AN INVESTIGATION ON STEEL PLANT SOLID WASTES' GEOTECHNICAL PROPERTIES IN FOÇA REGION

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by

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We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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The effective utilization of waste materials has gained importance in the world, recently. Parallel to the applications encountered in other countries, intensive efforts have also been made in Turkey for this subject.

Foça region is one of the industrial places of Turkey that there is a great solid waste potential resulting from steel plants established here. It is intended to determine the geotechnical properties of these wastes and to investigate the possible uses of these materials for geotechnical purposes. This study is expected to lead the investigators that will be interested in this subject.

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ABSTRACT

Recently, due to rapidly increasing rate of industrialization, large amount of waste has been resulted. For this reason, research and development efforts have been directed towards the effective utilization of these materials in both developed and developing countries.

Parallel to the other countries, the importance of this subject has also been taken into consideration in Turkey. Intensive investigations on this subject have been carried out during the past decade.

Steel plants located in Foça region, which is one of the industrial areas in Turkey, possess considerable solid waste potential. The aim of this study has been to determine the geotechnical properties of these solid wastes and to investigate their possible use for geotechnical purposes.

As a result of the tests carried out in the content of this study, the subject matter solid wastes are determined to be proper for use in various geotechnical applications. This study is expected to be an initial step for future studies.

ÖZET

Son yıllarda, hızla artan sanayileşme nedeniyle çok miktarda atık oluşmaktadır. Bu nedenle, gelişmiş ve gelişmekte olan ülkelerde bu atıkların etkin bir şekilde kullanımı konusu da araştırma-geliştirme faaliyetleri kapsamına girmiştir.

Diğer ülkelere paralel olarak bu konunun önemi Türkiye'de de dikkate alınmıştır. Bu konuda son on yıl içinde yoğun araştırmalar yürütülmektedir.

Türkiye'nin endüstriyel alanlarından biri olan Foça yöresindeki çelik üretim fabrikaları önemli ölçüde katı atık potansiyeli içermektedir. Bu çalışmanın amacı, bu katı atıkların geoteknik özeliklerinin belirlenmesi ve geoteknik amaçlı muhtemel kullanım olanaklarının araştırılması olarak saptanmıştır.

Bu çalışma kapsamında sürdürülen deneyler sonucunda, söz konusu katı atıkların çeşitli geoteknik uygulamalarda kullanımının mümkün olduğu belirlenmiştir. Bu çalışmanın gelecekte bu konuda yapılacak çalışmalara bir başlangıç olacağı umulmaktadır.

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CHAPTER ONE
INTRODUCTION

1.1 Environmental Geotechnology

The rapidly increasing rate of industrialization in developing countries of the world may cause the change of the ecological balance of the planet and endanger the health of the humanity. Therefore, scientists need to understand, detect and identify the potential environmental problems, to propose rational solutions to them, to develop the current regulations and to make new arrangements which will guide the people for living safely. The complexity of the encountered problems, the lack of time and resources, and the available unsafe practices have forced scientists, engineers, lawyers and regulators for better cooperation and collaboration (Usmen & Acar, 1992).

For this reason, firstly Soil Mechanics & Foundation Engineering branch was formed by Civil Engineering, Geology, Mechanics, Hydraulics and Mathematics branches in 1950's. In the following years (especially in 1980's), Geotechnical Engineering which consists of Soil Mechanics & Foundation Engineering was developed. Besides, Environmental Science and Engineering was constituted by Civil Engineering, Chemistry, Statistics, Biology and Sanitary Engineering branches in the same decade. It was followed by the formation of Environmental Geotechnology branch in 1990's with supporting contribution of Geotechnical Engineering and Environmental Engineering scientists (Fang, 1987).

Environmental Geotechnology is an interdisciplinary science branch which covers the behavior of soil and rock interacted with various environmental cycles, problematic soil regions, sanitary landfills and waste problems. It has grown rapidly since the First International Symposium organized in 1986 at Lehigh University. Various international, national and regional conferences and symposia on this subject have been promoted

during between 1986 and 1997. Theoretical and practical concepts have been developed, and in many universities environmental geotechnology is suggested as a main course (Fang, 1986 & 1992).

1.2 Iron and Steel Industry and The Environment

The iron and steel industry has always had considerable impact on the environment, because of not only its manufacturing enterprise, but also its large production potential and the effect of their products on human lifestyle. The iron and steel industry globally produced 747 million tonnes of steel in 1979 (Holschuh, 1980). It is estimated that in excess of 900 million tonnes of steel are produced and also generated considerable tonnages of atmospheric, liquid and solid wastes each year. The steel industry is faced with four main environmental problems. These are air pollution, water pollution, waste disposal and noise pollution.

In major industrialized countries, increasingly stricter administrative rules and regulations have been enforced to ensure the disposal of industrial wastes not to be destructive to the environment. In the 15 July 1975 Directive, European Economic Community provided "Member states take the necessary measures to ensure that waste materials are disposed of without endangering human health or the environment." (Philipp, Endell, Raguin & Dechelette, 1986, p. 9).

After the national and local government authorities in most countries had arranged the environmental situation, it has led to make regulations to enforce control of air, water and noise pollution in iron and steel industry. The development of the environmental movement in iron and steel industry began with the establishment of the International Iron and Steel Institute (IISI) in Brussels (1967). The Institute moved for a better quality of life in industrial regions and made environmental regulations. IISI then organized the committee on Environmental Affairs. The committee's aim was to fasten the exchange of information and experiences among the member countries. On the other hand, the committee helped IISI members to understand the current problems and to facilitate the installation of efficient pollution abatement equipment in these countries. In February 1974, the Symposium on Environmental Control in the Steel Industry was held in Tokyo. This was the first

symposium on an international basis. A second symposium on the same subject was held in June 1979, in Chicago. Steel industry pollution problems were presented in this symposium. During the years between the two symposia, the technical problems of pollution abatement had largely been solved. In the following years, IISI has improved the studies about the application of environmental regulations that prevent air, water and noise pollution and has maintained communication with the various UN agencies such as WHO, UNEP and ILO (Holschuh, 1980).

The European Economic Committee's environmental policy has three main purposes:

1. Prevention of the waste production.
2. Safe elimination of nonrecoverable residues.
3. Recycling and reuse of wastes.

In this manner, some attempts included in investigations about recycling of scrap metal, reducing heat and noise pollution in plants, reuse and recycling of solid wastes have been made in iron and steel industry.

In this thesis, some introductory studies on the possible use of steel plants solid wastes for geotechnical purpose have been made. Thus, an investigation program has been planned to determine:

- The waste potential of steel plants in Foça (İzmir) region.
- The physical and chemical properties of the selected pilot steel plant's solid wastes.
- The geotechnical properties of these wastes.

A general knowledge on steel production methods are presented in Chapter Two. A brief review of the iron and steel plants' solid wastes is given in Chapter Three. The waste potential of steel plants in Foça (İzmir) region and the investigation program laboratory tests on the materials used together with the obtained results in Chapter Four. Results expressed in graphical form are also included in this chapter. Discussion of the results obtained in this study takes place in Conclusions.

CHAPTER TWO
ELECTRIC FURNACE STEELMAKING

2.1 Historical Development of Steel Production Methods

The first modern process for steelmaking was the pneumatic or Bessemer process (1856). This process involved blowing air through a bath of molten pig iron contained in a bottom blown vessel lined with acid (siliceous) refractories. It was developed by Henry Bessemer and William Kelly, independently. This process was the first large scale method which pig iron could be refined and converted to molten steel rapidly and cheaply. Kelly was unable to apply his invention. Bessemer developed the process and it came to be known as the acid Bessemer process. Since the process converted pig iron to steel, the vessel in which the operation was carried out came to be known as a converter. In this process, sufficient heat was generated in the converter by the chemical oxidation of silicon, manganese and carbon and simple blowing of cold air through molten pig iron without the need for an external source of heat. From 1870 to 1910, this process was the world's steel supply. Although, annual Bessemer steel production in the United States was approximately 55% of total steel production of the country in 1871, raw steel was no longer being produced by Bessemer process after 1910.

Following the invention of the Bessemer (pneumatic) process, the regenerative type furnace, now known as the open-hearth furnace, became adapted to steelmaking. Open-hearth furnaces were open for visual inspection of the hearth after every heat of steel had been tapped from the furnace. Karl Wilhelm Siemens invented the regenerative principle in 1850's. Great saving of fuel and producing high temperatures in furnaces could be obtained by this principle. The lack of refractory materials capable of withstanding high temperatures and complexity of chemical reactions in the process retarded the development of the process quickly. A successful open-hearth furnace was designed and operated in 1870. In the

following years, silica refractories were manufactured and large scale furnaces were designed. The Bessemer process could produce steel cheaply, but it was restricted to ores having limited phosphorus content and its scrap usage was also limited. The open-hearth process was not subjected such restrictions, so the annual production of steel by this process increased rapidly, and passed the annual production by the Bessemer process in 1908 (Lankford, Samways, Craven & McGannon, 1985).

Open-hearth furnace provided some advantages. These are:

1. Any available gaseous or liquid fuel, and even pulverized coal can be used. Changing from one type of fuel to another is possible without interrupting the production. Selection of fuel is governed by taking into consideration availability, convenience and price.
2. Metallic materials for the furnace charge varies in a wide range.
3. All compositions of alloy and carbon steels, except the high-chromium nickel and heat resisting steels, have been melted in this process.
4. Any lost of refractory material from the hearth could be replaced promptly.

Open-hearth process was used efficiently up to 1950's. However, raw steel production by using this process has decreased dramatically after Basic oxygen process was developed. Total raw steel production by open-hearth furnace in the United States fell about 10% in 1982 (Figure 2.1).

The open-hearth process was supplanted by basic oxygen steelmaking process which consists of blowing high purity oxygen onto the surface of molten pig iron by a water cooled vertical pipe or lance inserted through the mouth of the vessel. Blowing with oxygen was investigated by R. Durrer, C.V. Schwarz and Hellbrugge. Plants utilized top blowing of oxygen firstly in 1952-53. The top blown oxygen process is now known as the basic oxygen steelmaking process. In this process, the oxidation of silicon, carbon, manganese, phosphorus and iron provide energy required to melting the scrap, forming the slag, increasing the temperature of the molten metal to desired value.

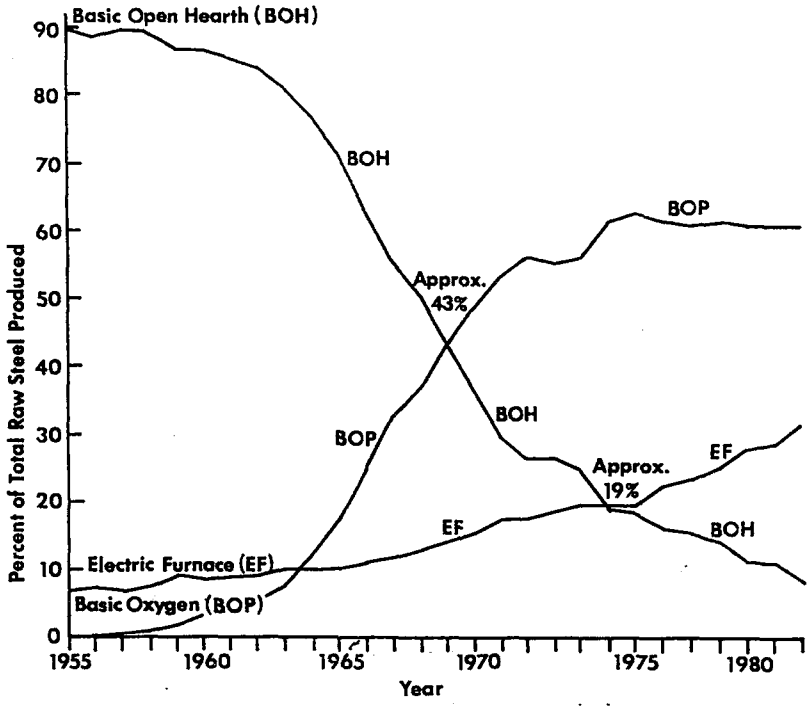

Figure 2.1 Proportions of the Total Annual Raw Steel Production in the United States (Lankford et al., 1985, p.34)

Both open-hearth process and basic oxygen process produce carbon and alloy steels having the same general gradation. Basic oxygen process has been used to produce stainless steels which cannot be made in open-hearth process. Also, basic oxygen process has the same speed as did the Bessemer process, with none of the chemical limitations latter. Basic oxygen process does not possess the flexibility of the open-hearth or electric arc furnace processes with regard to the amount of scrap charged and melted.

In the basic oxygen process, preheating of the scrap is made either outside the furnace before charging or inside the furnace before adding molten pig iron. Oxygen blowing operation through lances increase the overall heat supply and permit the usage of larger amounts of scrap. The open-hearth charge usually contains 45-55% of scrap. The speed of reactions in the basic oxygen process creates more critical problems than that are in slower open-hearth and electric arc furnace processes.

Basic oxygen process has been used since 1950's increasingly and total raw steel production by this process in the United States reached about 60% in 1982 (Figure 2.1).

In the scope of this thesis, electric furnace steelmaking process has been used in the investigated steel plants. Therefore, a brief explanation has been made about this process.

