102	204	74	77	2.36	342	2.16	313	Combined
	2		101	204	68	71	2.2	319			Combined
	3		102	205	60	63	1.92	278			Combined
	1	28	102	202	62	65	2.01	292	1.85	267	Combined
	2		101	204.5	58	61	1.89	274			Combined
	3		101.5	204.5	50	53	1.63	236			Combined

Table 6.7 (a): Splitting tensile strength of concrete specimens (replacement with IF fine aggregate, contd.)

slag %	Sample no.	Age in days	Average diameter (mm)	Average length (mm)	Max load (KN)	Calibrated max load (KN)	splitting tensile strength (MPa)	splitting tensile strength (psi)	Average splitting tensile strength (MPa)	Average splitting tensile strength (psi)	Type of failure
75%	1	7	102	203	58	61	1.88	273	1.79	260	Combined
	2		101.5	204.5	36	39	1.2	174			Combined
	3		101	204	52	55	1.7	247			Combined
	1	14	102	204	70	73	2.24	325	1.92	278	Combined
	2		101	204	60	63	1.95	283			Combined
	3		102	204.5	48	51	1.56	226			Combined
	1	28	101	204	52	55	1.7	247	1.58	229	Combined
	2		101	204	50	53	1.64	238			Combined
	3		101.5	204.5	42	45	1.39	202			Combined
100%	1	7	102	205	60	63	1.92	278	1.91	277	Combined
	2		101.5	205	68	71	2.18	316			Combined
	3		101.5	204	50	53	1.63	236			Combined
	1	14	102	205	72	75	2.29	332	1.99	288	Combined
	2		102	204	50	53	1.63	236			Combined
	3		102	204	64	67	2.05	297			Combined
	1	28	102	204	56	59	1.81	263	1.95	283	Combined
	2		102	204	64	67	2.05	297			Combined
	3		102	204	62	65	1.99	289			Combined

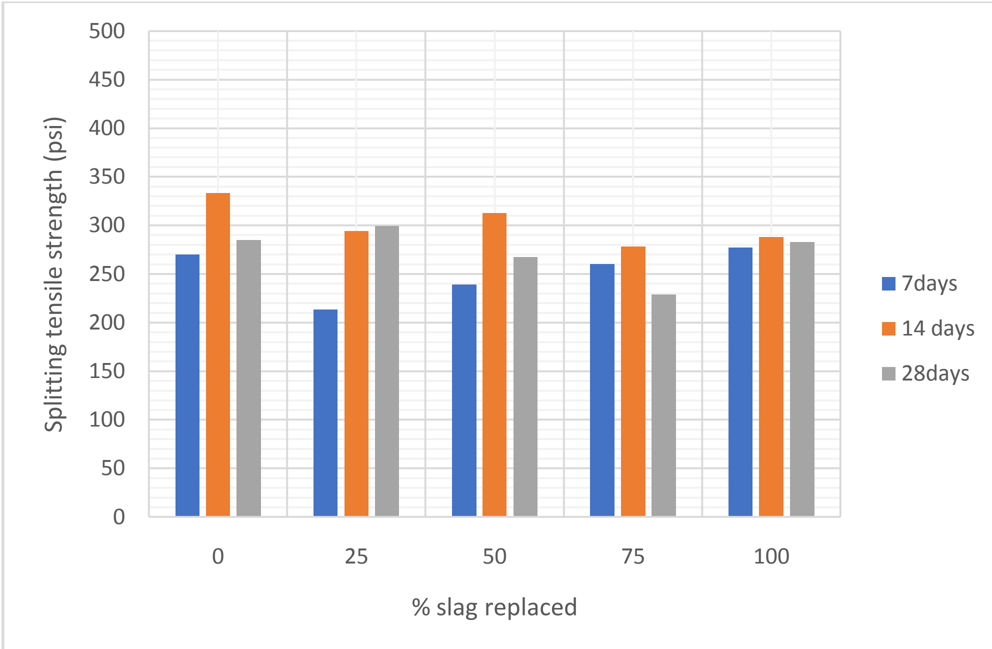


Figure 6.9 (a): Splitting tensile strength IF fine aggregate

Table 6.7 (b): Splitting tensile strength of concrete specimens (replacement with IF coarse aggregate)

