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Feasibility of Expanding the Use of Steel Slag as a Concrete Pavement Aggregate

Brad A. Fronek
Cleveland State University

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FEASIBILITY OF EXPANDING THE USE OF STEEL SLAG AS A CONCRETE PAVEMENT AGGREGATE

BRAD A. FRONEK

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Cleveland State University

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Department of Civil and Environmental Engineering,
and the College of Graduate Studies by

Thesis Committee Chairperson, Dr. Paul Bosela

Department, Date

Dr. Norbert Delatte

Department, Date

Dr. Lutful I. Khan

Department, Date

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ABSTRACT

Sustainability has become an important aspect of developed countries throughout the world. Sustainability is the ability to use byproducts and or waste materials from industry and recycle these materials in such a way that the application of the materials provides a beneficial use in the manufacturing or construction sector. As the United States and the rest of the world continue to grow, so too does the demand on the limited natural resources throughout the world. It is this demand on the resources that has brought the idea of sustainability to the forefront of research and design.

The transportation industry continues to incorporate sustainability into its projects. The industry is constantly trying new and innovative ways to recycle materials that would otherwise be sent to a landfill. Slag, a byproduct from the production of steel, is one of these materials. The transportation sector has used slags as aggregates for subbase and base layers in roads. Some slags, like blast furnace slag, have been used in portland concrete cement (PCC) applications as well. The focus of this research is to investigate the feasibility of using steel slag as an aggregate for use in portland concrete cement.

An important aspect of this research was to complete a comprehensive review of other research that has been conducted on the use of steel slag as an aggregate. The literature reviewed included of laboratory studies that focused on the physical, mechanical, chemical, and expansive characteristics of the steel slag. The research on the use of steel slag was gathered from 16 different countries, which include the United States, Spain, Japan, China, Germany, Finland, and Saudi Arabia. Some of these studies have found that properly treated slag may be non-expansive and used in PCC. The possible expansion of the steel slag is the most important characteristic. The expansion of the steel slag aggregate can have detrimental effects on a pavement. This research investigated some of the treatment processes that are being used to alter the composition of the slag so that it is no longer expansive. It also examines testing methods used to test for the expansion of the steel slag.

Seven State Department of Transportation specifications were also reviewed. Some DOT's allow its use as an aggregate in asphalt pavements but do not allow its use in portland concrete cement. A review of the ASTM standards relating to the use of the slag as an aggregate was also completed in this study. Different slag associations like the National Slag Association and the Australian Slag Association were contacted during this research, as well as 19 different steel companies, to try and get an understanding of the public perception of the use of the steel slag as an aggregate in PCC, and also to try and locate possible case studies. Several case studies were identified, and two of them resulted in a failure of the pavement. In those cases it is unknown what, if any, treatment process was used on the slag prior to its use in the portland concrete pavement.

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Conversion Factors from English to SI Units

Symbol	_	Known quantity	_	Multiply By	_	To Find	_	Symbol
Length								
in		inches		25.4		millimeters		mm
ft		feet		0.305		meters		m
yd		yards		0.914		meters		m
mi		miles		1.61		kilometers		km
Area								
in^2		square inches		645.2		square millimeters		mm^2
ft^2		square feet		0.093		square meters		m^2
yd^2		square yards		0.836		square meters		m^2
mi^2		square miles		2.59		hectares		ha
ac		acres		0.405		square kilometers		km^2
Volume								
fl oz		fluid ounces		29.57		milliliters		ml
gal		gallons		3.785		liters		L
ft^3		cubic feet		0.028		cubic meters		m^3
yd^3		cubic Yards		0.765		cubic meters		m^3
Mass								
oz		ounces		28.35		grams		g
lb		pounds		0.454		kilograms		kg
T		short tons (2000 lbs)		0.907		mega grams or "metric ton"		Mg or "t"
Temperature								
^{0}F		Fahrenheit		(F-32) / 1.8		Celsius		^{0}C
Illumination								
fc		foot candles		10.76		lux		lx
fl		foot-Lamberts		3.426		candela/m^2		cd/m^2
Force / Pressure / Stress								
lbf		Pound force		4.45		Newtons		N
lbf/in^2		Pound force per square inch (psi)		6.89		kilopascals		kPa

SI is the symbol for th International System of Units. In order to comply with Section 4 of ASTM E380, the appropriate rounding should be made.