Electric arc furnaces began to operations with the invention of the carbon arc by Humphrey Davy in 1800, but their practical application was made by William Siemens who constructed, operated and patented furnaces in 1878. Alternating-current direct arc furnaces are generally used for steelmaking. In these furnaces, current passes from one electrode down through an arc to the metal charge, and then from the charge up through an arc to another electrode. Although single-, two-, and three-phase currents can be used for steelmaking, furnaces working with three-phase current are used almost exclusively.

The first electric furnace used for steelmaking was a Heroult direct arc furnace developed by Dr. Paul Heroult and began to operations in 1906. In 1800's, the availability of electric power was limited and its cost was high, also carbon electrodes for carrying sufficient current with required quality had not been developed. Thus, the development of an electric melting furnace awaited the improvement of the electric power industry and advances in carbon electrodes. When the first electric arc furnaces were installed, large amounts of electric power were not available. Later, as more electric power became available, cold melting became feasible. Then, as basic oxygen process developed, the utilization of heavy scrap increased the trend to the arc furnace steelmaking because of the reduced consumption of heavy scrap in basic oxygen process. The electric arc furnace charge usually consists entirely of scrap. Other reasons for preferring electric arc furnaces included in the increasing demand for alloy steels for new applications that previously used carbon steels. The electric arc furnace steelmaking then became a favourite process for producing high-alloy, stainless, bearing and other high quality steels. Its field was enlarged to include the production of low-alloy steels later (Lankford et al., 1985).

Electric arc furnaces possess the advantages of relatively low investment cost, and the ability to:

1. Produce steels of a wide range of steel compositions (Carbon, alloy and stainless steels)
2. Take advantage of changing costs of scrap.
3. Produce quality steels without source of hot metal.

The production of electric arc furnace steels has shown the increasing trend between 1936 and 1982. Total tonnage of raw steel production by electric arc furnaces in the United States reached about 30% in 1982 (Figure 2.1).

Electric arc furnace steelmaking is selected as more economical steel production method than the others when:

1. Carbon and low-alloy steel production requirements are insufficient to justify using the combination of a blast furnace and a basic oxygen furnace.
2. Steel plants are located in industrial areas of high scrap availability and low-cost electric power, but at a distance from natural sources. (coke, limestone and high-grade iron ore)
3. Molten steel must be supplied within the limited time.

2.2 Metallurgical Processes in Three-Phase Electric Arc Furnaces

Electric arc furnaces are charged with segregated and selected scrap. Electric arc furnace steelmaking process entails the direct melting of scrap using an electric arc as the primary heat source. There are three main categories of scrap:

1. Home or internal arising scrap: Scrap that generates from the circulating reject materials which are involuntary by-products of casting, rolling mill, and other steel manufacturing processes (e.g. Ingot moulds, mill rolls, scrap sheets, etc.).
2. Prompt industrial scrap: Scrap that results from normal machining, stamping, and fabricating operations in the production of materials made from steel.
3. Obsolete or capital scrap: Scrap that finished its working life, and was discarded (Bartlett, 1990).

It is necessary to separate the available scrap for several reasons. These are:

1. Conservation of the valuable alloy content of steel scrap.
2. Economical usage of virgin alloys.
3. To ensure that only the elements desired in the finished steel are introduced in making the steel. Non-oxidizable elements (i. e. nickel and copper) should not be permitted to enter the charge.

Then charging buckets are loaded by scrap at ground level and moved by an overhead crane to the furnace level. It usually takes three buckets of scrap to fill the furnace. These buckets are charged into the furnace from the furnace level. Top charging has the advantage of speed, because the entire charge is quickly placed in the furnace by drop-bottom buckets.

The melting period is the most expensive period, since power and electrode consumption are at the maximum rate during this period. The three-phase electrodes melt the portion of scrap beginning from the surface and bore through the scrap. Heating of the charge material is continued until it becomes molten metal (Figure 2.2).

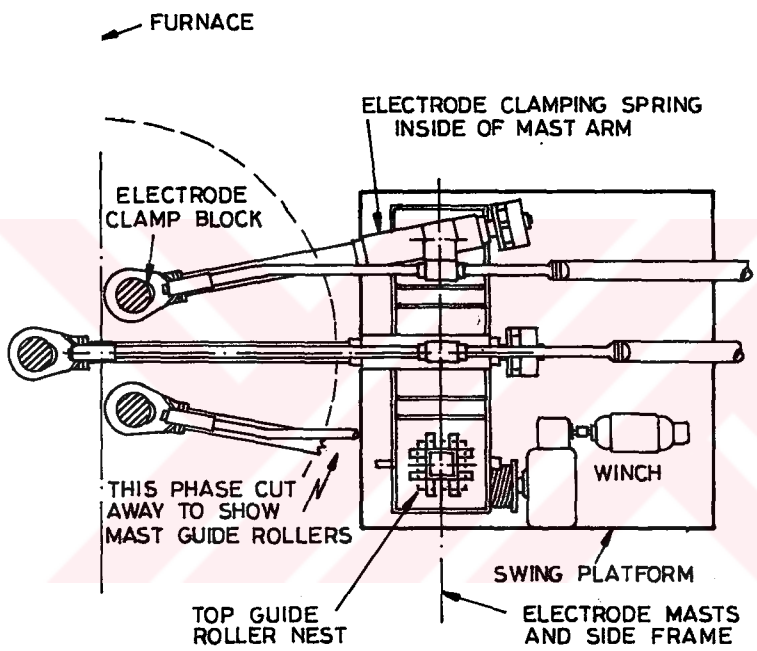

Figure 2.2 Schematic Arrangement of the Electrodes and Related Units for an Arc Furnace (Lankford et al., 1985,p.649)

Oxy-fuel burners preheats the scrap charge in the furnace at the same time. The excess carbon in molten metal is removed with oxygen injection (oxidizing period). Oxygen usage for rapid decarburization of the molten bath has decreased power consumption and the amount of time required to produce a heat of steel.

After the melting period, the electrodes are raised high enough, the top hole is opened, the furnace is tilted by a mechanism and the molten steel is drained from the furnace into the ladle. The slag is tapped from the downhole (Electric arc furnace slag). The ladle is held by

a teeming crane during tapping to minimize the exposure of the stream to air and reduce the abrasion of ladle refractories.

Then, the steel is refined by a ladle metallurgy treatment to remove sulphur and oxygen from the steel. This period is called as the composition and temperature adjustment period. Ladle metallurgy is a secondary step of the steelmaking process performed in a ladle after the initial refining process in an electric arc furnace is completed. The purpose of this step is to produce "clean" steel which satisfies stringent requirements of surface, internal and microcleanliness quality and mechanical properties. As the demand for high quality steel increased, ladle metallurgy became a routine step in the production of steel.

Initially, steelmakers reluctantly accepted the ladle metallurgy process. However, they realized that ladle metallurgy got some advantages, especially in the production of high quality steel. Additionally, it was found that control over many processing conditions -even for high quality steel production- should be made, including:

1. Increasing the temperature.
2. Deoxidation.
3. Decarburization (Especially in the production of low carbon steel).
4. Additional adjustment for chemical composition.
5. Increasing production rates with decreasing the process time.

(Lankford et al., 1985)

Steelmaking process are adopted to achieve various objectives, including:

1. Control of gases: Degassing (Decreasing the concentration of oxygen and hydrogen in steel).
2. Low sulphur contents.
3. Microcleanliness (Removal of undesirable nonmetallics-oxides and sulphates).
4. Inclusion morphology (Changing the composition and / or shape of steel).
5. Mechanical properties (Transverse properties, toughness, ductility of plates).

(Lankford et al., 1985).

Effective utilization of secondary steelmaking process is provided with achieving some prerequisites. These are:

1. Temperature and chemical composition of steel must have certain properties in the electric arc furnace and maintain during tapping into the ladle.
2. The transfer of electric arc furnace slag into the ladle must be minimized during tapping to improve the effectiveness of the ladle process. Electric arc furnace slag in the ladle affects the deoxidation of steel, since part of the deoxidizing elements (i. e. silicon and aluminum) are used up in deoxidizing the slag.
3. Accurate and precise assessment of temperature, chemical composition and quantity of steel in the ladle are very important.
4. Usage of higher quality refractories contribute to achieve the best results from ladle process (Lankford et al., 1985).

After the ladle process is completed, molten steel is tapped from the downhole to the tundishes. The molten steel is cut into the required shape and transferred to the cooling molds. The slag accumulated on the surface is tapped from an another hole on the top. The slag taken after the ladle process is called electric arc furnace ladle refining slag.

CHAPTER THREE
SOLID WASTES OF IRON & STEEL PLANTS

3.1 General Classification of Wastes

Waste materials can be classified in three major categories : Industrial, mineral and domestic wastes. A brief classification is given in Table 3.1.

Table 3.1 Classification of Waste Materials (Miller & Collins, 1976, p. 30)

WASTE MATERIALS		
Industrial Wastes	Mineral Wastes	Domestic Wastes
a. Ceramics Industry	Authracite Coal Refuse	Building Rubble
Brick Plant Rejects	Bituminous Coal Refuse	Discarded Battery Casings
Ceramic Tile Waste	Chrysotile or Asbestos Tailings	Incinerator Residue
Clay Pipe Waste	Copper Tailings	Plastic Waste
Pottery Waste	Dredge Spoil	Pyrolysis Residue
b. Chemical Processing Industry	Feldspar Tailings	Reclaimed Paving Material
Alumina Red and Brown Muds	Gold Mining Waste	Rubber Tires
Phosphate Slimes	Iron ore Tailings	Sewage Sludge
Phosphogypsum	Lead Tailings	Waste Glass
Sulfate and sulfite sludges	Nickel Tailings	
c. Electrical Power Industry	Phosphate Slag	
Fly Ash	Slate Mining Waste	
Bottom Ash	Taconite Tailings	
Boiler Slag	Zinc Tailings	
Scrubber Sludge	Zinc Smelter Waste	
d. Iron and Steel Industry		
Iron Blast Furnace Slag		
Steelmaking Slags		
Foundry Waste Products		

As shown in Table 3.1, waste materials are classified mainly as industrial, mineral, and domestic wastes depending upon their origin. By-products obtained from ceramics industry, chemical processing industry, electrical power industry and iron steel industry are main components of the industrial wastes. In progressing countries, new industrial branches are developed and the wastes produced by them are added to the available ones. Nuclear wastes, radioactive wastes, power plant wastes can be given as examples to these wastes. Mineral originated wastes are generally obtained from ore processing facilities and mineral removal units. Domestic wastes include non recoverable materials, toxic and hazardous wastes and polymer originated materials. Insufficiency of natural resources in the world caused scientists think whether these waste materials can be used instead of the natural resources or not. Iron and steel industry wastes are taken into consideration in this manner, and research & development activities have been developed by progressing countries. İn the following sections; fundamental properties and potential applications of iron and steel wastes are given in detail (Miller & Collins, 1976).

3.2 Iron & Steel Industry Wastes

The main metallurgical processes in the iron and steel industry have different types of solid wastes. These wastes all have common metallurgical functions, however they vary widely in chemical and physical properties. Major waste products from the steel industry are iron blast furnace slag, steelmaking slags, fume and dusts from the steel production facilities and foundry wastes.

Slag is the common name of the fusible material formed by the chemical reaction of a flux with the impurities oxidized during the refining of a metal, with the ash from a fuel, or with the gangue of an ore. The compounds in the slag are formed by the neutralization of basic and acid oxides with the chemical reactions at ordinary temperatures. Impurities are separated from molten metal, accumulated on the surface of the metal and removed from the furnaces in both iron- and steelmaking processes. Slags also serve as a heat insulator for molten iron and steel, especially when the metal is being held in ladles.

In both iron- and steelmaking processes, slags are in direct contact with the molten metal and chemical reactions readily occur between them. Therefore, chemical composition of the

molten metal is controlled partially by the chemical composition of the slag. In steelmaking processes, the slag is the primary means by when phosphorus and sulphur are removed. Steelmaking slags, with their high iron and manganese contents, are frequently used as blast furnace burden. In this way, most of the useful metallics in the slag are recovered. The amount of steelmaking slag that can be recycled into the blast furnace burden is limited by the phosphorus content of the slag. If too much phosphorus is available in the slag, the phosphorus content of the molten metal could exceed the specifications for the product (Lankford et al., 1985).

General properties and possible uses of blast furnace slag, steelmaking slags and arc furnace dust are given below.

3.2.1 Blast Furnace Slag

Blast furnace slag is defined as "The nonmetallic product consisting essentially of silicates and aluminasilicates of calcium and other bases, that is developed in a molten condition simultaneously with iron in a blast furnace." (ASTM C 125).

Blast furnace slag is a by-product of ironmaking process. In this process, the blast furnace is charged with iron-bearing materials (iron ore, sinter, pellets), fluxing stone (limestone, dolomite), and fuel (coke). This layer of raw materials is known as blast furnace burden. After the reduction of iron from the iron ore at a temperature of 1600^{o}C, iron blast furnace slag results from the fusion of fluxing stone with coke ash. Silica and alumina residues are separated from the molten iron. Thus, a surface layer of molten slag which floats on top of the heavier molten iron is formed. The blast furnace operation is a continuous process with the carefully controlled raw materials being fed in burden and the molten iron and molten slag being drawn off at regular intervals.