slag %	sample no.	Age in days	Average diameter (mm)	Average length (mm)	Max load (KN)	Calibrated max load (KN)	Splitting tensile strength (MPa)	Splitting tensile strength (psi)	Average splitting tensile strength (MPa)	Average splitting tensile strength (psi)	Type of failure
0%	1	7	101.75	204	30	34	1.05	152	1.86	270	Combined
	2		101	204	50	53	1.64	238			Combined
	3		101	204	64	67	2.08	302			Combined
	1	14	101	204	84	87	2.69	390	2.3	333	Combined
	2		101.25	204	70	73	2.25	326			Combined
	3		101.25	204	60	63	1.95	283			Combined
	1	28	101	204	62	65	2.01	292	1.97	285	Combined
	2		101	204	60	63	1.95	283			Combined
	3		101.5	204	60	63	1.94	281			Combined
25%	1	7	101	204	62	65	2.01	292	1.75	254	Combined
	2		101	204	50	53	1.64	238			Combined
	3		101	203	48	51	1.59	231			Combined
	1	14	101	204	48	51	1.58	229	1.73	250	Combined
	2		101	204	48	51	1.58	229			Combined
	3		101.5	203	62	65	2.01	292			Combined
	1	28	102	204	34	37	1.14	165	1.26	183	Combined
	2		102	204	42	45	1.38	200			Combined
	3		102	204	38	41	1.26	183			Combined
50%	1	7	101	205	46	49	1.51	219	1.58	228	Combined
	2		102	204	44	47	1.44	209			Combined
	3		101	203	54	57	1.77	257			Combined
	1	14	101.5	204	48	51	1.57	228	1.64	237	Combined
	2		102	203	58	61	1.88	273			Combined
	3		101.5	204	44	47	1.45	210			Combined
	1	28	102	204	70	73	2.24	325	1.84	267	Combined
	2		102	204	50	53	1.63	236			Combined
	3		101	203	50	53	1.65	239			Combined

Table 6.7 (b): Splitting tensile strength of concrete specimens (replacement with IF coarse aggregate, contd.)

slag %	sample no.	Age in days	Average diameter (mm)	Average length (mm)	Max load (KN)	Calibrated max load (KN)	Splitting tensile strength (MPa)	Splitting tensile strength (psi)	Average splitting tensile strength (MPa)	Average splitting tensile strength (psi)	Type of failure
75%	1	7	101	205	50	53	1.63	236	1.46	212	Combined
	2		101	204	40	43	1.33	193			Combined
	3		101	205	43	46	1.42	206			Combined
	1	14	102	205	50	53	1.62	235	1.79	260	Combined
	2		102	204	58	61	1.87	271			Combined
	3		102	203	58	61	1.88	273			Combined
	1	28	101	204	62	65	2.01	292	1.8	260	Combined
	2		102	204	50	53	1.63	236			Combined
	3		102	204.5	54	57	1.74	252			Combined
100%	1	7	101	204	70	73	2.26	328	1.98	288	Combined
	2		101.5	204	52	55	1.7	247			Combined
	3		101	204	42	45	1.4	203			Combined
	1	14	102	204	64	67	2.05	297	2.06	298	Combined
	2		102	204	66	69	2.12	307			Combined
	3		102	204	62	65	1.99	289			Combined
	1	28	102	204	54	57	1.75	254	2.03	294	Combined
	2		102	204	72	75	2.3	334			Combined
	3		101.5	204	42	45	1.39	202			Combined