NOMENCLATURE

AASHTO	American Association of State Highway and Transportation Officials
ACBFS	Air Cooled Blast Furnace Slag
AES	Atomic Emission Spectrometry
AOD	Argon Oxygen Decarburization
AWQC	Ambient Water Quality Criteria
ASTM	American Society for Testing and Materials
BOF	Basic Oxygen Furnace
CTE	Coefficient of Thermal Expansion
COI	Constituents of Interest
CCS	Crushed Carbonate Stone
DI	Distress Index
EAF	Electric Arc Furnace
EDS	Energy Dispersive Spectrometry
Euroslag	The European Slag Association
FHWA	Federal Highway Administration
FS	Foundry Sand
GBFS	Granulated Blast Furnace Slag
GGBFS	Ground Granulated Blast Furnace Slag
HI	Hazard Index
ICP	Inductively Coupled Plasma
IDOT	Illinois Department of Transportation
IR	Infrared
LFS	Ladle Furnace Slag
LMA	Light Mineral Aggregates
MCS	Mineral Commodity Summaries
MDOT	Michigan Department of Transportation
MLE	Most Likely Exposure
RME	Reasonable Maximum Exposure
NSA	National Slag Association
NWC	Normal Weight Concrete
ODOT	Ohio Department of Transportation
OPC	Ordinary Portland Cement
PADOT	Pennsylvania Department of Transportation
PCC	Portland Concrete Cement
PS Ball	Precious Slag Ball
PSVs	Polished Stone Values

SAT	Slag Atomizing Technology
SEM	Scanning Electron Microscopy
SG	Specific Gravity
UCL	Upper Confidence Limit
USGS	United States Geological Survey
w/cm	Water-to-cementitious Materials Ratio
XRD	X-Ray Diffraction

CHEMICAL COMPOUNDS AND FORMULAS

CaO	Calcium oxide
SiO_2	**S**ilicon dioxide
Fe_2O_3	Iron (III) oxide
Al_2O_3	Aluminum oxide
MgO	Magnesium oxide
MnO	Manganese oxide
SO_3	Sulfur trioxide
P_2O_5	Phosphorus pentoxide
TiO_2	Titanium dioxide
Na_2O	Sodium oxide
K_2O	Potassium Oxide
Free CaO	Free Lime
Free MgO	Free Magnesium
Ca_2SiO_4	Dicalciumsilicate
Ca_2FeO_5	Dicaliumferrite
FeO	Wusite
$Ca(OH)_2$	Slaked Lime

CHAPTER I

INTRODUCTION & OBJECTIVE

1.1 Introduction

The need to recycle materials in society today has become more important as the demands on our natural resources continue to grow. As the population of the United States and the rest of the world continues to grow, so too does the need to expand and repair the infrastructure. Two of the main components of the infrastructure are steel and concrete and this is why these two industries have seen a steady increase in demand over the last thirty to forty years.

Concrete is a very versatile building material that is used in nearly every aspect of the infrastructure of developed countries. It is used in structural components such as beams, columns, floors, walls and dams. It is also used in pavement applications like parking lots, roads, and bridges. Concrete is comprised of fine and coarse aggregates, which account for 60 to 70% of the concrete, and the remaining components are water and the cement, which is the binding material that solidifies and holds the mixture together. With such a large portion of concrete being comprised of aggregates, this has put an increasing demand on the limited supply of natural aggregates.

This increase in demand has led to many innovations and reuse of products that would have been considered waste materials and disposed of in landfills. With only so many natural resources available for use and a limited amount of space for landfill, it is very important to finds ways to reuse and recycle materials that would otherwise be disposed. Steel slag is a leftover component from the steel making process and is a material that at one time was considered a waste material that was disposed of in landfills. Today steel slag is no longer considered a waste material and is now considered a byproduct from the steel making process that is used in a variety of different ways.

The use of the steel slag as a replacement for part or all of the natural aggregates in concrete could be beneficial to the environment in many ways. Some of the environmental impacts that could be seen from using the slag in concrete would be a reduction in the amount of landfill, reducing the CO_2 produced by equipment during the mining of natural aggregates, and lowering the cost of shipping if there is a steel plant closer to the concrete plant than the location of the natural aggregates. Reducing the distance the aggregate is shipped would also reduce the emissions from trucks during shipping. This report focuses on the use of steel slag as a replacement for natural aggregates in concrete pavement applications.

1.2 Objective

The objective is to support the FHWA Office of Pavement Technology to conduct research to summarize available literature, research files, testing standards, examine the technical properties of steel slag, specifications, and case studies. This research will provide guidance to state highway agencies, steel-slag producers and suppliers, and paving contractors concerning the potential use of steel slag as an aggregate in concrete for paving applications.

In order to provide guidance to government agencies, slag producers / suppliers and paving contractors, a thorough and comprehensive review of literature was conducted. The literature consisted of laboratory studies and documents from government agencies from 16 countries around the world. While conducting the literature reviews, companies and government agencies were contacted to try and obtain a general understanding on the perception and reputation of steel slag and also to locate possible field case studies. Various personal were asked questions regarding the physical and chemical properties of steel slag. During the questioning and interview process, it became apparent that steel slag's tendency for differential expansion was the main reason that it was not currently used as an aggregate in concrete. When asked if it had ever been used in portland cement concrete as an aggregate, none of the companies contacted knew of any such case. Current applications of steel slag and the possibility of using the steel slag as an aggregate in PCC were discussed. The companies and agencies contacted during this research can be found in Table 1.