The major contents of blast furnace slag are silica and alumina originating with iron ore, and lime and magnesia originating with the flux. They comprise 95% or more of the whole. Chemical compositions of most blast furnace slags fall within the ranges shown in Table 3.2 (Elverici, 1966, Apaydın, 1974, & Lankford et. al. , 1985)

Table 3.2 Chemical Composition Ranges of Blast Furnace Slags

Constituent	Ranges (%)
Silica (SiO_2)	30-40
Alumina (Al_2O_3)	8-18
Lime (CaO)	30-45
Magnesia (MgO)	5-15
Sulphur (S)	1-2
Iron Oxide (Fe_2O_3)	0.1-1
Manganous Oxide (MnO)	0.2-2

Depending upon the manner in which the molten slag is cooled and solidified, four types of blast furnace slag can be produced: Air-cooled, expanded or foamed, granulated and pelletized blast furnace slags.

1) Air-Cooled Slag : The molten slag is permitted to run into a pit adjacent to the furnace or transported in large ladles and poured into a pit at some distance away from the furnace. Solidification takes place under the ambient conditions. Cooling may be accelerated by spraying water on the solidified mass. Solidified slag has a vesicular structure with many nonconnected cells. Air-cooled slag can be crushed to angular, roughly cubical pieces.

The bulk specific gravity of air-cooled slag falls between 2.0 and 2.5. Smaller slags have higher specific gravities, since large pores cannot exist in them. The unit weight changes with the method of measuring; size, grading and bulk specific gravity of the slag. Air-cooled slag has a lower unit weight than most natural aggregates (1.12 - 1.36 t/m^3), also it is highly resistant to weathering. Little or no adverse effect has been found against freezing / thawing and wetting / drying. High temperatures have very little effect on slag. Air-cooled slag fines are nonplastic (Emery, 1982 & Lankford et al., 1985).

2) Expanded Slag : Treatment of molten slag with controlled quantities of water accelerates the solidification and increases the vesicular nature of the slag. Expanded slag is a lightweight product. Its unit weight ranges between 0.8 - 1.04 t/m^3. The solidified slag is crushed and screened for use as a lightweight aggregate. It has some durability characteristics as air-cooled slag (Emery, 1982 & Lankford et al., 1985).

3) Granulated Slag : Molten blast furnace slag is quenched quickly in water to form a product which has a vitrified (glassy) state. It is the most rapid cooling process and little or no crystallization occurs. Granulated slag is crushed, screened or pulverized for various applications, besides it has excellent hydraulic properties. When it is compacted in the presence of moisture, it sets up similar to cement (Emery, 1982).

4) Pelletized Slag : Molten blast furnace slag is soldified by water and quenched in air in conjunction with a spinning drum. Pelletizing process is a new process, it has been applied for twenty years. In this process, a controlled slag flow (up to 3 tonnes/min) is expanded under water sprays on a vibrating feed plate, and then passed over the internally cooled spinning drum (280 rpm) where the eight concave throwing vanes break up the slag and hurl it into the air for a sufficient time that the surface tension forms pellets. More crystalline pellets for aggregate applications, or more vitrified pellets (with increasing drum speed and using more cooling water) for cementitous applications can be produced. Other benefits of pelletizing are immediate pellet removal, minimized space requirements, low installation costs and water conservation (Emery, 1982 & Lankford et al., 1985).

3.2.2 Specific Applications of Blast Furnace Slag

Blast furnace slag is used succesfully for many commercial purposes. Principle uses of blast furnace slag is summarized in Table 3.3.

Totally 13.4 million tonnes of blast furnace slag (valued of about $65 million) were available as reported by the United States Bureau of Mines. Annually, 120 million tonnes of globally blast furnace slag production (about 23% of total iron production) was reported in 1980 (Emery, 1982).

Table 3.3 Principle Uses of Blast Furnace Slag (Lankford et al., 1985, p.336)

Air-Cooled Slag	Expanded Slag
Railroad ballast	Aggregate in lightweight concrete and lightweight-concrete products
Aggregate in concrete and concrete products	Aggregate in lightweight fill and embankment
Aggregate in bituminous-paving applications	Manufacture of portland cement
Aggregate in bases and subbases	Thermal-insulation fill
Aggregate in surface courses, shoulders and berms	
Slope protection	
Anti-skid material	**Granulated Slag**
Manufacture of portland cement	Aggregate in lightweight concrete and lightweight-concrete products
Porous backfill and underdrains	Aggregate in bases and subbases
Embankments and fills	Aggregate in fill and embankment
Sewage trickle-filtre media	Manufacture of portland cement
Roofing granules	Manufacture of slag cement
Mineral wool	Manufacture of portland blast furnace slag cement
Glass sand	Soil conditioner

Typical ferrous slag production statistics for several countries show a trend in Europe towards more granulation (for cementitious applications) than in North America where air-cooling (for aggregate applications) currently predominates. However, pelletizing and granulating applications are growing as slag cement production (Emery, 1982).

Air-cooled slag has been used mainly as an aggregate. It is preferred material where high strength, durability, lightweight and economy are important factors.The characteristic rough surface and angular shape of slag particles, provide them to be hydrophobic in nature and makes them suitable for bituminous constructions. Besides, chemical bonds established between the slag and cement mortar indicate that many structures constructed with air-cooled slag concrete have given excellent performence. Bituminous and concrete surfaces constructed with air-cooled slags exhibit good skid resistance under wet or dry conditions. Air-cooled slag also has proved of value as a filter material (Especially in northen states where filter medium is subjected to freezing / thawing and wetting / drying actions).

Air-cooled slag's low compacted bulk density (1.20-1.45 t/m^3) reduces dead load, lateral pressures and transportation costs on volumetric basis. High stability and friction angle (approximately 45°), ability to stabilize soft soils, usability in almost any weather conditions,

durability with good resistance to weathering, free draining and being non-corrosive to steel and concrete, make it attractive for civil engineering purposes.

Expanded slag is used as aggregate in the manufacture of lightweight concrete for structural purposes. Structural lightweight concrete made with expanded slag shows high strength, low unit weight, durability, low heat transmission, low shrinkage and is free from alkali reactivity. Expanded slag concrete is excellent for precast and prestressed construction materials because of its light weight.

Expanded slag is used for embankments of all types, since it compacts easily and has cementing action along with relatively high permeability. It is valuable as a fill material for embankments over weak soil layers by minimizing the dead load and providing cementitious strength.

Expanded slag usage as a raw material in portland cement manufacture has increased significantly. It is used as the insulating blanket under pavements to reduce frost susceptibility, especially in Sweden and Finland (Lankford et al., 1985).

Granulated slag is used mainly in the manufacture of cement due to its vitrified (glassy) state. Since granulated slags have excellent cementitious properties, the bearing capacity increases with time like pozzolanic base. Large quantities of granulated slag have been used in manufacture of portland cement. Slag cement (ASTM C 595) is made by intergrinding portland cement clinker with granulated slag, or separately grinding granulated slag and blending it with portland cement. Concrete made from slag cement is very workable and resistant to sulphate. It has a low slump loss and a low heat of hydration.

Granulated slag, which is light in weight and highly permeable, is used for ideal backfill and foundation fill material. It is also used as a soil conditioner.

Pelletized slag has the same characteristics of expanded and granulated slags. Therefore, it is used for slag cement production and as a lightweight aggregate.

3.2.3 Steelmaking Slags:

The chemical composition of steelmaking slags varies depending upon the type of steelmaking process in which they originate. Constituents of steelmaking slag types (basic oxygen, open hearth and electric arc furnace steelmaking slags) fall within the ranges shown in Table 3.4 (Apaydın, 1974, Emery, 1982, Lankford et al., 1985).

Table 3.4 Chemical Composition Ranges of Steelmaking Slags

Constituent	Ranges (%)			
	Open-Hearth Slag	Basic Oxygen Slag	EAF Slag	EAF Ladle Refining Slag
Silica (SiO_2)	12-20	13-20	15-27	20-30
Alumina (Al_2O_3)	1-5	1-5	8-12	5-10
Lime (CaO)	20-30	35-45	40-50	45-55
Magnesia (MgO)	7-15	5-10	1-5	10-15
Manganous Oxide (MnO)	8-12	7-12	4-6	1-2
Iron Oxide (Fe_2O_3)	20-30	15-25	15-20	(Fe_2O_3+MnO)

The major chemical components of steelmaking slags are lime, silicates, magnesia and iron compounds as given in Table 3.4.

Three points must be emphasized in considering steel slags:

1. Large variations can be obtained in steel slags, even for the same plant and furnace.
2. The economical value of steel slag for recycling to blast furnace burden and other applications.
3. A management strategy must be developed as for all by-products.

Steelmaking slags are generally suitable for recycling to blast furnace burden. Chemical composition, phosphorus and zinc content is critical in determining the amount that is

recycled. An additional benefit is a reduction in energy costs compared to a flux charge, because the lime and magnesia are in precalcined form in steelmaking slags.

The United States Bureau of Mines reported that 4.3 million tonnes (valued at $14.6 million) of steelmaking slag were used in 1982. Besides, approximately 53 million tonnes of steelmaking slag (based on a generation of 18% of steel production and 60% recycled to blast furnace burden) were producted globally (Emery, 1982).

Steel slags have high bulk density (in excess of 2.4 t/m^3) and potential expansive nature (Volume changes of up to 10%) while blast furnace slags have a relatively low bulk density and are stable. In addition, steelmaking slags have high specific gravity of 3.2 to 3.5 compared to 2.2 to 2.5 for blast furnace slags (Ahmed & Lowell, 1992).

The mineral composition of steel slags is extremely different from blast furnace slags where calsium and magnesium oxides are always combined in silicate and aluminasilicate minerals. However, these oxides are not completely combined in steel slags. The hydration of unslaked lime (free CaO) and magnesium oxide (MgO) in contact with water causes the expansive nature of steel slags. The unslaked lime hydrates rapidly in a few weeks and large volume changes can be observed during this period. Magnesium oxide hydrates more slowly, so long term expansion which may take several years can be observed (Emery, 1982).

There is a large amount of steel slag used for applications such as bases, fills or other construction purposes. These slags should be checked for potential expansion for such applications. Since aging in large dumps for long term does not guarantee the elimination of expansive behavior. However, there are many applications where expansion is tolerable, has been controlled by suitable aging. But, steel slags shouldn't be used in portland cement concretes since expansion may result in rapid destruction of concrete.

While the main uses of available steel slags continue to be ballast material and in pavement bases, shoulders and fills, its favour usage in asphalt mixes have been developed. Steel slags show excellent skid resistance in surface course bituminous-concrete mixes and have been used in asphaltic concrete mixes since 1969. There has been no problems with the

quality and durability of steel slag asphaltic concrete pavements. Pavement trials using a blend of air-cooled blast furnace slag (coarser portion) and steel slag (finer portion) in asphaltic concrete surface indicate a good performance. Also, the high unit weight and interlocking properties are good features for using steel slag as railroad ballast material.

Well graded and angular material that is relatively free of metallics is obtained with processing of steel slags. Removing the steel from steelmaking slags is highly desirable, since this is very time consuming affair. Processed steelmaking slag has still high ranges of iron, lime and manganese so that it is possible to return of especially the large ones to blast furnace burden. However, there are still many operations where most of the slags cannot be returned to blast furnace burden for several reasons:

1. Steel production may involve additions that prevent full or partial return.
2. Equipment is not available for return.
3. Economical situation is not favorable.
4. The operation is not integrated with blast furnaces (Lankford et al., 1985).

3.2.4 Electric Arc Furnace Dust:

Electric arc furnace dust (EAF dust) is a by-product of electric arc steelmaking process. During the scrap charge and melting period in electric arc furnaces, dust existed in scrap surface is collected by electrostatic precipitators used for air-cleaning of furnace.

EAF dust contains appreciable amounts of zinc (typically 10-40 %) that result from the processing of scrap (especially from industrial scrap). Smaller quantities of iron (15-30 %), lead (3-6 %), cadmium and chromium are existed in EAF dust.

EAF dust has been classified as a hazardous waste (K061) by the U.S. Environmental Protection Agency and its safe disposal represents a major problem. Although the EAF dust problem has been extensively studied, really satisfactory solutions have not yet been made. Removal of zinc existed in dusts is the only possible solution for avoiding to dump of dusts containing toxic materials (Philipp et al., 1986, Wheatley & Pooley, 1990).

Leaching tests have been made on some wastes including steelmaking slags and dusts for controlling the pollution risk of waste deposited regions. The IISI concentrated a research on leaching test methods used in eight countries (official or professional). Leaching tests were made officially in Germany, France, Japan, the United States as well as those made by iron and steel plants or research centers in England, Australia and Italy. Tests were made on six different materials. Results obtained from the tests made on EAF dust and EAF ladle refining slag are given in Table 3.5 and Table 3.6, respectively (Philipp et al., 1986).