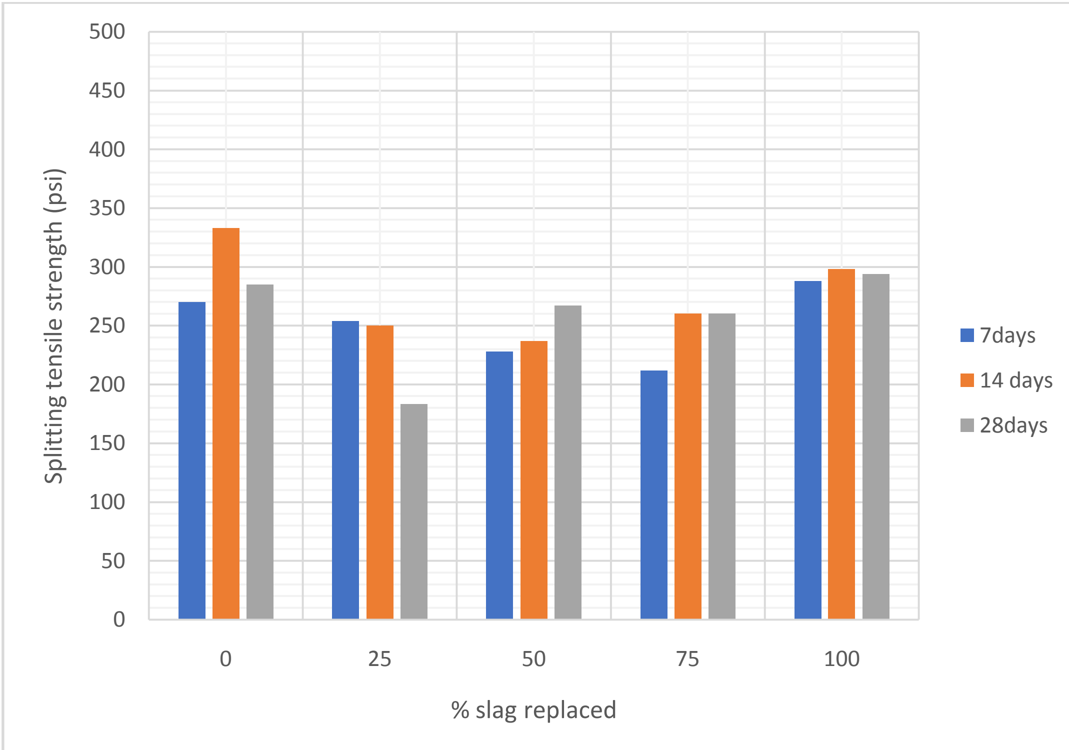


Figure 6.9 (b): Splitting tensile strength IF coarse aggregate

Table 6.7 (c): Splitting tensile strength of concrete specimens (replacement with EAF coarse aggregate)

slag %	sample no.	Age in days	Average diameter (mm)	Avergare length (mm)	Max load(kn)	Calibrated max load (kN)	Splitting tesile strength (MPa)	splitting tensile strength (psi)	Average splitting tensile strength (MPa)	Average splitting tensile strength (psi)	Type of failure
0%	15	7	101.75	204	30	34	1.05	152	1.86	270	Combined
	12		101	204	50	53	1.64	238			Combined
	16		101	204	64	67	2.08	302			Combined
	27	14	101	204	84	87	2.69	390	2.3	333	Combined
	26		101.25	204	70	73	2.25	326			Combined
	18		101.25	204	60	63	1.95	283			Combined
		28	101	204	62	65	2.01	292	1.97	285	Combined
			101	204	60	63	1.95	283			Combined
	21		101.5	204	60	63	1.94	281			Combined
25%	24	7	101	204	66	69	2.14	310	2.05	297	Combined
	27		101.75	204	64	67	2.06	299			Combined
	18		101	204	60	63	1.95	283			Combined
	12	14	101.5	204	70	73	2.25	326	2.44	353	Combined
	15		101.5	204	80	83	2.56	371			Combined
	10		101.5	204	78	81	2.5	363			Combined
	11	28	101	204	60	63	1.95	283	2.08	301	Combined
	13		101	204	66	69	2.14	310			Combined
	1		101	205	66	69	2.13	309			Combined
50%	7	7	101	204	80	83	2.57	373	2.58	374	Combined
	10		101	204	73	76	2.35	341			Combined
	11		101	204	88	91	2.82	409			Combined
	1	14	101	204	82	85	2.63	381	2.75	399	Combined
	3		101.25	204	90	93	2.87	416			Combined
	14		101.25	204	66	69	2.13	309			Combined
	19	28	101	204	94	97	3	435	2.73	396	Combined
	13		101	205	84	87	2.68	389			Combined
	25		101	204	78	81	2.51	364			Combined