Company	Location	Company	Location
ArcelorMittal	Cleveland, Ohio	The Timken Company	Canton, Ohio
Wheeling Corrugating Co, Division of Pittsburg Steel	Wheeling, W. Virginia	U.S. Steel – Lorain Tubular Operations	Lorain, Ohio
Severstal North America	Wheeling West Virginia	Severstal North America	Dearborn, Mi.
Tomas Steel Strip Corp.	Warren, Ohio	McDonald Hopkins LLC	Cleveland Ohio
Charles Hesse Associates	Cleveland, Ohio	Cliffs Natural Resources	Cleveland Ohio
Tube City IMS	Gary, IN	Tube City IMS	Glassport, PA
Edw. C. Levy Co.	Northville, MI	Edw. C. Levy Co.	Valparaiso, IN
AK Steel	West Chester, Ohio	Nucor Steel Marion Inc.	Columbus, Ohio
Public Affairs Associates	Hudson, Ohio	Stein Inc.	Cleveland, Ohio
URS Greiner Engineering	Tampa, Florida	ODOT	Materials Office, Cleveland, Ohio
FLDOT	Materials Office, Gainesville, FL	Steel Manufacturers Association	Washington, DC
National Slag Association	Pleasant Grove, UT		

Table 1: Companies, Agencies, and Organizations contacted.

The possibility of using steel slag in concrete will not only depend on its availability, but also its physical properties, mechanical properties and chemical properties. The following report contains an overview of steel slag, the physical properties of steel slag, the mechanical and durability aspects of concrete containing the slag, the chemical properties of steel slag, all aspects related to expansion and volume stability, a review of state DOT specifications, and finally case studies and recommendations.

The overview of steel slag includes descriptions of the three types of steel slags discussed throughout this report. They are basic oxygen furnace slag, electric arc furnace slag and ladle furnace slag. The production of steel and steel slag in the United States and the world is examined along with recent trends and current uses and applications. Steel slag must possess similar or superior physical properties to natural aggregates that are currently used in portland concrete cement.

The physical properties evaluated in this reported are the gradations of the slag, its density, porosity, absorption, and abrasion resistance. Acquiring the proper gradations of the aggregates for concrete applications is crucial. Concrete containing aggregates that do not meet the gradation requirements can increase the amount of cement required for the concrete and increase the void spaces between the aggregates. The porosity of an aggregate is significant because the higher the porosity, the more surface area there is for the cement paste to bond to the aggregate. The absorption of an aggregate is also a significant property since aggregates that have a low absorption will consume less water, which will make more water available for the hydration of the cement. Finally, the examination of steel slag's resistance to abrasion is studied. The abrasion resistance of an aggregate is its ability to resist wear, and this is of concern since an aggregate with a low abrasion factor can lead to a decrease in the performance and life of the pavement.

A major factor in the use of steel slag as an aggregate in concrete is that it needs to have similar mechanical properties as concrete containing natural aggregates. The mechanical properties of concrete reviewed and discussed are: the compressive, splitting tensile and flexural strengths, the elastic modulus of concrete, and the resistance to penetration of water. The durability of concrete containing steel slag is another important criterion that must be met in order for it to be used as an aggregate in concrete. The laboratory results of durability testing on concrete containing steel slag includes freezing and thawing, wetting and drying, high temperature exposure, and the durability of concrete to resist attach from chloride ions.

It is important to maintain good workability of concrete containing steel slag. If the concrete is unable to maintain the proper slump and is too difficult to work with and finish, then it is likely that it will have a difficult time gaining acceptance by the paving industry. The results of slump tests from concrete containing steel slag are compared to DOT specifications, and the ability to pump the concrete into place has also been reviewed.

The chemical composition and properties of steel slag can be separated into three parts consisting of the overall chemical and mineralogical compositions, the environmental aspects related to the alkalinity and leaching of metals from the slag, and the components, which are responsible for the expansion concerns of the slag. The chemical properties of steel slag are dependent on the type of process used to produce the steel. The chemical compositions of each of the three types of slag were examined in order to determine their chemical and mineralogical differences. The chemical components of BOF, EAF and LF slag were compiled from literature and then compared to ranges suggested by other authors.

There are some environmental concerns that are indirectly related to its use in concrete. Steel slag has a high pH value and contains some metals that are leftover components from the production of steel. Since the slag will be contained and bound in the concrete, it is unlikely that the metals would be able to leach from the concrete. However, the slag must be processed, aged, and handled prior to its use in the concrete, and therefore the human and ecological risk assessments were reviewed and discussed.

The final chemical components of the slag that are discussed are perhaps the most important because they are responsible for the volume instability of the steel slag. They are free lime (CaO) and periclase (MgO). The origins of the free lime and free periclase are discussed, as well as limits on these components, which have been suggested by different authors and task groups. The feasibility of using steel slag as an aggregate will depend on eliminating or reducing these chemicals so that the expansion of the steel slag is not detrimental to the concrete.