Table 3.5 Leachate Characteristics of EAF Dust (Philipp et al., 1986, p.26)

Analysis Items	France	United States	Germany	Australia	Japan	England	Italy
pH	12.50	5.00	12.59	12.52	12.80	11.7	-
Cd,mg/L	<0.05	0.05	<0.01	0.02	<0.01	<0.05	<0.01
Cr total	31.40	17.00	31.00	71.00	29.90	16.00	23.00
Pb,mg/L	13.30	<0.10	16.00	23.60	1.50	11.20	<0.01
Zn,mg/L	3.05	<0.10	3.50	4.30	0.03	3.10	<0.02

Table 3.6 Leachate Characteristics of EAF Ladle Refining Slag (Philipp et al., 1986, p.26)

Analysis Items	France	United States	Germany	Australia	Japan	England	Italy
pH	11.90	5.00	12.57	12.18	12.50	11.00	-
Cd,mg/L	<0.05	<0.05	<0.01	<0.01	<0.01	<0.05	<0.05
Cr total	<0.05	<0.10	<0.04	<0.01	0.04	<0.05	<0.05
Pb,mg/L	<0.05	0.10	0.38	<0.01	0.01	<0.05	<0.01
Zn,mg/L	<0.05	<0.10	0.13	<0.01	0.05	<0.05	<0.02

Several parameters, affecting the test results, have been summarized below.

1. Leachate pH : Iron and steel plant wastes usually contain high lime concentration. Thus, the leaching water pH tends to become basic, unless acid medium extraction procedure is followed (the pH is maintained at about 5 by the addition of asetic acid). Additionally, reducing the equilibrium pH by adding asetic acid causes an increase in the extraction rate of certain heavy metals such as zinc and lead. Reducing the pH by adding hydrocloric acid causes less increment of the solubility of heavy metals.

2. Stirring Time : Dissolved elements can dissapear because of parasite reactions, which are not balanced. Therefore, the kinetics of leaching tests are very complex. The results can vary considerably due to the kinetics of leaching and stirring time particulary in solubilization and adsorption reactions.

3. Stirring Conditions : Intensity of stirring has a determinant effect on test results when the transfer conditions at the solid / liquid interface control dissolution. Over stirring can cause abrasion of brittle solid materials and lead to high solubilization.

4. Number of Leachings : Leaching is rapid and complete for several elements such as free lime. However, it is slow and durable as for chromium and calcium associated phase.

5. Liquid / Solid Mass Ratio : The ratio of liquid to solid mass affect test results depending of the elements involved :
   a. For very soluble elements, the concentration of leachates is inversely proportional to the L/S.
   b. For less soluble elements, leaching is independent of the L/S ratio when the liquid is saturated.
   c. The L/S ratio affect the concentration of elements likely to be absorbed and desorped from the solid phase.
   d. The L/S ratio has an indirect effect on the concentration of elements and the solubilization of low solubility elements can be affected.

6. Grain Size of Waste : Leaching methods are generally applied at untreated wastes. However, the specimen is crushed - particularly slag specimens. Slag specimens are crushed as their size of less than 4.0 mm (Philipp et.al.,1986).

Typical ferrous slags were tested by Calspan Corporation for Environmental Protection Agency. Results of these tests made on different slag types are indicated in Table 3.7.

Table 3.7 Leachate Test Results of Typical Ferrous Slags (Emery, 1982, p.101)

Slag Type	Analysis of Filtrate (mg / L)					
	Cr	Cu	Mn	Pb	Zn	pH
Blast Furnace	<0.01	<0.03	<0.01	<0.20	<0.01	10.6
Open - Hearth	0.01	0.04	<0.01	0.30	<0.01	12.5
Basic Oxygen	0.03	0.03	<0.01	0.20	<0.01	12.5
Electric Arc Furnace	0.27	0.03	<0.01	0.44	<0.01	12.4

Leachate characteristics of ferrous slags are not critical values for toxic constituents. Therefore, ferrous slags are considered as non-hazardous materials. Toxic materials should be leached at less than 1.0 mg/L for considering non-hazardous. Great tolerances for Cr, Pb, Zn and Mn can be observed from Table 3.6 and 3.7.

However, the EAF dust leachates contain significant amounts of toxic constituents (especially Cr, Pb, Zn) as indicated briefly in Table 3.5. Leaching tests made in most countries have given approximately the same results. Therefore, EAF dust is considered as a hazardous waste and dumping of this material should be made by following the environmental regulations carefully (Philipp et.al.,1986).

3.3 Evaluation of Iron & Steel Plant Wastes

3.3.1 Evaluation of Iron- and Steelmaking Slags in the World

Expanded and granulated iron blast furnace slag production has increased especially in Europe due to the demand for portland cement. Cement producers have begun to look into possibility of purchasing granulated slag from slag processing plants and grinding it at cement plants. It has increased the amount of cement available. However, if all blast furnace slags have been produced in a vitrified form for cementitious uses, approximately 15% of the world cement requirement could be met by saving significant amounts of energy. Also, high energy contained materials, such as asphalt and portland cement have caused an increment of production costs and have increased slag cement production. Granulated and pelletized blast furnace slag production has grown as slag cement manufacture has developed. Besides, ferrous slags have been used in pavement design for centuries. Air-cooled blast furnace slags and steelmaking slags have been produced for aggregate applications especially in America. Ferrous slags have been evaluated as valuable by-products processed for construction purposes and they have not been seemed as waste materials. Ferrous slag trade has also increased steadily since 1992. Researches have been continued to determine the performance of cement-slag blends and effective replacement of portland cement with blast furnace slag for oil field use (Emery,1982).

21 million tonnes of iron- and steelmaking slag, valued at $154 million, were used or sold in the United States (1995). About 60% of this amount were ironmaking slags, valued at $126 million, and the rest were steelmaking slags, valued at $28 million. Blast furnace slags have been processed at 27 facilities in 12 States as air-cooled, expanded and granulated types. Steelmaking slags obtained from open-hearth, basic oxygen and electric arc furnaces have been processed at 76 facilities in 28 States. Approximately 60% of the iron and steel slag production have been made in Indiana, Ohio, Michigan and Illinois. Typical uses of iron- and steelmaking slags with their proportions are given in Table 3.8.
(Web Site: http://minerals.er.usgs.gov/minerals/pubs/mcs/ironslag.txt)

Table 3.8 Statistics of Iron- and Steelmaking Slag Usage in the United States

Typical Usage	Ironmaking Slags (%)	Steelmaking Slags (%)
Pavement Base Material	45	40
Asphaltic Concrete Aggregate and other Concrete Applications	34	15
Fill Material	8	17
Other	13	28

7% of all iron- and steelmaking slags produced have been collected in plant sites. Steel slags can be recycled to blast furnaces directly or as agglomerates, as a source of iron and flux materials. About 80% of the steel slag generated each year is estimated being recycled. Ferrous materials recovered from slag during processing is also recycled to blast and steel furnaces.

3.3.2 Evaluation of Iron- and Steelmaking Slags in Turkey

5300000 tonnes of blast furnace slag were obtained in Turkey between 1950 and 1970. However, only 300000 tonnes of this amount (i.e. 6% of total steel production) were evaluated by using and marketing as granulated slag. The remaining portion has not yet been evaluated. In the following years, evaluation of granulated slag in cement production gained importance. Production amounts and evaluation rates of slag obtained from the steel plants in Turkey is briefly given in the following paragraphs.

Blast furnace slag has been produced at three major plants -Karabük, İskenderun, and Ereğli Iron and Steel Plants- in Turkey. Karabük Iron and Steel Plant was installed in 1932 and production has been made by three blast furnaces. Slags obtained as a by-product of process have partly been used as granulated slag and have been utilized by Bartın Cement Plant. In this plant, steel slag is obtained from Siemens-Martin furnaces. Siemens-Martin steelmaking process is another type of open-hearth process.Total slag production and usage amounts between 1983 and 1985 are given in Table 3.9 (Ilıcalı,1988, p.67).

Table 3.9 Slag Production and Evaluation of Karabük Iron & Steel Plant

Reference Year	Blast Furnace Slag (tonnes)	Granulated Slag (tonnes)	Steel Slag (tonnes)	Total Production (tonnes)	Usage Amount (tonnes)	Usage (%)
1983	201157	80367	152011	433535	80367	18
1984	195938	123138	138744	457820	123138	27
1985	183546	133223	148000	464769	133223	29

Granulated slag has excellent hydraulic properties, depending upon its MgO and Al_2O_3 contents, therefore it has been used for cementitious applications. Steel slag was recycled to blast furnace burden until 1972. Then, evaluation of it was ignored because of both obtaining manganous iron ore and raising of the costs.

Blast furnace slag has been obtained from two blast furnaces in Ereğli Iron and Steel Plant. Steel slag is produced by basic oxygen process. Blast furnace slags have partly been evaluated as granulated slag, the remaining part has been accumulated at plant site.

450000 tonnes of blast furnace slag and 250000 tonnes of steel slag were obtained annually in 1984. 20000 tonnes of granulated slag , that was 3% of the total amount of slag, were utilized by the cement plants. 920000 tonnes of blast furnace slag (690000 tonnes of this amount were granulated slag) were obtained annually from Karabük and Ereğli Iron and Steel Plant between 1990 and 1994 (Ilıcalı,1988).

Blast furnace slag, granulated slag and steel slag have been obtained as by-products in İskenderun Iron and Steel Plant. Steel slag has been produced by the basic oxygen steelmaking process in this plant. Only granulated slag has been evaluated by marketing to cement plants. The remaining part of wastes have been accumulated at plant site. Total slag production and usage amounts between 1983 and 1985 are given in Table 3.10
(Ilıcalı, 1988, p. 66).

Table 3.10 Slag Production and Evaluation of İskenderun Iron & Steel Plant

Reference Year	Blast Furnace Slag (tonnes)	Granulated Slag (tonnes)	Steel Slag (tonnes)	Total Production (tonnes)	Usage Amount (tonnes)	Usage (%)
1983	168604	202882	67832	439318	172000	39
1984	253108	226540	106272	585920	234432	40
1985	190468	383012	129009	702489	262935	37

Granulated slags are used partly for slag-cement production, but grinding and utilizing them as mineral additive for cement production have not yet been applied in Turkey. Utilizing blast furnace slags for cementitious applications, both these materials are evaluated effectively and high quality concrete can be produced. For this reason, standards and specifications should be prepared for the usage of granulated blast furnace slags for concrete production in Turkey (Erdoğan, 1995).

The production and evaluation of blast furnace slag, granulated slag and steel slag in three major iron and steel plants are mentioned in previous paragraphs. Solid wastes of steel plants in Foça region, where the electric arc furnace steelmaking process is used, is briefly explained in Chapter Four.

CHAPTER FOUR
IRON & STEEL PLANTS' SOLID WASTES IN FOÇA REGION

4.1 General Description of Iron and Steel Plants

Electric arc furnace steelmaking process has already been used at steel plants located in Foça region. The industrial area in which steel plants were located is about 50 km north of İzmir. Besides, steel plants were constructed approximately 5 km away from Nemrut Bay industrial facilities. High quality scrap used for electric arc furnace steelmaking process is obtained from these facilities. Thus, scrap transportation to steel plants is made simply by trucks. Also, natural resources (high grade iron ore, coke, etc.) are not available and low-cost electric power can be obtained in this area. Therefore, five steel plants using the electric arc furnace steelmaking process were installed in Foça region. Steel production capacities, technological possibilities and solid waste potential of these plants are summarized below.

1. Çukurova Steel Plant: In this plant, steel production began with the operation of the first electric arc furnace in 1981. It was followed by the roar of the second furnace in 1982. Installation of third arc furnace in 1985 and the fourth one in 1986 followed them. These furnaces have 80 tonnes of molten steel capacity. With these furnaces, this plant has the largest production capacity in the region. However, three of the furnaces were seriously damaged by the fire on December 1995. Therefore, only one furnace have been used for about two years.

Three types of solid waste are obtained as by-products of the process: Electric arc furnace slag (EAF slag), electric arc furnace ladle refining slag (EAF ladle slag) and electric arc furnace dust (EAF dust). EAF slag of about 10 tonnes and 1 ton of EAF ladle slag are

obtained per melting of the furnace. Usually 18-20 melting works are made with an arc furnace during a day. Thus, total slag production is about 200 tonnes/day for a furnace (i.e. approximately 125 kg slag/ton of molten steel). EAF dust is collected by electrostatic precipitators that have a collection capacity of 2400000 Nm^3/h. 20-25 tonnes/day of EAF dust is collected from a furnace.

Annually, 70000 tonnes of slag (64000 tonnes of EAF slag and 6000 tonnes of EAF ladle slag) are obtained from this plant.

EAF slags are solidified with water quenching. EAF ladle slags are solidified under the ambient conditions (Air-cooling). Then they are blended and accumulated in the plant site irregularly. Approximately 1625000 tonnes of slag have been accumulated in this way since 1981. These slags have not been evaluted for any purpose and slag hills have been formed in the plant site.

A few years ago, a slag evaluation unit was installed. By this unit, the recycling of iron and steel existed in slags into the arc furnaces was aimed. Slags have been processed in this slag evaluation unit located in the plant site. Iron and steel existed in EAF slags and EAF ladle slags are removed by magnetic separators available in the unit. Removed iron and steel are recycled into the arc furnace with scrap materials for charge. Processed slags are accumulated at different sites of plant. 300000 tonnes of processed slag have already been existed in the plant .

2. İzmir Iron and Steel Plant: Steel production has been made using one electric arc furnace that has an 80 tonnes of molten steel capacity. Annually, 700000 tonnes of steel is produced by this plant and 80000 tonnes of slag is obtained (approximately 120 kg slag/ton of molten steel). Iron and steel are removed from slags and they are recycled into the arc furnace. EAF dusts are collected by electrostatic precipitators. Approximately 1500000 tonnes of slag have been accumulated in the plant site .