Table 6.7 (c): Splitting tensile strength of concrete specimens (replacement with EAF coarse aggregate, contd.)

slag %	sample no.	Age in days	Average diameter (mm)	Avergare length (mm)	Max load(kn)	Calibrated max load (kN)	Splitting tesile strength (MPa)	splitting tensile strength (psi)	Average splitting tensile strength (MPa)	Average splitting tensile strength (psi)	Type of failure
75%	5	7	101	204	82	85	2.63	381	2.56	371	Combined
	2		102	204	78	81	2.48	360			Combined
											Combined
	6	14	101.75	204	84	87	2.67	387	2.77	401	Combined
	15		101.75	204	90	93	2.86	415			Combined
											Combined
	4	28	101	204	78	81	2.51	364	2.59	376	Combined
	21		101	204	90	93	2.88	418			Combined
	17		101	204	74	77	2.38	345			Combined
100%	9	7	102	204	92	95	2.91	422	2.43	353	Combined
	8		101	204	60	63	1.95	283			Combined
											Combined
	20	14	101	204	96	99	3.06	444	3.1	449	Combined
	12		101.5	204	120	123	3.79	550			Combined
	19		101	204	98	101	3.13	454			Combined
		28	101	205	80	83	2.56	371	3.03	440	Combined
	14		101	204	110	113	3.5	508			Combined
											Combined