It is essential to develop treatment methods that can reduce the chemical components that are responsible for the expansion. The most common method currently used for treating the slag is aging the slag in stockpiles while spraying it with water. This method hydrates the free lime and free periclase. This hydration can reduce the expansion of the slag. Another method that is currently in use in Europe is the treatment of the steel slag by the addition of silica sand and oxygen into the molten slag, which chemically alters the slag (Yunxia et al., 2008). Some other treatment options that have been used are the cooling of the slag rapidly by quick quenching methods instead of allowing the slag to cool slowly in slag pits. There are also some newer methods that have been suggested in literatures such as steaming the slag for periods of time that range from three hours to days. These methods work on the same principals as spraying the slag with water to hydrate the free lime and free periclase. The final method discussed is to remove the free lime by chemically treating the slag, which removes the free lime from the steel slag (Eloneva et al., 2008). All the methods for treating the slag discussed are effective to some degree at reducing or removing the components responsible for the expansion, but they do not eliminate the need to test for the expansion.

The expansion of the slag is the single and most significant aspect related to the feasibility of its use as an aggregate in concrete paving applications. The expansion of the slag aggregate over time is dependent on the amount of free lime and free periclase contained in the slag. The hydration of the free lime usually takes place over a short period of time, while the hydration of free periclase takes place over a long period of time. While a small amount of expansion should not cause harm within the concrete matrix, the effects of the expansion could have serious consequences if it becomes too large. Due to the concerns with the expansion of steel slag there have been different methods developed to test the steel slag for expansion.

Since the expansion of the slag is such a key aspect of its use in concrete, and slag produced at different steel plants will have different chemical compositions, it is imperative that quick and reliable testing methods be developed to test the slag for expansion. One such test that is currently used is the PennDot Test, which tests for the expansion of the slag for use in unbound applications like a compacted shoulder of a road and also for use in bound applications like an asphalt pavement. Another test that has been developed and is currently an accepted method of testing for the expansion in Europe is the German Steam Test, also known as the accelerated swelling test (Motz et al., 2001). Other methods have been developed and used in laboratory studies to test for the expansion of the slag. They are the autoclave test, the accelerated aging test, and the delayed autoclave test.

Steel slag is currently being used as an aggregate in the production of a masonry stone called Armour stone. This stone is used in applications in hydraulic structures like a decorative waterfall. A new test called the boiling test was developed by the Expert

Group “Armourstone,” so they could utilize the steel slag in their product (Motz et al., 2001). One final test that has been developed is the expansion force test. This testing method is used to determine the expansion force generated by steel slag particles during the hydration process (Wang, 2010). This testing method may eventually be able to predict whether the expansion of a slag will be enough to cause issues with the integrity of the concrete. The expansion force test might also be used in the future to construct expansion curves based on the forces generated, that could then be used to accept or reject a slag based on the forces generated during this test.

A comprehensive review of laboratory testing on PCC containing steel slag as an aggregate was completed. Over the past decade, there has been considerable testing of concrete specimens containing steel slag as an aggregate in PCC. Many of these studies have been conducted using steel slag in PCC as a fine aggregate, coarse aggregate or both. The results of these studies and the results of laboratory expansion testing of steel slag as an aggregate have been examined.

The feasibility of using steel slag as an aggregate in PCC pavement applications will only be possible if the material specifications for pavements allow for its use. A review of seven DOT material specifications was conducted to see what restrictions, if any, have been placed on the use of steel slag. Generally speaking, steel slag is widely accepted as an aggregate in unbound applications as a base course, shoulders and as a fill material. In recent years it has obtained some acceptance as an aggregate in bituminous asphalt concretes by some state DOT’s. At the current time, no state DOT has approved the use of steel slag in portland concrete cement as an aggregate in pavement applications.

This research sought possible case studies in which steel slag had been used as an aggregate in a pavement. If successful applications could be located, it would help to demonstrate that steel slag could be used in PCC pavement applications effectively. There were two case studies located in the United States that used the steel slag in an econocrete subbase pavement in Florida. The first case study was Interstate 75, which used the slag in an econocrete pavement in the late 1970’s and failed in part due to the expansion of an electric arc furnace steel slag (Armaghani et al., 1988). The second case study examined was the runway at Tampa International Airport, which resulted in the catastrophic failure of the econocrete base and overlying pavement. It is unknown if the steel slag had been aged prior to its use in either of the econocrete pavements. The weathering of steel slag in stockpiles did not begin in the United States until the mid to late 1980’s. There were several case studies located overseas, but these applications did not use the steel slag in traditional pavement applications.