- Habaş, Çebitaş and Ege Metal Steel Plants: In these plants, 90-120 kg of slag per one ton of molten steel is obtained. Annually, 400000-500000 tonnes of steel is produced and

35000-55000 tonnes of slag is obtained. Accumulated slags have not yet been evaluated for any purpose in these plants.

In addition to the above mentioned plants, a brief explanation about the production capacity and the solid waste potential of Metaş Steel Plant is given below.

Metaş Steel Plant was located in Pınarbaşı (İzmir) region. An electric arc furnace having 50 tonnes of molten steel capacity is present in this plant. 70 kg slag/ton of molten steel is obtained. Besides, 5 tonnes/day of EAF dust (about 1500 tonnes/year) is collected by electrostatic precipitators. The first dust collection unit in İzmir began to operate at Metaş Steel Plant in 1980. Annually, 300 000 tonnes of steel is produced and 20 000 tonnes of slag is obtained.

Following the determination of the waste potential, Çukurova Steel Plant was selected as the pilot plant for the investigation program of this thesis. Fresh EAF slag, EAF ladle slag and EAF dust samples were obtained and tests for the determination of geotechnical properties of these by-products have been made at the Soil Mechanics Laboratory of Dokuz Eylül University, Civil Engineering Department.

Test procedures, results obtained from these tests and interpretations of the results are explained in the following sections.

4.2 Laboratory Testing Program for Slag and Dust

The slag and dust samples obtained from Çukurova Steel Plant have been used in the testing program.

The basic idea of this investigation was the determination of the geotechnical properties of these wastes. For this reason, the determination of the chemical compositions, index and engineering properties of these wastes have been planned.

4.2.1. Selection and Preparation of Samples

Fresh EAF slag, EAF ladle slag and EAF dust samples were selected and brought to the laboratory. EAF slags have a vitrified (glassy) state due to the rapid cooling process (water quenching). They also have angular and large blocky grains with black colour. Depending upon its chemical composition (Fe_2O_3 + MnO = 20-30 %), EAF slag has a rather large unit weight. EAF ladle slags have a pulverizing structure with light gray colour. They are solidified under ambient conditions. Large blocks are not present in EAF ladle slags. Due to the difference of its chemical composition (Fe_2O_3 + MnO = 1-2 %), EAF ladle slag is lighter than EAF slag. Suitable portions of EAF slag and EAF ladle slag were selected from the pile, and chemical compositions of these metarials were determined at Çukurova Steel Plant Wet Analysis Laboratory. Chemical analysis results are shown in Table 4.1.

Table 4.1 Chemical Analysis Results of Çukurova Steel Plant Slag Samples

Constituent	EAF Slag (%)	EAF Ladle Slag (%)
Silica (SiO_2)	19.21	25.74
Alumina (Al_2O_3)	10.42	6.23
Lime (Cao)	43.16	50.69
Magnesia (MgO)	4.03	12.16
Manganous Oxide (MnO)	5.17	0.71
Iron Oxide (Fe_2O_3)	17.62	1.72

The chemical analysis results presented in Table 4.1 resemble the ranges shown in Table 3.4.

EAF dust is very fine powder with light brown color. It is collected by electrostatic precipitators during the steelmaking process. It contains appreciable amount of zinc and iron contents (30% ZnO and 17% Fe_2O_3).

Besides (in smaller quantities of) lead, cadmium, chromium oxides and other components exist in EAF dust. Fresh EAF dust sample was selected from the collection site and all materials were brought to the Soil Mechanics Laboratory of Dokuz Eylül University, Civil Engineering Department.

Slag samples were needed to crush into small particles for the preparation of the test samples. These slag samples were fresh samples. They had not been processed in the slag evaluation unit of the plant and they contained iron and steel in their original structure. They could not been crushed by the grinder present in the Soil Mechanics Laboratory. They were crushed by the Los Angeles Abrasion Testing Device existed in the Construction Materials Laboratory of DEU Civil Engineering Department. Slag samples were extremely stiff materials due to their iron and steel contents. Therefore, 3000 revolutions for EAF slag and 1000 revolutions for EAF ladle slag have been sufficient to crush them until the maximum grain diameter was less than the No.4 sieve (4.75 mm). This diameter was decided as an appropriate maximum diameter for the preparation of the test samples. Sieve analyses of both slag samples were conducted before the crushing process initially. Sieve analysis test results are given in Appendix (Table A.1).

4.2.2 Determination of the Index Properties

Slag samples were prepared for the determination of grain size distribution in accordance with the ASTM D 421. A representative portion of the slag sample was selected by the quartering method. The amount of this portion should be sufficient to perform sieve analysis of the material. Generally it is determined according to the maximum grain size diameter of the material. Sieve analyses of slags were done both before the crushing (original state) and after the crushing (crushed state). Grain size analyses of slags were conducted in conjunction with the ASTM D 422. Sieve analysis test results are shown in Appendix (Table A.1). Grain size distribution curves of EAF slag and EAF ladle slag are given in Figure 4.1 and Figure 4.2, respectively. The effect of crushing on the material's grain size distribution can be observed from these figures.

EAF dust was washed through the No.200 sieve (0.074 mm) and it has been observed that 99% of dust passed through the No.200 sieve. Hydrometer analysis was conducted on this material. An ASTM 151 H hydrometer was used for this purpose (Lambe & Whitman, 1969; Bowles, 1970).

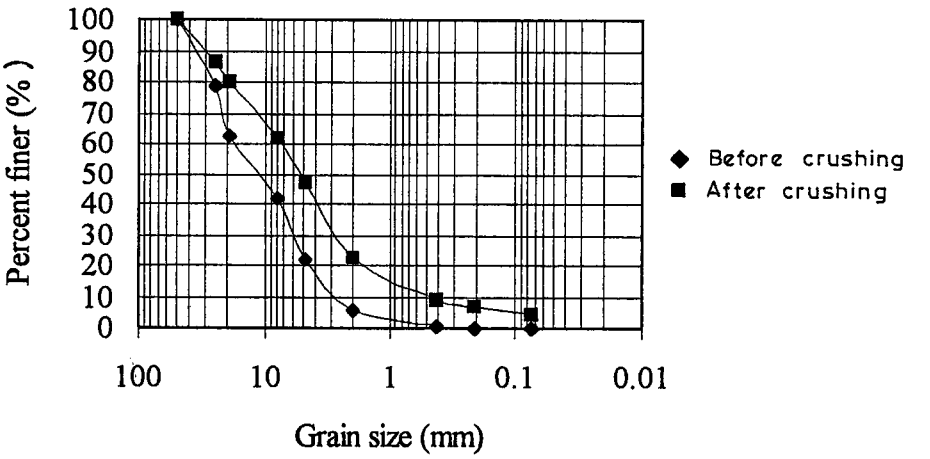

Figure 4.1 Grain Size Distribution of EAF Slag

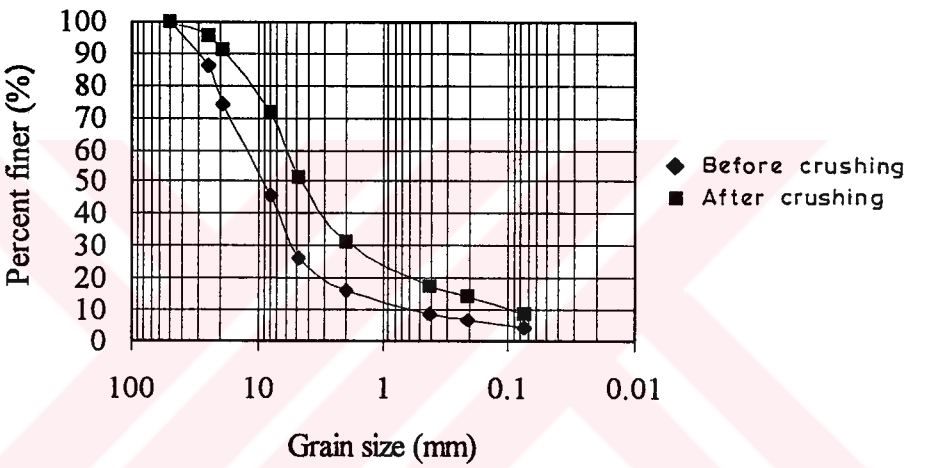

Figure 4.2 Grain Size Distribution of EAF Ladle Slag

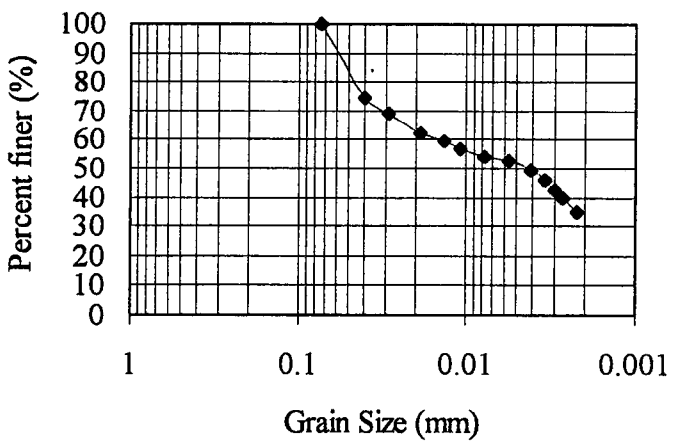

Figure 4.3 Grain Size Distribution of EAF Dust

A 125 ml solution of sodium hexametaphosphate was prepared (40 g of sodium hexametaphosphate/litre of solution) as a dispersing agent for 50 g of EAF dust sample.

Hydrometer test results are given in Appendix (Table A.2), grain size distribution of EAF dust is presented in Figure 4.3. It can be concluded from this figure that EAF dust consists of generally silt sized materials.

Slags fines (-No.40 portion) and EAF dust were determined to be non-plastic. Tests, for the determination of the plastic limit, were conducted in accordance with ASTM D 424 The liquid limit was determined according to Fall Cone Method (Fig 4.4). The shrinkage limit was found in conjuction with ASTM D 427. The liquid limit and the shrinkage limit test results are given in Appendix (Table A.3 and Table A.4, respectively).

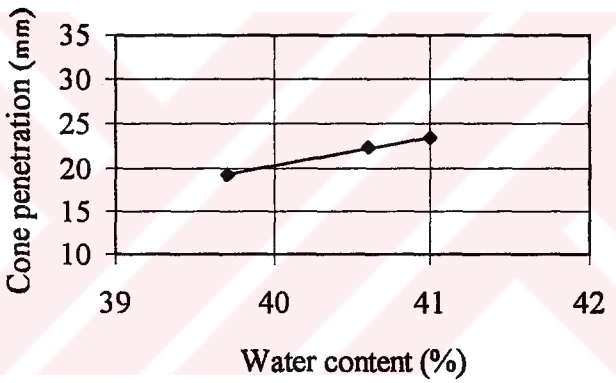

Figure 4.4 Liquid Limit Determination of EAF Dust

EAF dust's liquid limit was found as $w_L = 0.40$ (Figure 4.4) and its shrinkage limit was determined as $w_S = 0.24$. Although a relatively high liquid limit value was found, the plastic limit for EAF dust couldn't been determined. This is a specific characteristic of this material.

Original EAF slag and EAF ladle slag are classified as poorly graded gravel (GP) according to the Unified Soil Classification System. Similarly, crushed EAF slag can be classified as well graded gravel (GW), and crushed EAF ladle slag is classified as poorly graded silty gravel (GP-GM). EAF dust is classified as non-plastic silt (ML). Classifications were made according to ASTM D 2487.

The specific gravity of EAF slag was determined as G_s=3.40 in accordance with ASTM D 854. Tests on the EAF ladle slag resulted a value of G_s=3.25. These values are considerably high in comparison with those fall in the range of 2.65-2.75 for most soils. Iron and steel present in slag samples has been effective on these results. The specific gravity values are in accordance with the range encountered in the literature (3.20-3.50) for steel slag (Emery, 1982).

EAF dust attained to a foamy state after distilled water had been added and dust-water suspension had been mixed. During the removal of air with the partial vacuum, the surface of the suspension could not be observed clearly due to the foamy state. The foamy part was taken by a pipette and the retained dust-water suspension was dried in the oven and the net dust weight was determined. The average specific gravity value of EAF dust was found to be G_s=2.71. Related calculations are shown in Appendix (Table A.5). However, during the evaluation of other tests made on EAF dust it has been realized that the specific gravity value obtained from the Standard test is could not proper. This improper result was assumed to be due to the foaming in the pycnometer. It has been encountered in the literature that the specific gravity value of this material is expected to be in excess of 3.0 due to its high zinc, iron and other heavy metal contents (Kumbhojkar, 1986). For this reason, the specific gravity value of EAF dust has been evaluated as G_s=4.40. This value was used in the evaluation of other test results.

4.2.3 Compaction Tests

Standard and Modified Proctor Compaction tests were performed on crushed EAF slag, crushed EAF ladle slag and EAF dust samples in accordance with ASTM D 698 and D 1557, respectively.

EAF slag was compacted following Method D explained in ASTM D 698 and D 1557. In this method; a 6 in (152.4 mm) diameter mold and a material passing a ¾ in (19.0 mm) sieve, corrected by replacement for material retained on a ¾ in sieve are used. EAF ladle slag was compacted in accordance with Method C explained in both related standards.