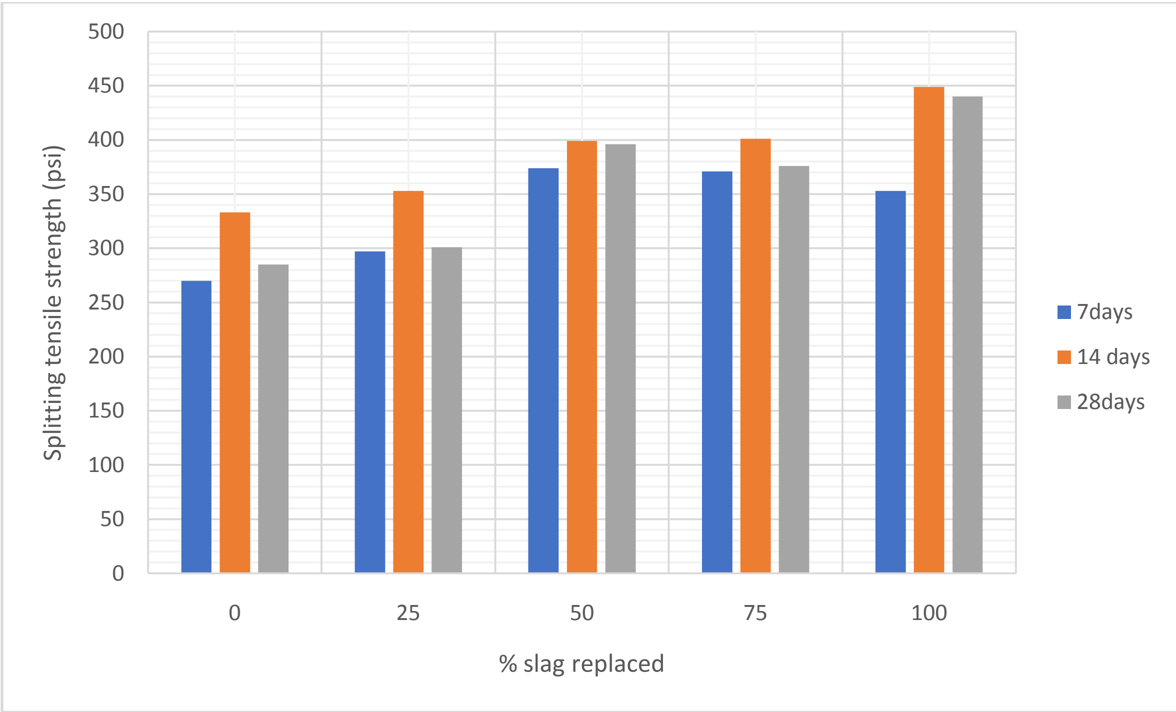


Figure 6.9 (c): Splitting tensile strength EAF coarse aggregate

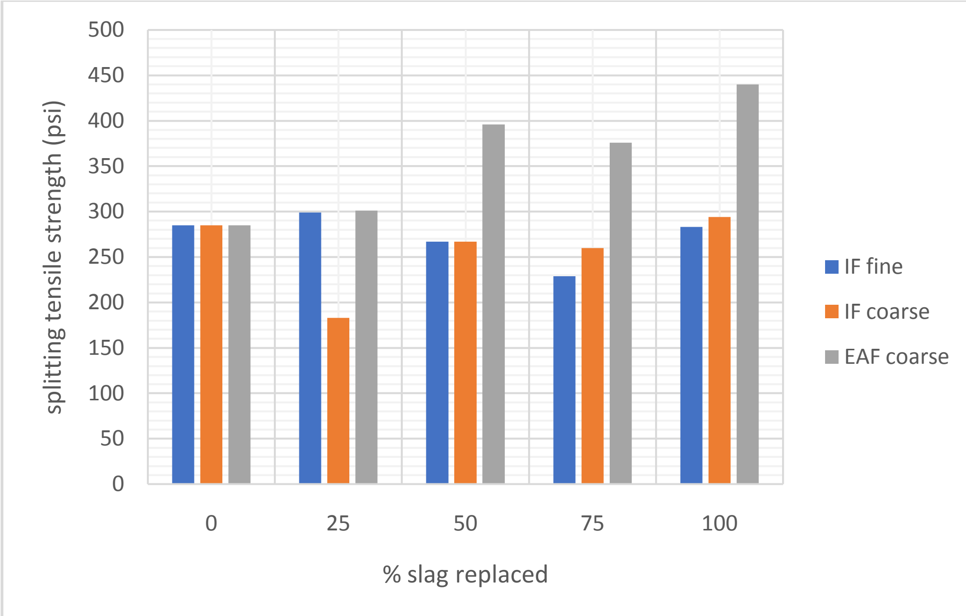


Figure 6.10: Comparison of splitting tensile strength of the concrete specimen after 28 days.

6.9 Results on Structural Bricks

These experiments were exploratory in nature. Even then encouraging results were obtained.

6.9.1 Effect of Brick forming Pressure on the Compressive Strength

The results are presented in Tables 6.7 and Table 6.8. It is evident that, with increasing pressure applied during shaping the bricks, there is a rise in the magnitude of the compressive strength in both the cases of incorporation of induction furnace slag and electric arc furnace. However, the bricks with electric arc furnace slag exhibit superior compressive strength value.

Table 6.8: Compressive strength of brick (IF)

sample no.	Pressure applied (psi)	Compressive strength (MPa)	Average compressive strength (MPa)	Average compressive strength (kg/sq.cm)
1	1000	3.14	3.78	39
2		4.41		
1	2000	5.50	5.94	61
2		6.37		
1	3000	6.66	6.83	70
2		7.00		

Table 6.9: Compressive strength of brick (EAF)

sample no.	Pressure applied (psi)	Compressive strength (MPa)	Average compressive strength (MPa)	Average compressive strength (kg/sq.cm)
1	1000	6.56	6.78	69
2		7.00		
1	2000	15.51	14.47	148
2		13.42		
1	3000	16.69	16.20	165
2		15.70		