The first international case study is the Labein-Tecnalia Kubik Building in Madrid Spain (Chica et al., 2011). The slag concrete was used in a structural application, which consisted of the basement walls and the reinforced foundation slab. The aggregates used in the construction of the basement floor slab and the walls consisted of 100% EAF slag for the fine and coarse aggregates. Two other case studies used a stainless steel slag as an aggregate in concrete. These case studies were both in Belgium, with one application as a subbase layer for a slag storage facility, and the other as a roller compacted concrete for a rural road (De Bock & Van den Bergh, 2004). The stainless steel slag that was used in both of the case studies originated from an electric arc furnace. The final case study is a mixture called Ferroform and is comprised of GGBFS as a binding agent and steel slag as an aggregate, which has comparable mechanical properties as concrete. This material can be used to construct concrete blocks, natural stones, and concrete (Matsunaga et al., 2008). The Ferroform mixture is comprised of steel slag as the fine and coarse aggregate, GGBFS, fly ash and an alkali activator such as slaked lime and water. The Ferroform mixture has been used in Japan for the filling of a basement floor in 2003 and in the construction of blocks, which can be mass-produced in a manufacturing plant and are cured by steam. Ferroform blocks have also been used by Japan in the repair and construction of ports and harbor sea walls.

CHAPTER II

OVERVIEW OF STEEL SLAG

Slag that is produced from the production of metals can be classified into two different types of slag, ferrous and nonferrous. The ferrous slags can then be divided into two different types of slags, blast furnace slag and steel slag. Nonferrous slags can be subdivided into ferronickel slag and copper slag (Nippon Slag Association, 2006).

Blast furnace slag is formed with the molten steel by the melting of iron ore or pellets with lime or dolomite, coke or fly ash. The fluxing agent such as lime combines with the silicates and other elements, which results in the production of the slag. The slag not only helps to remove impurities from the smelted steel, but it also helps to protect the lining of the furnace. There are three types of blast furnace slag that can be produced: air cooled (ACBFS), expanded, and granulated slag (GBFS) (Kalyoncu, 2001). Steel slag is produced in a similar manner to blast furnace slag and can be separated into categories depending on the process used to form the steel.

2.1 Steel Slag

After the iron ore is smelted in the blast furnace, the pig iron that is produced from the process can then be used in a second process to produce steel. It is this second process that produces the steel slag. Steel slag is formed as a fluxing agent like lime or dolomite reacts with the molten iron ore or molten scrap metal. The fluxing agent reacts with the molten steel and the impurities from the mixture form the slag. After removing the entrained metals from the slag, the contents of the slag consist mainly of oxides and silicates (Department Of The Army, Sept. 15, 1999). The American Society for Testing and Materials (ASTM) defines Steel Slag as a non-metallic product, consisting essentially of calcium silicates and ferrites combined with fused oxides of iron, aluminum, manganese, calcium and magnesium, that is developed simultaneously with steel in basic oxygen, electric arc, or open hearth furnaces (National Slag Association (d), No Date).

Steel slag can be produced from a variety of processes that include Open Hearth Furnace (OHF), Basic Oxygen Furnace (BOF), and an Electric Arc Furnace (EAF). Due to the amount of time the OHF takes to produce the steel, most of them have been closed since the early 1990's, and have been replaced by BOF and EAF processes.

2.1.1 Basic Oxygen Furnace Slag

Basic oxygen furnace (BOF) slag is produced when the hot molten iron from the blast furnace process is combined with scrap metals and a fluxing agent like lime or dolomite. Oxygen is then blown into the chamber and through the molten iron, which lowers the carbon content. This results in a reaction that produces a high quality steel product and the by-product steel slag. The BOF process was developed in 1948 by Robert Durrer, but was not commercialized until 1952 (A Steel, Grade, 2011). Basic oxygen furnace slag can also be referred to as converter slag

2.1.2 Electric Arc Furnace Slag

An electric arc furnace uses cold steel or scrap steel to produce a new alloy steel from the recycled steel. The scrap steel is placed into the furnace and then the graphite electrodes are lowered into place. The contents placed in the furnace have to be carefully monitored in order to control the chemical composition of the mixture. Chemical elements are added to the mixture to help remove impurities from the molten steel. The amount of chemicals added to the mixture will vary from furnace to furnace. Some of the elements that are added to the mixture are magnesium, aluminum, and silicon. An electrical current is then passed through the electrodes, and an arc is produced, which melts the steel scrap. Oxygen is then blown in to the furnace in order to produce a low carbon steel. Once the process is complete, the molten steel can be used to cast new steel or it can be poured into a separate ladle for further processing. The impurities that have been removed from the molten steel form the by-product, which is known as steel slag. Electric arc furnace slag can also be known as black slag (due to its color), acid slag, and oxidizing slag (Polanco et al., 2011).