In this method, and the material passing a ¾ in (19.0 mm) sieve is compacted in a 6 in (152.4 mm) mold.

The standard compaction tests for both slag samples were conducted by compaction of three layers of material in a mold with 1/13.33 ft^3 (2124 cm^3) in volume. Each layer of material was compacted with 56 blows by a hammer of 5.5 lb (24.5 N) weight with a 12 in (30.48 cm) drop (Das, 1983).

The compactive effort can be determined as :

$$\frac{(5.5 \text{ lb/blow}) (3 \text{ layers}) (56 \text{ blows/layer}) (1 \text{ ft drop})}{1/ 13.33 \text{ ft}^3} = 12320 \text{ ft.lb/ft}^3 (\cong 590 \text{ kJ/m}^3)$$

In the Modified Proctor Compaction tests, the same mold for the Standard Proctor Compaction tests was used. But, the compactive effort was different from the value that was calculated for the Standard Proctor Compaction test.

The Modified Proctor Compaction tests were conducted by compaction of five layers with a 10 lb (44.5 N) hammer giving 56 blows to each layer . The drop height was 18 in (457.2 mm.). The compactive effort can be calculated as:

$$\frac{(10 \text{ lb/blow}) (5 \text{ layers}) (56 \text{ blows/layer}) (1.5 \text{ ft drop})}{1/13.33 \text{ ft}^3} = 56000 \text{ ft.lb/ft}^3 (\cong 2690 \text{ kJ/m}^3).$$

Compaction test results are given in Appendix (Table A.6). The dry unit weight vs. moisture content relations and zero-air-void curves of both slag samples are shown in Figure 4.5 and Figure 4.6, respectively.

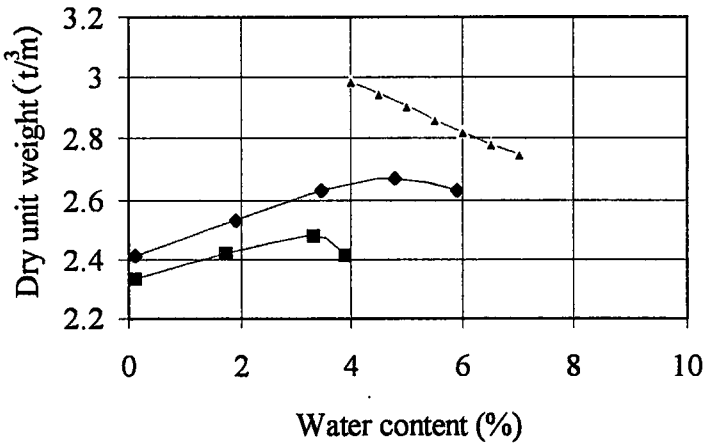

Figure 4.5 Compaction Curves of EAF Slag

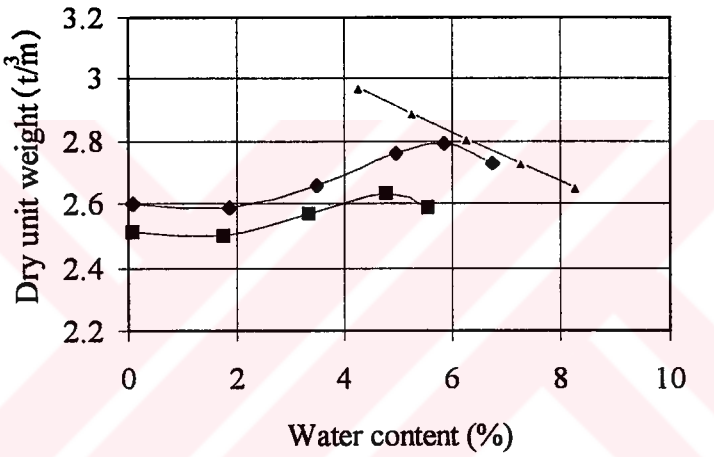

Figure 4.6 Compaction Curves of EAF Ladle Slag

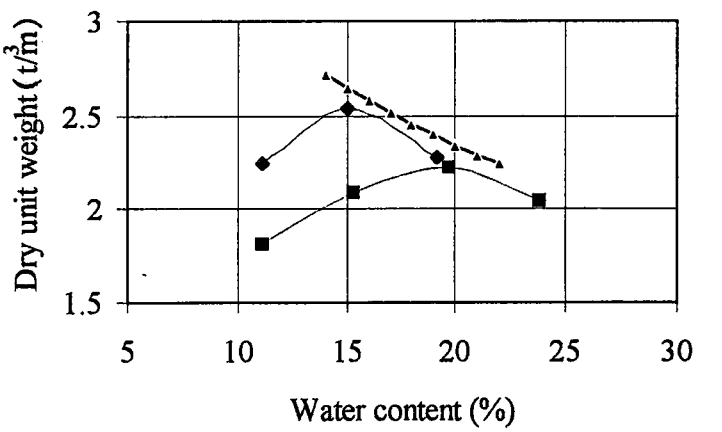

Figure 4.7 Compaction Curves of EAF Dust

If these figures are examined carefully, the same behavior is observed for both slag samples. The maximum dry unit weight has increased with the increment of the compactive effort. The optimum moisture content has increased at the same time. This is an unexpected behavior for compaction tests. It is estimated that the gradation of the material and the difficulty of the control over the moisture content in gravelly materials cause this trend. Also, the pulverized nature of the EAF ladle slag encourages the capillary forces. As known, the dry unit weight initially decreases as a result of the capillary tension in the pore water, then increases up to the optimum moisture content. Besides, the maximum dry unit weight values are rather high due to the large unit weight of the material (Das,1983).

EAF dust was compacted in accordance with Method A explained in ASTM D 698 and D 1557. In this method, in a 4 in. (101.6 mm) mold , the material passing a No.4 (4.75 mm) sieve is compacted . The Standard Proctor Compaction test was performed by compaction of three layers of material with 25 blows by a hammer of 5.5 lb (24.5 N) weigh with a 12 in (30.48 cm) drop (Das,1983).

The compactive effort can be determined as :

$$\frac{(5.5 \text{ lb/blow})\ (5 \text{ layers})\ (25 \text{ blows/ layer})\ (1 \text{ ft drop})}{1/30 \text{ ft}^3} = 12375 \text{ ft. lb/ft}^3\ (\cong 593 \text{ kJ/m3}).$$

The Modified Proctor Compaction test was conducted by compaction of five layers with a 10 lb (44.5 N) hammer giving 25 blows to each layer. The height of drop was 18 in (457.2 mm).

The compactive effort can be calculated as :

$$\frac{(10 \text{ lb/blow})\ (5 \text{ layers})\ (25 \text{ blows/layer})\ (1.5 \text{ ft drop})}{1/30 \text{ ft}^3} = 56250 \text{ ft. lb/ft}^3\ (\cong 2694 \text{ kJ/m}^3)$$

Compaction test results for both slag and dust samples are given in Appendix (Table A.6).

The dry unit weight vs. moisture content relation and zero-air-void curve of EAF dust is shown in Figure 4.7.

The optimum water content and maximum dry unit weight values obtained from both Standard and Modified Proctor Compaction tests for all materials are summarized in Table 4.2.

Table 4.2 Summary of Compaction Test Results

Material Type	Test Type	Optimum Moisture Content w (%)	Maximum Dry Unit Weight γ_d (t/m^3)
EAF Slag	Standard	3.2	2.48
	Modified	4.8	2.67
EAF Ladle Slag	Standard	4.8	2.63
	Modified	5.9	2.79
EAF Dust	Standard	20.0	2.22
	Modified	15.1	2.54

Compaction test results have shown that, these materials have compressibility properties under compaction and especially slags can be used as fill material. However, it should be noticed that soft layers (if available) should be strengthened under the applied fill in which the heavy materials have been used. Besides, these materials are used effectively in embankments.

4.2.4 Permeability Tests

EAF slag and EAF ladle slag are gravel sized materials in their original state. Hence, these materials can be considered as permeable materials depending upon their gradation. EAF dust is a silt sized material which has a low permeability.

The Falling Head Permeability test was performed on EAF slag and EAF ladle slag laboratory samples passing No.4 sieve (4.76 mm) in accordance with ASTM D 2434. The coefficient of permeability values were obtained of about 10^{-4} cm/sec for both slag samples.

These values resemble to the typical values of coefficient of permeability for fine sand and loose silt (10^{-4} - 10^{-2} mm/sec) (Das, 1983). These tests were made to determine order of magnetude only. Test conditions should be controlled and sufficient number of tests should be conducted to determine the exact values.

EAF slag and EAF ladle slag can be used as filter material between the fine section and the toe of an earth dam if they satisfy the following requirements:

1. The size of voids in filter material should be small enough to hold the larger particles of the protected material in place.
2. The filter material should have a high permeability to prevent large seepage forces and hydrostatic pressures in filters.

Besides, grain size distributions of these materials should satisfy the required range of a good filter material (Das, 1983).

4.2.5 Direct Shear Tests

Direct Shear tests were conducted on compacted slag and dust samples in accordance with ASTM D 3080. Tests were performed on -No.4 slag specimens. All samples were compacted at 100% Standard Proctor densities and at their optimum moisture contents.

The test specimens were compacted in the shear box. They were 6^{cm}x6^{cm} in plan and 2 cm. in height. Test specimens were prepared with some difficulty. It was very hard to achieve the required density during the compaction process due to the granular characteristics of the materials. For this reason, specimen heights were measured after compaction and required density values were obtained in this way.

Direct shear test results of EAF slag, EAF ladle slag and EAF dust samples are given in Appendix (Table A.7, A.8, and A.9 respectively). As shown in these tables, specimens were subjected to 12, 24 and 36 kg. of normal loads. Dry unit weight and corresponding Standard Proctor density values are shown in these tables. Besides, shear deformation, normal stress and shear strength values obtained from each test are given in these tables.

Shear strength diagrams under the peak and residual conditions are presented in Figures 4.8, 4.9 and 4.10 for EAF slag, EAF ladle slag and EAF dust, respectively.

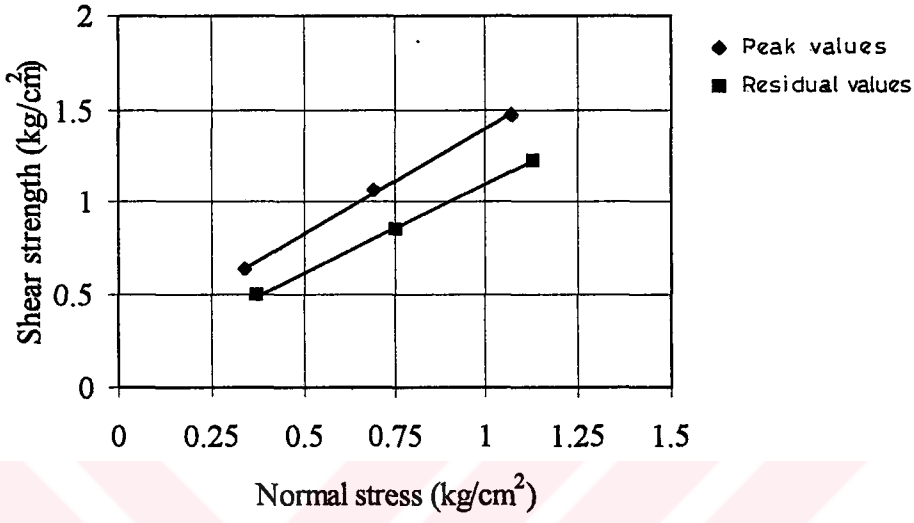

Figure 4.8 Shear Strength Diagrams of EAF Slag

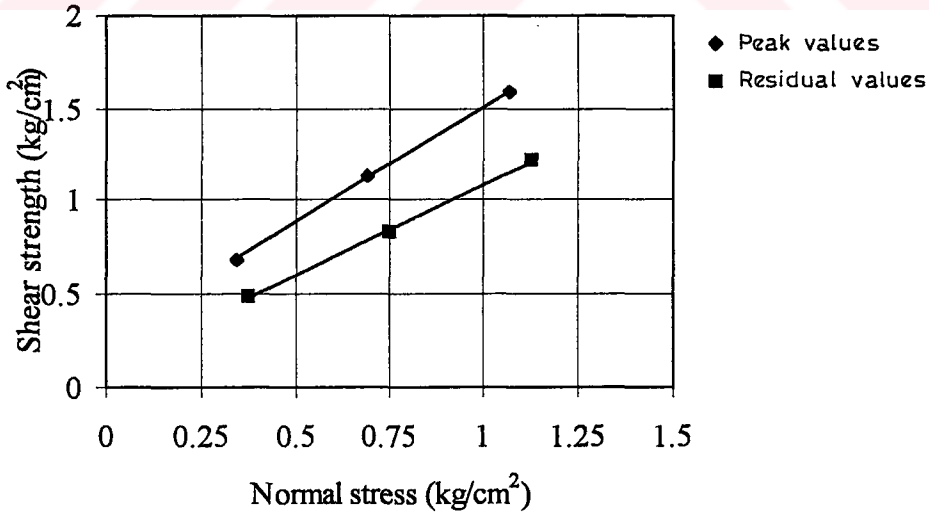

Figure 4.9 Shear Strength Diagrams of EAF Ladle Slag

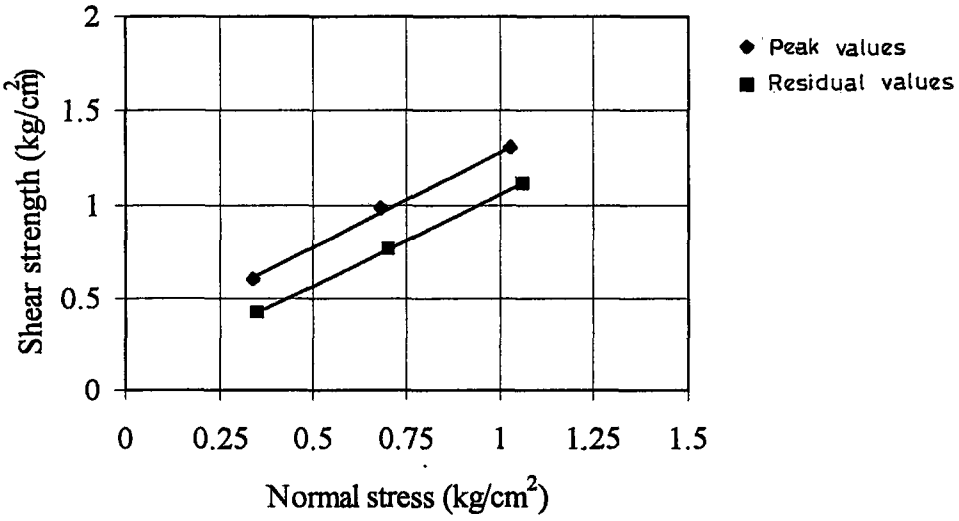

Figure 4.10 Shear Strength Diagrams of EAF Dust

Peak and residual strength parameters of EAF slag , EAF ladle slag and EAF dust are summarized in Table 4.3.