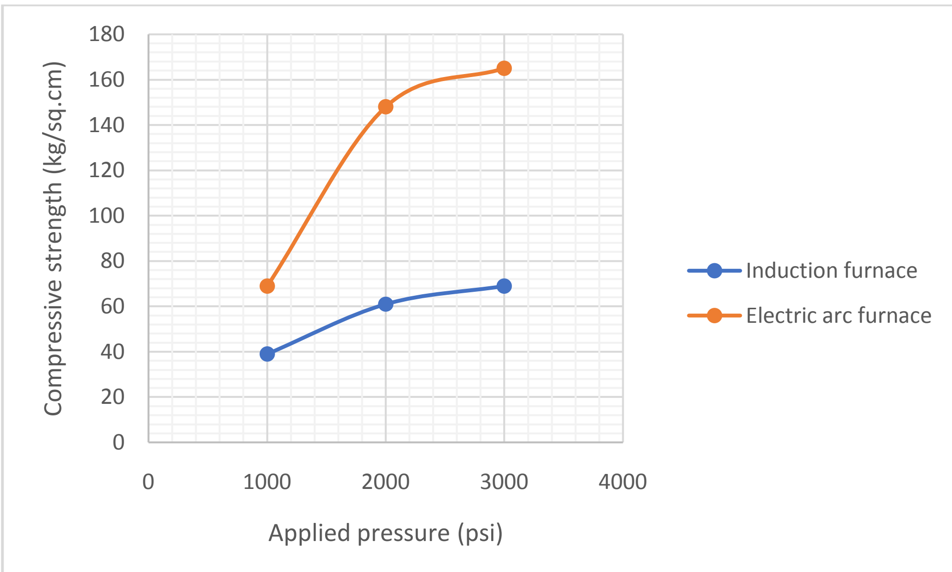


Figure 6.11: Comparison of compressive strength values of bricks formed at different forming pressures

The compressive strength of generally used burnt bricks are (i) 35kg/sq.cm for ordinary bricks, (ii) 70 kg/sq.cm for the second-class bricks, (iii) 105 kg/sq.cm for the first class bricks.

The brick sector in Bangladesh has grown rapidly in the last decade, led by continuous economic expansion since the 1990s and the subsequent construction boom. Because of the lack of stone aggregates and other alternative building materials, the clay in Bangladesh’s Ganges River delta provides abundant raw materials for bricks, which have underpinned the country’s civil construction in building, road pavement, irrigation, bridges, and other essential infrastructure, and as aggregate in concrete mix. In 2011, available market data indicate that there are 4,880 brickfields in Bangladesh, 92% of which are polluting fixed chimney kilns. The brick sector grew at an average rate of about 5.6% per year during

1995–2005, and is estimated to be currently growing at 7%–8% per annum. The available data also indicate that the brick sector in Bangladesh burns about 203 tons of coals and emits about 576 tons of CO_2 per 1 million bricks manufactured. With about 17 billion bricks produced annually, the industry's annual CO_2 emissions are estimated to be 9.8 million tons. In the capital city of Dhaka, the north Dhaka cluster of brickfields contributes about 40% of the fine particulate pollution in the city during the operating season (November to April).

The bricks under this study were not burnt bricks, they were cured bricks. The manufacture of the bricks involved no CO_2 emission and this is a definite advantage. Thus, the results obtained (70 kg/sq.cm for induction furnace slag bricks and 165 kg/sq. cm for electric arc furnace slag) so far show a possibility of using slag in the manufacture of structural bricks also. However, there are so many aspects of investigation and it is possibly too early to make a definite comment.

Chapter 7
Conclusions and Recommendations

Steel slag is an industrial waste, byproduct of steel making and refining process. More than 400 steel mills, of different categories and sizes, currently produce steel and about 250 000 tons of steelmaking slag in Bangladesh. With the progress of economy, the per capita consumption of steel, presently estimated as 25 kg, will increase leading to generation of higher volumes of slag. There is no comprehensive industry statistics on slag produced versus slag utilized in Bangladesh. In most cases landfill is the main solution for all the slag generated in Bangladesh. Therefore, improving the utilization of steel slag is a necessity to realize sustainable development in the steel sector.

This study examined the nature of slag generated in the steel plants in Bangladesh in the process of its possible utilization in some useful products primarily used in the construction sector. Steelmaking slag, both electric furnace (EAF) slag and induction furnace (IF) slag, were collected from some selected steel plants. Experiments were carried out to evaluate the effects of replacing natural aggregates (coarse and fine) by slag (EAF and IF) on concrete strength properties. A different set of experiments were carried out to examine its suitability in making structural bricks.
There was enough indication that steelmaking slag can be converted into or incorporated in building materials. Such use of slag can help manage the ever-increasing volume of slag generated in steel plants in Bangladesh and also help establish a cleaner environment in the steel sector. At the same time, this will help reduce CO_2 emission in Bangladesh.

The work done can be summarized as follows:

- During steelmaking in induction furnaces 6-8 per cent slag is generated per ton of steel produced while about 20 per cent slag is generated in EAF per ton of steel produced. This leads to an estimate that around250 000 tons of slag is generated in Bangladesh.