2.1.3 Secondary slags

Secondary slags are produced from the further refining of the EAF process in which the molten steel is poured from the EAF to a ladle and the steel is processed again. This secondary refining process can produce special high quality steels such as stainless steel. This process leads to Argon Oxygen Decarburization (AOD) slags, (Bohmer, et al., 2008). Argon Oxygen Decarburization is a process that is used to refine the molten steel to produce stainless steel. Prior to its use, the amount of chromium in the steel needed to be increased after the steel had been decarburized, since the decarburization caused the oxidation of the chromium. The decarburized process is accomplished by subsurface blowing with the Argon / Oxygen gas mixture, which allows the steel to be decarburized without the oxidation of the chromium (Heise, 1973). Ladle furnace slags break down very rapidly after being exposed to the outdoors and weather, usually within a week, unless the Argon Oxygen Decarburization process is used in the processing of the steel. The breaking down of LF slag is called slaking and is due to the expansion of the free lime and periclase, which react with the moisture and water to produce hydroxides. The volume of the slag essentially doubles and turns to dust that can be blown away by the wind (Manso et al., 2005).

2.2 Steel Slag Production

The steel industry and ferrous foundries produced products that were estimated to be worth approximately $139 billion dollars in 2010. There are approximately 56 companies in the U.S. that produced raw steel, with a combination of iron and steel production of 108 million tons. The largest producing states were Indiana, accounting for 24% of total raw steel production, with Ohio accounting for 10%, Michigan and Pennsylvania accounting for 7% each (United States Geological Survey, 2011). BOF production has seen a decrease in production from 42.9% in 2006 to 39% in 2010, while EAF production has seen a slight increase from 57.1% in 2006 to 61% in 2010.

2.2.1 Domestic Production

Slag production data is not available since it is not measured on a routine basis, but it can be estimated based on a ratio of slag to metal produced. Steel slags are produced at a rate of approximately 0.2 tons of slag per ton of crude steel. Approximately 50% of the ferrous metal in the slag can be recovered during the processing of the slag. The result of this processing is that the overall amount of slag produced per ton of crude steel is reduced to approximately 0.1 to 0.15 ton per ton of crude steel. This is the amount of steel slag that is available for uses in applications such as an aggregate base (United States Geological Survey, MYB, 2009). Sales have ranged from a high of $21.6 million in 2005 to a low of $12.5 million in 2009. Steel slag accounted for $5.7 million of the $12.5 million in sales in 2009. The unit value of the slags has seen a relatively steady increase from $6.63 per ton in 1993 to $19.0 per ton in 2009 (United States Geological Survey, 2011).

According to the USGS Mineral Commodity Summaries (MCS) 2011, slag productions were estimated to have increased by 30%, from 11 million tons to 15 million tons in 2010. This is attributed to the increase in demand of steel, which was answered by the restarting of many furnaces that had not been used in recent years. In 2010, 15 million tons of iron and steel slag were sold for approximately $290 million. The sales from steel slag accounted for 40% of the tonnage sold, but only accounted for 15% of the total sales. Approximately 30 companies process slag across 32 states.

2.2.2 World Steel Production

The production of steel has been fairly constant since the 1950’s to the present with an exception of a small period during the late 2000’s. The growth rate from 1996 to 2000 was 2.4% and from 2000 to 2006, it increased to a rate of 6.1%. During the late 2000’s, however, the rate showed a decrease and was reduced to 4.3%. The world growth rate of steel production increased from 2000 to 2006 and decreased when the world's economy slowed in 2008 – 2009 period. The top steel producing countries, with China leading the production of steel, producing 626.7 million metric tons in 2010, which accounted for 44.3% of the world's steel production. Japan produced 109.6 million metric tons, which accounted for 7.75% of the world's production and the United States produced 80.5 million metric tons which was 5.69% of production (World Steel Association, 2011).

2.2.3 Events, Trends, and Issues

According to the USGS MCS, BOF slags have become less available due to the decrease in the production of steel and due to the increase in the amount of slag that is recycled back into the furnace while EAF slags continue to be accessible. When the slag sales have remained stable, sales to the construction sector remained less volatile then natural aggregates (United States Geological Survey, 2011). Many steel plants were forced to shut down or go idle for a period of time in the last decade due to lack of demand for steel. Due to the decrease in production of steel from electric arc furnaces and basic oxygen furnaces during the recent economic times, the amount of slag being stockpiled and stored maybe limited.

2.3 Current Uses and Applications

While the use of slag dates back many centuries, the slag industry continues to find new applications. At one time slag was hauled away as a waste material and deposited in a landfill. In more recent years, steel slag has found use as an aggregate in asphalt pavements, in the production of cement, agricultural uses, railroad ballast and as an aggregate as a base or subbase.

2.3.1 Bituminous / Asphalt Paving

The use of steel slag in bituminous pavements has been well documented. EAF slag sand was used in the Illinois Tollway in 1994. This pavement mixture termed F-4 consisted of 36% slag sand, which provided a high skid resistance that is needed near the toll plazas. EAF slag was also used in the surface layer of I-94 in which the asphalt layer consisted of 85% slag. EAF slag was also used in the asphalt pavement in the construction of Colorado's Glenwood Canyon corridor on 1-70 (National Slag Association). The slag provided the durability needed for this stretch of road and when used in a 25% by weight mixture it provided a 20% increase in stability of the pavement.