Table 4.3 Peak and Residual Shear Strength Parameters of Slag and Dust Samples

Material Type	Shear Strength Parameters			
	Peak		Residual	
	c_p (kg/cm^2)	$\varnothing_p$ (°)	c_r (kg/cm^2)	$\varnothing_r$ (°)
EAF Slag	0.25	49.0	0.13	44.2
EAF Ladle Slag	0.26	51.3	0.12	44.2
EAF Dust	0.28	45.0	0.10	43.8

If 4.8 to 4.10 figures and Table 4.3 are examined, it is observed that all materials have high values of the peak and residual shear strength parameters. EAF slag and EAF ladle slag have almost the same peak and residual parameters. The peak internal friction angles obtained for slag specimens fall into the range given for sandy gravel and gravelly soils (Das, 1983; Lambe & Whitman, 1979). The residual friction angles are very high compared with the range given for the same soils.

The residual cohesion parameters obtained from tests for slag specimens are apparent cohesions. The particle geometry and packing conditions cause the occurence of the apparent cohesion.

4.2.6. Consolidation Tests

4.2.6.1 Possible Swell Potential

As mentioned in Section 3.2.3, steel slags have an expansive nature depending upon their chemical compositions. The hydration of CaO and MgO causes the expansive nature of steel slags. CaO hydrates rapidly, thus expansion occurs in a few weeks. In contrast of CaO, MgO hydrates slowly. Consequently, an expansion can be observed in a long term.

A swell test was performed on compacted EAF slag, EAF ladle slag and EAF dust samples to determine the swelling behaviour. Test specimens were prepared at their maximum dry densities and optimum water contents obtained from standart Proctor compaction tests.

1 psi (0.07 kg/cm^2) seating pressure were subjected to these specimens. After a week, no expansion could be observed for any specimen. However, the effect of aging should be taken into account.

Testing at high temperatures (60^o-80^o) and using the fresh metarials cause the observation of expansion in a short term. Using aged or coarse grained material restricts the expansion rate. Testing at room temperatures is also a limiting factor (Emery,1982).

The swell potential should be analyzed with long-termed tests. (Especially, before the use of these materials as a fill material)

4.2.6.2 Oedometer Tests

Oedometer tests were performed on the compacted slag dust samples according to ASTM D 2435. The test specimens were compacted at their 100% Standard Proctor densities. The slag specimens having maximum grain diameter passing No.4 sieve

(4.76 mm) were used in the tests. Initially, the compacted specimens were subjected to the seating pressure of 1 psi (0.07 kg/cm^2). Then the load increments have been applied according to ASTM D 2435.

The test results for EAF slag, EAF ladle slag and EAF dust are shown graphically in Figures 4.11, 4.12, 4.13, and the related calculations in Tables A.10, A.11 and A.12, respectively.

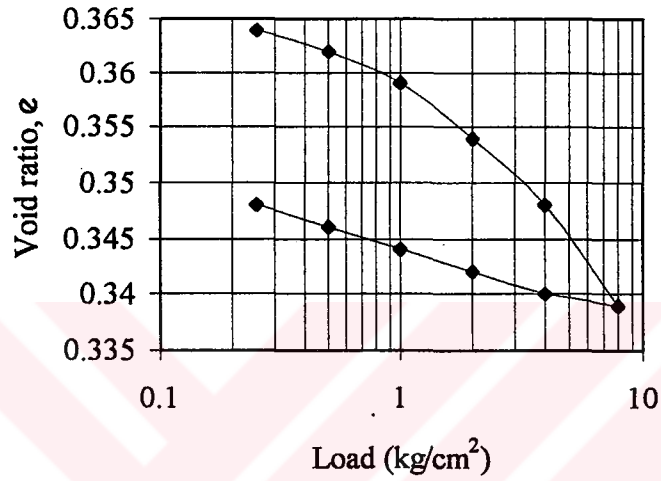

Figure 4.11 Compression Diagram of EAF Slag

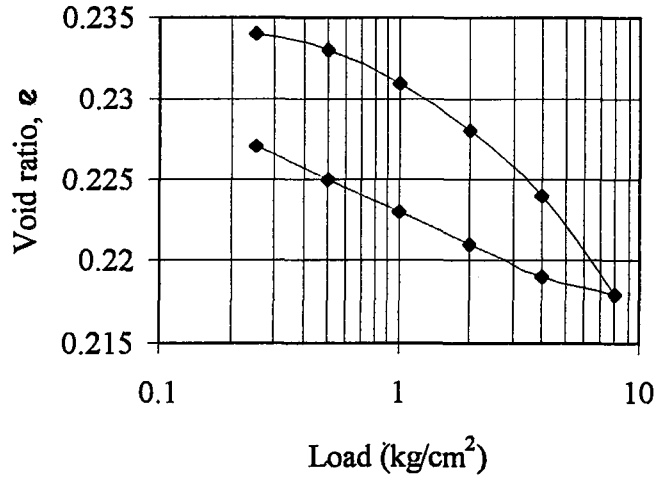

Figure 4.12 Compression Diagram of EAF Ladle Slag

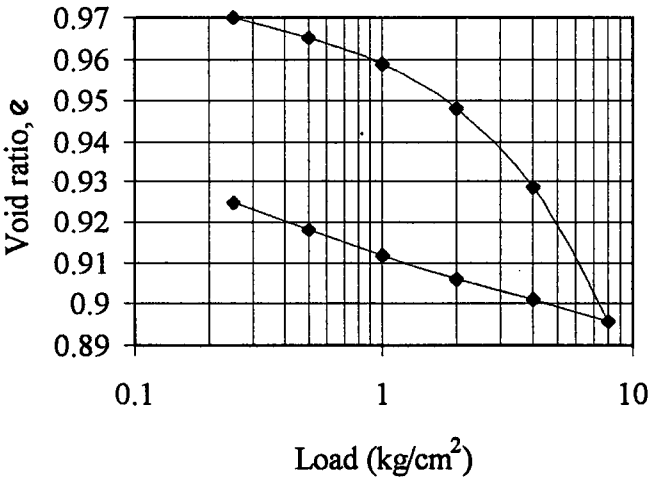

Figure 4.13 Compression Diagram of EAF Dust

The compression index (C_c) and the swelling index (C_s) values obtained from the oedometer tests for the slag and dust samples are shown in Table 4.4. As shown in the figures 4.11 to 4.13 and Table 4.4, the slag samples have shown similar trends. Differently, the dust sample has shown more compressibility and more swelling.

Table 4.4 Oedometer Test Results of Slag and Dust Samples

Material Type	Compression index C_c	Swell index C_s
	(-)	(-)
EAF Slag	0.030	0.007
EAF Ladle Slag	0.020	0.007
EAF Dust	0.110	0.022

CHAPTER FIVE
CONCLUSIONS

In both developed and developing countries, research and development efforts have been directed towards the effective utilization of industrial by-products in various fields. Parallel to the applications in other countries, the effective utilization of the industrial by-products has gained importance in Turkey, recently. Intensive efforts have been made steadily for this subject during the past decade.

Iron and steel industry solid wastes have an important place among the industrial by-products. These wastes are blast furnace slag, steelmaking slags and dusts collected from the electric arc furnaces. Utilization of these materials for construction purposes has been investigated for a long time. With the increase of the steel production, the disposal of these by-products will be expected to create more serious problems in the future. For this reason, usage possibilities of these materials should be enlarged.

In Turkey, slag utilization is limited to the production of small quantities of slag cements, other means of utilization are not put into practice. However, a lot of possible usage areas for these materials already exist in civil engineering.

The aim of this thesis was to investigate the possible utilizations of steel plants' solid wastes for geotechnical purpose. Hence, an investigation program has been planned. The determination of steel plants' solid waste potential in Foça region was the initial step of this study. It was observed that the steel plants' solid wastes created a great environmental problem in this region. For possible utilization; the physical, chemical and geotechnical properties of these wastes were determined with laboratory tests.

Considering the test results obtained from the subject matter steel plants' solid wastes, it can be concluded that steel slags have good strength properties, hence they can be utilized in embankment construction. The high unit weight and interlocking properties are good features for using steel slag as railroad ballast material. They also can be used as fill or base material. It should be pointed out that, large unit weight and potential expansion of slags have gained importance for such applications. Using steel slag in asphaltic concrete pavements are expected not to create any problems for the quality and durability. High permeability functions of steel slags make their utilization possible as filter material in dam construction. Also, they can be used as coastal fill material. However, the chemical interaction between the slag components and the sea water should be investigated. Large variations can be observed for these materials, even for the same plant and furnace .Thus, laboratory works should be made before the utilization of these materials for constructional purpose.

With the light of the test results obtained in the scope of this thesis, the following recommendations can be made for the future efforts on this subject:

i) Research and development efforts can be continued for using these materials effectively.

ii) Investigations may be enlarged to include different types of slags from various steel plants.

iii) Better coordination and collaboration can be maintained between iron and steel producers and technological institutions and universities.

iv) Educational courses may be arranged among the steel producers. Public concern may be taken into account to this subject.

This study is expected to lead the investigators that will be interested in this subject.

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APPENDIX

LABORATORY TEST RESULTS

Table A.1 Sieve Analysis Test Results

Sieve No	% Passing				
	EAF Slag		EAF Ladle Slag		EAF Dust
	Original Sample	Crushed Sample	Original Sample	Crushed Sample	
2″	100.0	100.0	100.0	100.0	
1″	78.9	86.3	86.4	95.8	
3/ 4″	62.3	80.1	74.3	91.1	
3/ 8″	41.8	61.8	46.2	72.0	
No.4	22.0	46.8	26.4	51.5	
No.10	6.1	22.9	16.2	31.5	
No.40	0.4	9.0	8.9	17.7	100.0
No.70	0.3	7.0	7.0	14.4	99.9
No.200	0.2	4.5	4.4	8.8	98.8

Table A.3 Liquid Limit Test Results of EAF Dust

Test No	1	2	3
Weight of Water (g)	2.76	3.73	4.19
Weight of Dry Sample (g)	6.96	9.18	10.23
Water Content (%)	39.7	40.6	41.0
Cone Penetration (mm)	19.3	22.4	23.5

Table A.2 Hydrometer Test Results of EAF Dust

	Elapsed Time (min)												
	1	2	5	10	15	30	60	120	180	240	300	480	1440
RH	1.0296	1.0277	1.0251	1.0240	1.0232	1.0222	1.0211	1.0198	1.0185	1.0174	1.0164	1.0143	1.0101
RH_w	1.0008	1.0009	1.0010	1.0011	1.0012	1.0013	1.0008	1.0008	1.0008	1.0009	1.0010	1.0009	1.0008
N (%)	74.5	69.4	62.4	59.3	56.9	54.1	52.5	49.2	45.8	42.7	39.9	34.7	24.1
D (mm)	0.0400	0.0291	0.0190	0.0137	0.0109	0.0079	0.0057	0.0042	0.0034	0.0030	0.0027	0.0022	0.0013

Hydrometer no : ASTM 151 H
Meniscus correction : 0.20

Dry Weight : 50.0 g
Specific Gravity : 4.40

RH : Hydrometer reading in suspension
RH_w : Hydrometer reading in distilled water
N : % Passing
D : Effective grain size (mm)

Table A.4 Shrinkage Limit Test Results of EAF Dust

Test No	1	2	3
Volume of Wet Sample (cm^3)	13.00	13.00	13.00
Volume of Dry Sample (cm^3)	10.58	10.74	10.42
Weight of Dry Sample (g)	20.91	20.30	20.17
Water Content (%)	35.3	35.3	35.3
Shrinkage Limit (%)	23.7	24.2	22.5

Table A.5 Specific Gravity Test Results

	EAF Slag			EAF Ladle Slag			EAF Dust		
Volume of Pycnometer (ml)	500	500	500	500	500	500	500	500	500
Temperature (°C)	23	23	23	23	23	23	21	21	21
Weight of Dry Sample (g)	50.0	50.0	50.0	50.0	50.0	50.0	47.6	47.8	47.9
Weight of Pyc.+ Water + Sample (g)	658.3	658.3	658.3	657.6	657.6	657.6	653.0	653.2	653.2
Weight of Pyc.+ water (g)	623.0	623.0	623.0	623.0	623.0	623.0	623.0	623.0	623.0
Specific Gravity (G_s)	3.40	3.40	3.40	3.25	3.25	3.25	2.70*	2.72*	2.71*

* These values are not considered as representative due to the foaming effect.