- A complete chemical and mineralogical analysis of slag was performed. It has been observed that slag generated in the induction furnaces in the different steel plants in Bangladesh are similar in composition and mineralogy, while the slag generated in EAF is different both in composition and in mineralogy.

- Slag produced in EAF steelmaking contains a greater amount of lime, while the slag generated in induction furnacesare almost free from lime.

- The physical and mechanical properties of the slag samples were determined and compared with those of natural aggregates.

- Possibility of using slag generated in the steel plants in Bangladesh in concrete blocks and in structural bricks were examined. The following is the findings:

  (a) Compressive strength of concrete samples replaced with IF fine slag has the highest value of 3699 psi after 28 days with 100 percent slag replaced.

  (b) Compressive strength of the concrete specimens replaced with IF coarse slag was almost the same for the replacement of slag from 25% to 100% and the highest value was 3578 psi.

  (c) In the case of EAF steel slag, the compressive strength of samples replaced with slag in varied ratios by weight shows superior numerical values compared to the concrete with no slag in it. The highest strength attained was 5850 psi.

  (d) This shows that concrete with steel slag aggregates achieves similar strength compared to normal strength concrete (3000-6000 psi).

  (e) Compressive strength of the bricks made using 70% induction furnace slag was 70 kg/sq.cm and 165 kg/sq. cm for the bricks made with 70% electric arc furnace slag. The compressive strength of generally used burnt bricks are (i) 35 kg/sq.cm for ordinary bricks, (ii) 70 kg/sq.cm for the second-class bricks, (iii) 105 kg/sq.cm for the first class bricks. Thus, the results obtained so far show a possibility of using slag in the manufacture of structural bricks also.

  It can be concluded that:

  i. Incorporation of slag (both IF and EAF slag) in concrete and in building materials is a definite possibility.
  ii. Incorporation of EAF slag showed more encouraging result.

- The leachability of slag is being tested. The results will require some more time (2 – 3 weeks from now). This result will help determine health hazards, if any, of using slag as a construction material. This will also give indications on long time behavior of its incorporation in building materials.

- Reduction in CO_2 emission due to reuse of such slag were estimated. Owing to the lack of availability of stone aggregate in Bangladesh, most of the structures are constructed with crushed bricks as coarse aggregates.The available data indicate that the brick sector in Bangladesh burns about 203 tons of coals and emits about 576 tons of CO_2 per 1 million bricks manufactured. With about 17 billion bricks produced annually, the industry's annual CO_2 emissions are estimated to be 9.8 million tons. From the present study, it can be said that use of steel slag as coarse and fine aggregate in concrete will reduce the use of natural resources/crushed bricks in Bangladesh. Moreover, the bricks made under this study were not burnt bricks, they were cured bricks. The manufacture of the bricks involved no CO_2 emission. This is a definite advantage.

Limitations of the Study

Most of the tests were conducted in laboratory environment. Field tests to examine the validity of the laboratory test results in actual application will yield more reliable data.
The tests for hardened concrete are susceptible to variation with time due to possible ageing effects. This is particularly true for EAF slag that contains CaO. Lime is hygroscopic in nature. Any indication of long time behavior of incorporation in building materials could not be ascertained.
There was a serious time constraint.

Suggestions for Future Research

A much more extensive field study on a concrete structure made with steel slag aggregates used in the mixture should be conducted and changes in mechanical properties should be investigated and correlated to laboratory results.

The two types of slag generated in the steel plants in Bangladesh showed difference in composition and mineralogy. The incorporation of these different types of slag yielded significantly different results. The following studies may be undertaken

- Addition of additives (particularly CaO) to adjust the composition of IF slag to EAF slag and its effects on the resultant properties of concrete blocks and structural bricks
- The slag from two different routes of steelmaking may be mixed and used as a single raw material for incorporation in concrete blocks and structural ricks.
- The following investigation will also be helpful for a final decision.
    - (a) Resistance of concrete with steel slag aggregates to (i) attack by sulfates and sea water.
    - (b) The behavior of steel slag aggregate concrete under corrosive environments and its fire resistance
    - (c) Compatibility of concrete with reinforcing steel.