2.3.2 Manufacture of Portland cement

In 1999, Texas Industries, Inc. (TXI) and Chaparral Steel introduced a new process of adding chunks of steel slag to the kiln for the production of cement (National Slag Association (b), No Date). This process was named the CemStar process. Portland cement clinker is similar to steel slag in its composition, which in turn means that the fuel cost to convert it to cement is low. The addition of the steel slag to the process of manufacturing cement has shown an increase in production of 15% without increasing the emissions from the manufacturing process. This not only saves money in fuel cost, but also reduces the amount of CO_2 produced from the processing. The emissions of CO_2 have been reduced by 5 to 10% per ton of CO_2 per ton of clinker. The addition of the steel slag has also reduced the emissions of NO_x by 25 to 45% on a pound per short ton of clinker.

2.3.3 Agriculture

According to the National Slag Association, steel slag has been used in agriculture as a liming agent for over a hundred years. It has been used as an agricultural amendment in Alabama, Illinois, Indiana, Kentucky, Maryland, Ohio, Pennsylvania, and West Virginia (National Slag Association (a), 2010). The chemical composition of the steel slag allows the slag to react with the soil and this reaction can reduce the pH of the soil. The steel slag is used as a fertilizer in soils for corn, rice, and soybeans. Some beneficial chemical components of the slag that can add valuable nutrients to the soil for plant life include Fe, P, S, Mn, Mo, and amounts of calcium silicate. The calcium in the slag reacts with the water and forms $Ca(OH)_2$, which then reacts with the soils acidity rapidly. The silicates in the slag will provide a long term buffering of the soil for the pH since it will react more slowly.

2.3.4 Other Applications

Steel slag has been used in applications for controlling erosion on the banks of lakes and rivers. It has also been used to adjust the pH of water coming from mines. Steel slag has even been used in the construction of reefs and sea walls. Steel slags have also been used as railroad ballast (National Slag Association (e), No Date). Its higher density allows for more resistance to movement on the lateral directions on turns in the railroad and its higher density also makes it less susceptible to being washed away. It is used in this application not only because it has a high density, but also because it has a low electrical conductivity. Steel slag is also used as an aggregate for roadway base and subbase. Steel slag can be found as a fill for landowners that need a stable and dense material to fill in low and uneven lands. One final application is by a company called Roxul, which is using the steel slag and a basalt rock to make mineral wool insulation for systems furniture panels. This material is reported to be able to withstand temperatures up to 2150^0 F (1177^{0}C) (Roxul, 2010).

2.4 Conclusions

The two main types of slag are ferrous and nonferrous slags produced from the production of metal. Steel slag is separated by the type of furnace that is used to produce the steel, and whether it is the primary process or secondary process. The three types of steel slag discussed are basic oxygen furnace (BOF) slag, electric arc furnace (EAF) slag and ladle furnace slag (LFS). There are approximately 56 companies that produce raw steel in the United States. The production of steel slag has seen a 30% increase from 2010 to 2011.

Steel slag has a wide range of uses, which include its use as an aggregate in asphalt pavement, railroad aggregate, and for base and subbase applications. Steel slag continues to be used in different applications that demonstrate that it is a durable and versatile aggregate. The use of steel slag as an aggregate in portland concrete cement will be discussed later in Chapter 8, which reviews case studies and other concrete applications which contain steel slag in concrete. The viability of using the different types of steel slag will not only depend on its availability for use, but also its ability to demonstrate that its physical, mechanical and chemical composition will not adversely affect the properties and durability of the concrete for pavement applications.

CHAPTER III

PROPERTIES OF STEEL SLAG

The physical and mechanical properties of the aggregates used in PCC are a very important aspect of the concrete. These aggregates can greatly affect the overall strength and durability of the mixture. The proper water to cement ratio is also a very important aspect of PCC. There have been many laboratory studies conducted in order to determine the different physical and mechanical properties of steel slag and the affects that they have on PCC. Steel slag has been used as a fine aggregate and a coarse aggregate in these studies. Since the steel slag aggregate has different properties than other fine and coarse aggregates, it is important to study what effects the steel slag has on the different properties of the concrete mixture.

Another aspect of steel slag that can have an effect on the concrete is the composition of the slag. Different steel plants control the input of scrap and chemicals differently, which means that EAF slags can vary in physical and chemical composition from plant to plant and country to country. This chapter examines the different physical and mechanical properties, the durability of concrete containing steel slag, and the workability of concrete mixtures with steel slag.

3.1 Physical Properties

The physical properties of steel slag are important to its potential ability to be a replacement for natural aggregates. In order for the slag to be used it must be able to meet the gradation requirements set by ASTM, and it must exhibit the qualities of natural aggregates that are currently used in portland concrete cement pavements. The physical properties discussed in this section are gradation of the slag, specific density, porosity, absorption, and abrasion resistance.