Table A.6 Compaction Test Results

EAF Slag						EAF Ladle Slag					
Standard Proctor Test			Modified Proctor Test			Standard Proctor Test			Modified Proctor Test		
γ_n (t/m^3)	w (%)	γ_d (t/m^3)	γ_n (t/m^3)	w (%)	γ_d (t/m^3)	γ_n (t/m^3)	w (%)	γ_d (t/m^3)	γ_n (t/m^3)	w (%)	γ_d (t/m^3)
2.33	0.10	2.33	2.41	0.09	2.41	2.51	0.08	2.51	2.60	0.08	2.60
2.46	1.73	2.42	2.58	1.90	2.53	2.54	1.74	2.50	2.64	1.87	2.59
2.56	3.31	2.48	2.72	3.45	2.63	2.66	3.35	2.57	2.75	3.48	2.66
2.50	3.87	2.41	2.80	4.77	2.67	2.75	4.76	2.63	2.90	4.96	2.76
			2.79	5.91	2.63	2.73	5.55	2.59	2.95	5.85	2.79
									2.92	6.75	2.73

EAF Dust					
Standard Proctor Test			Modified Proctor Test		
γ_n (t/m^3)	w (%)	γ_d (t/m^3)	γ_n (t/m^3)	w (%)	γ_d (t/m^3)
2.01	11.1	1.81	2.49	11.1	2.24
2.41	15.3	2.09	2.92	15.0	2.54
2.66	19.7	2.22	2.72	19.1	2.28
2.53	23.8	2.04			

Table A.7 Direct Shear Test Results of EAF Slag

Test No	Normal Load	Dry Unit Weight	Relative Density	Peak Residual	Deformation	Corrected Area	Normal Stress	Shear Strength
	N	γ_d	D_r	P/r	ΔL	A′	σ	τ
	(kg)	(t/m^3)	(%)	(-)	(cm)	(cm^2)	(kg/cm^2)	(kg/cm^2)
1	12	2.48	100	p	0.18	34.92	0.34	0.63
				r	0.54	32.76	0.37	0.49
2	12	2.47	100	p	0.20	34.80	0.34	0.64
				r	0.52	32.88	0.36	0.49
3	12	2.48	100	p	0.19	34.86	0.33	0.63
				r	0.48	33.12	0.37	0.48
4	24	2.47	100	p	0.22	34.68	0.69	1.06
				r	0.64	32.16	0.75	0.85
5	24	2.47	100	p	0.20	34.80	0.69	1.05
				r	0.64	32.16	0.76	0.85
6	24	2.48	100	p	0.24	34.56	0.70	1.06
				r	0.66	32.04	0.75	0.86
7	36	2.48	100	p	0.40	33.60	1.07	1.47
				r	0.70	31.80	1.13	1.23
8	36	2.47	100	p	0.38	33.72	1.07	1.48
				r	0.68	31.92	1.12	1.23
9	36	2.48	100	p	0.44	33.36	1.06	1.47
				r	0.66	32.04	1.13	1.24

Table A.8 Direct Shear Test Results of EAF Ladle Slag

Test No	Normal Load	Dry Unit Weight	Relative Density	Peak Residual	Deformation	Corrected Area	Normal Stress	Shear Strength
	N	γ_d	D_r	P/r	ΔL	A′	σ	τ
	(kg)	(t/m^3)	(%)	(-)	(cm)	(cm^2)	(kg/cm^2)	(kg/cm^2)
1	12	2.63	100	p	0.16	35.04	0.34	0.68
				r	0.56	32.64	0.37	0.48
2	12	2.62	100	p	0.14	35.16	0.35	0.68
				r	0.60	32.40	0.37	0.49
3	12	2.63	100	p	0.18	34.92	0.34	0.67
				r	0.54	32.76	0.38	0.48
4	24	2.63	100	p	0.18	34.92	0.69	1.13
				r	0.66	32.04	0.75	0.83
5	24	2.62	100	p	0.20	34.80	0.68	1.13
				r	0.64	32.16	0.75	0.82
6	24	2.62	100	p	0.16	35.04	0.69	1.12
				r	0.68	31.92	0.74	0.83
7	36	2.63	100	p	0.33	34.00	1.07	1.59
				r	0.68	31.92	1.13	1.21
8	36	2.63	100	p	0.32	34.08	1.08	1.59
				r	0.72	31.68	1.13	1.20
9	36	2.62	100	p	0.36	33.84	1.07	1.60
				r	0.66	32.04	1.12	1.21

Table A.9 Direct Shear Test Results of EAF Dust

Test No	Normal Load	Dry Unit Weight	Relative Density	Peak Residual	Deformation	Corrected Area	Normal Stress	Shear Strength
	N	γ_d	D_r	P/r	ΔL	A′	σ	τ
	(kg)	(t/m^3)	(%)	(-)	(cm)	(cm^2)	(kg/cm^2)	(kg/cm^2)
1	12	2.22	100	p	0.12	35.28	0.34	0.61
				r	0.32	34.08	0.35	0.43
2	12	2.21	100	p	0.16	35.04	0.33	0.61
				r	0.30	34.20	0.34	0.43
3	12	2.21	100	p	0.10	35.40	0.34	0.62
				r	0.36	33.84	0.35	0.42
4	24	2.22	100	p	0.10	35.40	0.68	0.98
				r	0.38	33.72	0.70	0.77
5	24	2.21	100	p	0.08	35.52	0.69	0.98
				r	0.40	33.60	0.71	0.77
6	24	2.21	100	p	0.12	35.28	0.68	0.97
				r	0.36	33.84	0.70	0.78
7	36	2.21	100	p	0.16	35.04	1.03	1.30
				r	0.40	33.60	1.06	1.11
8	36	2.22	100	p	0.20	34.80	1.02	1.30
				r	0.44	33.36	1.06	1.12
9	36	2.22	100	p	0.18	34.92	1.03	1.31
				r	0.38	33.72	1.06	1.10

Table A.10 Oedometer Test Results of EAF Slag

Load Increment ΔP	Dial Readings Initial (D_b)	Final (D_f)	Change In Specimen Height $\Delta H_i=(D_f-D_b)x0.0002$	Change In Void Ratio $\Delta e_i=\Delta H_i/H_s$	Inst. Void Ratio $e_i=e_{i-1}-\Delta e_i$	Average Void Ratio $e=(e_i+e_{i-1})/2$	Coefficient of Compressibility $a_v=\Delta e_i/\Delta P$	Coefficient of Volume Compressibility $m_v=a_v/(1+e_0)$
(kg/cm^2)	(-)	(-)	(cm)	(-)	(-)	(-)	(cm^2/kg)	(cm^2/kg)
					$e_o=0.371$			
0.25	622	668	0.009	0.007	0.364	0.368	0.028	0.020
0.25	668	684	0.003	0.002	0.362	0.363	0.008	0.006
0.50	684	705	0.004	0.003	0.359	0.361	0.006	0.005
1.00	705	738	0.007	0.005	0.354	0.357	0.005	0.004
2.00	738	779	0.008	0.006	0.348	0.351	0.003	0.002
4.00	779	837	0.012	0.009	0.339	0.344	0.002	0.001

Load Decrement ΔP	Dial Readings Initial (D_b)	Final (D_f)	Change In Specimen Height $\Delta H_i=(D_f-D_b)x0.0002$	Change In Void Ratio $\Delta e_i=\Delta H_i/H_s$	Inst. Void Ratio $e_i=e_{i-1}-\Delta e_i$	Average Void Ratio $e=(e_i+e_{i-1})/2$	Coefficient of Compressibility $a_v=\Delta e_i/\Delta P$	Coefficient of Volume Compressibility $m_v=a_v/(1+e_0)$
(kg/cm^2)	(-)	(-)	(cm)	(-)	(-)	(-)	(cm^2/kg)	(cm^2/kg)
					$e_o=0.339$			
4.00	837	829	0.0015	0.001	0.340			
2.00	829	815	0.003	0.002	0.342			
1.00	815	800	0.003	0.002	0.344			
0.50	800	786	0.003	0.002	0.346			
0.25	786	770	0.003	0.002	0.348			

Table A.11 Oedometer Test Results of EAF Ladle Slag

Load Increment ΔP	Dial Readings Initial (D_b)	Final (D_f)	Change In Specimen Height $\Delta H_i=(D_f-D_b)x0.0002$	Change In Void Ratio $\Delta e_i=\Delta H_i/H_s$	Inst. Void Ratio $e_i=e_{i-1}-\Delta e_i$	Average Void Ratio $e=(e_i+e_{i-1})/2$	Coefficient of Compressibility $a_v=\Delta e_i/\Delta P$	Coefficient of Volume Compressibility $m_v=a_v/(1+e_0)$
(kg/cm^2)	(-)	(-)	(cm)	(-)	(-)	(-)	(cm^2/kg)	(cm^2/kg)
					$e_o=0.238$			
0.25	687	716	0.006	0.004	0.234	0.236	0.016	0.013
0.25	716	726	0.002	0.001	0.233	0.234	0.004	0.003
0.50	726	742	0.003	0.002	0.231	0.232	0.004	0.003
1.00	742	765	0.005	0.003	0.228	0.230	0.003	0.002
2.00	765	796	0.006	0.004	0.224	0.226	0.002	0.002
4.00	796	841	0.009	0.006	0.218	0.221	0.002	0.001

Load Decrement ΔP	Dial Readings Initial (D_b)	Final (D_f)	Change In Specimen Height $\Delta H_i=(D_f-D_b)x0.0002$	Change In Void Ratio $\Delta e_i=\Delta H_i/H_s$	Inst. Void Ratio $e_i=e_{i-1}-\Delta e_i$	Average Void Ratio $e=(e_i+e_{i-1})/2$	Coefficient of Compressibility $a_v=\Delta e_i/\Delta P$	Coefficient of Volume Compressibility $m_v=a_v/(1+e_0)$
(kg/cm^2)	(-)	(-)	(cm)	(-)	(-)	(-)	(cm^2/kg)	(cm^2/kg)
					$e_o=0.218$			
4.00	841	833	0.0015	0.001	0.219			
2.00	833	820	0.003	0.002	0.221			
1.00	820	806	0.003	0.002	0.223			
0.50	806	791	0.003	0.002	0.225			
0.25	791	775	0.003	0.002	0.227			

Table A.12 Oedometer Test Results of EAF Dust

Load Increment ΔP	Dial Readings Initial (D_b)	Dial Readings Final (D_f)	Change In Specimen Height $\Delta H_i=(D_f-D_b)x0.0002$	Change In Void Ratio $\Delta e_i=\Delta H_i/H_s$	Inst. Void Ratio $e_i=e_{i-1}-\Delta e_i$	Average Void Ratio $e=(e_i+e_{i-1})/2$	Coefficient of Compressibility $a_v=\Delta e_i/\Delta P$	Coefficient of Volume Compressibility $m_v=a_v/(1+e_0)$
(kg/cm^2)	(-)	(-)	(cm)	(-)	(-)	(-)	(cm^2/kg)	(cm^2/kg)
					$e_o=0.985$			
0.25	675	745	0.014	0.015	0.970	0.978	0.060	0.030
0.25	745	770	0.005	0.005	0.965	0.968	0.020	0.010
0.50	770	799	0.006	0.006	0.959	0.962	0.012	0.007
1.00	799	853	0.011	0.011	0.948	0.954	0.011	0.006
2.00	853	944	0.018	0.019	0.929	0.939	0.010	0.005
4.00	944	1104	0.032	0.033	0.896	0.913	0.008	0.004

Load Decrement ΔP	Dial Readings Initial (D_b)	Dial Readings Final (D_f)	Change In Specimen Height $\Delta H_i=(D_f-D_b)x0.0002$	Change In Void Ratio $\Delta e_i=\Delta H_i/H_s$	Inst. Void Ratio $e_i=e_{i-1}-\Delta e_i$	Average Void Ratio $e=(e_i+e_{i-1})/2$	Coefficient of Compressibility $a_v=\Delta e_i/\Delta P$	Coefficient of Volume Compressibility $m_v=a_v/(1+e_0)$
(kg/cm^2)	(-)	(-)	(cm)	(-)	(-)	(-)	(cm^2/kg)	(cm^2/kg)
					$e_o=0.896$			
4.00	1104	1081	0.005	0.005	0.901			
2.00	1081	1055	0.005	0.005	0.906			
1.00	1055	1027	0.0055	0.006	0.912			
0.50	1027	996	0.006	0.006	0.918			
0.25	996	960	0.007	0.007	0.925			