References

ASTM C29-97 R03, Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate

ASTM C39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

ASTM C127-01, Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate

ASTM C128-01, Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate

ASTM C136, Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates

ASTM C143, Standard Test Method for Slump of Hydraulic-Cement Concrete

ASTM C150, Standard Specification for Portland Cement

ASTM C150-12, Common Reference Type I Portland Cement for use in ASTM C989-12 Slag Activity Testing

ASTM C191-08, Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle

ASTM C192, Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory

ASTM C204-11, Standard Test Methods for Fineness of Hydraulic Cement by Air-Permeability Apparatus

ASTM C496, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens

ASTM C511, Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes

Abdulaziz I. Al-Negheismish, Faisal H. Al-Sugair and Rajeh Z. Al-Zaid (June 1996) Utilization of Local Steelmaking Slag in concrete.

Caijun Shi," Steel Slag-Its Production, Processing, Characteristics and Cementitous Properties"-Journal of Materials in Civil Engineering ASCE 2004.

Donald W Lewis, (Feb 1982) "Properties and Uses of Iron and Steel Slag"-NSA Presented a Symposium.

E.Anastasiou and I. Papayianni, (2006 Springer)" Criteria for the Use of Steel Slag Aggregates in Concrete" Measuring, Monitoring and Modeling Concrete Properties.

E.Anastasiou and I. Papayianni, (2006)"Cost Effective Mixtures for Concrete Pavements "Proceedings of the Airfield and Highway pavement conference.

GEOPAVE-Material Technology- (Nov-1993) "Steel Slag Aggregates"- Technical note 9 1993.

H.Beshr, A.A.Almusallam, M.Maslehuddin-,(2003) "Effect of Coarse Aggregates Quality on the Mechanical Properties of High Strength Concrete" - Construction and Building Materials 2003.

Ibrahim M. Asi, Hisham Y.Qasrawi, and Faisal L.Shalabi.(2007) Use of steel slag aggregates in asphalt concrete mixes.

Juan M Manso, Javier J Gonzalez and Juan A Polanco, (2004) "Electric Arc Furnace Slag in Concrete". Journal of Materials in Civil Engineering ASCE Nov 2004.

M Maslehuddin, M Shameem and N U Khan, (1999) "Performance of Steel Slag Aggregates Concrete", Exploiting Wastes in Concrete --Proceedings of the International Seminar held at the University of Dundee, Scotland, UK Sept 1999.

M.Maslehuddin, Alfarabi M Sharif, M.Shameem, M.Ibrahim and M.S.Barry, (2003)"Comparison of Properties of Steel Slag and Crushed Limestone Aggregates Concrete", Construction and Building materials 2003.

National Slag Association, MF186-1 Steel slag utilization in asphalt mixes by John Emery VP, Trow Ltd. consulting engineers. Taken from Canadian Technical Asphalt Association Proceedings, 1984.

Paul Bosela, Delatte, Obratil, Ashish Fresh and Hardened Properties of Paving Concrete with steel slag aggregates (2007) Cleveland State University, submitted a paper at TRB 87th Annual Meeting of Transportation Research Board Annual Meeting at Washington D.C and also presented at ICCP 9th annual conference at San Francisco CA (2008).

P. Kumar Mehta, (1999) "Advancements in Concrete Technology. Concrete International June 1999.

Rustu S Kalyoncu, (2001) "Slag iron and Steel." US Geological Survey Minerals Yearbook 2001.

State of Ohio Department of Transportation Columbus, Ohio. Construction and Material Specifications. January 2005.

Sidney Mindess, J Francis Young and David Darwin (2003) Concrete second edition

Tepordei, Valentin V., Natural Aggregates Foundation of Americas Future, www.nationalatlas.gov/articles/geology/a_aggregates.html. Accessed July 19, 2008.

Turner Fairbank Highway Research Center and Department of Transportation and Federal Highway Administration-steel slag-material description accessed 2007.

Van Oss, H.G., Iron and Steel Slag, Mineral Commodity Summaries, U.S. Geological Survey, January 2008.

Wagaman, T and W.J.Stanley (2005), "Slag: The Ultimate Renewable Resource." Pit and Quarry, May 24, 2007.