3.1.1 Gradation of Steel Slag as an Aggregate

In order for steel slag to be used as an aggregate in PCC, it must first be processed. This entails the removal of any metals like iron, which can be reused. The slag can then be separated by the size of the slag particles. Then the aggregates can be crushed to produce the necessary sizes for different applications. It is very important that the crushing of the aggregates takes place at this stage, because the slag must be properly treated to prevent volume instability. The volume instability will be discussed later in Chapter 6. The grading requirements for aggregates to be used in PCC follow ASTM C 33. The coarse aggregate is that which is 3 inches (76.2 mm) or less and is retained on the No. 4 sieve, and the fine aggregate is that which passes the No. 4 sieve.

The gradation of an aggregate refers to the distribution of the material given as the percent passing or percent retained on the particular sieve. Gradations may be characterized as uniform, dense and well-graded (National Stone Association, 1996). Aggregates usually make up 60 – 75% of the total volume of concrete. The combination of the coarse and fine aggregates helps to ensure that there are no voids between the aggregates and the cement paste. The gradation of the aggregate will depend on the thickness of the concrete and the spacing of the rebar, if used, since the aggregate must be able to pass through the rebar to the compacted base of the road. The aggregate size and shape also affects the paste requirements for the concrete. When well graded coarse and fine aggregates are used in the concrete mixture, the voids between the aggregates are reduced, which will in turn decrease the overall amount of cement paste needed for the concrete mixture.

In work conducted at Cleveland State University, a sieve analysis of a steel slag sample was compared to that of a fine graded aggregate and a coarse aggregate (Obratil et al., 2009). The results of the sieve analysis can be found in Figure 1. The results show that in this case the steel slag was a well-graded aggregate. Since crushing the steel slag is one of the processes that it under goes prior to being used, steel slag should be able to be processed in such a way to achieve the desired requirements of a coarse or fine aggregate. This study also compared the ODOT specifications for gradation of aggregates for class C pavements with the steel slag aggregate as it replaced the natural aggregate from 25% to 100 % replacement. The replacement of 25% of the natural aggregates with the steel slag resulted in the closest to the Class C, while 100 % replacement was the furthest from the curve for particles larger than 1 mm. The 25%, 50%, and 75% replacement percentages were able to achieve the required gradation for particle sizes less than 1 mm while the 100% replacement was slightly off. The results from that analysis can be found in Figure 2.

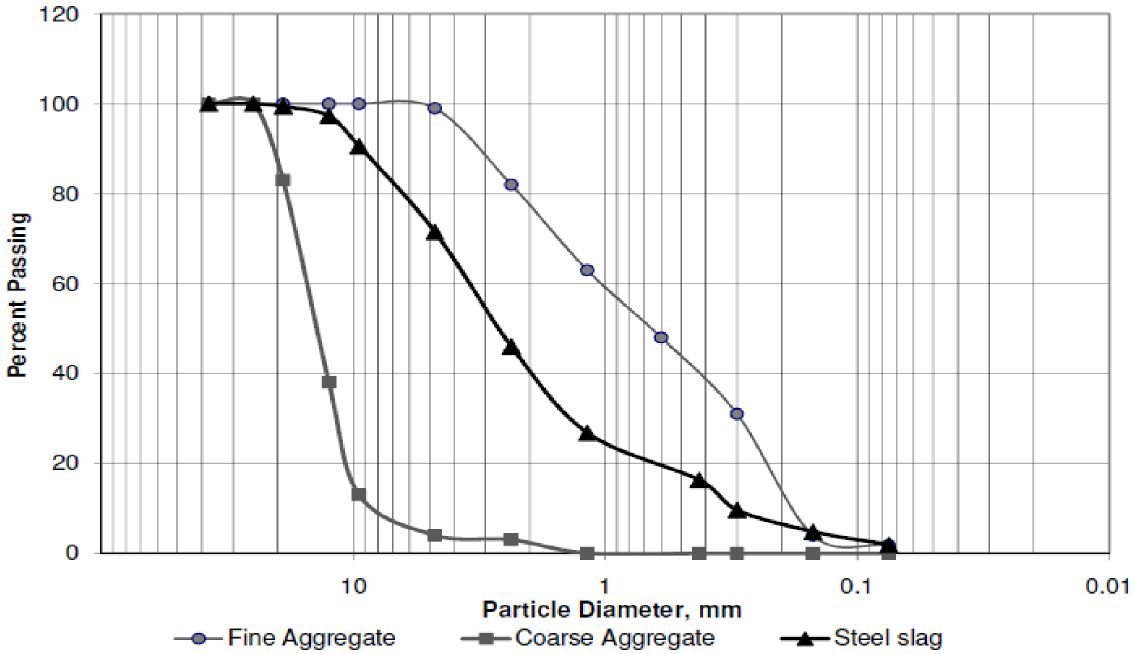


Figure 1: Sieve analysis results compared to course and fine aggregates (Obratil et al., 2009).

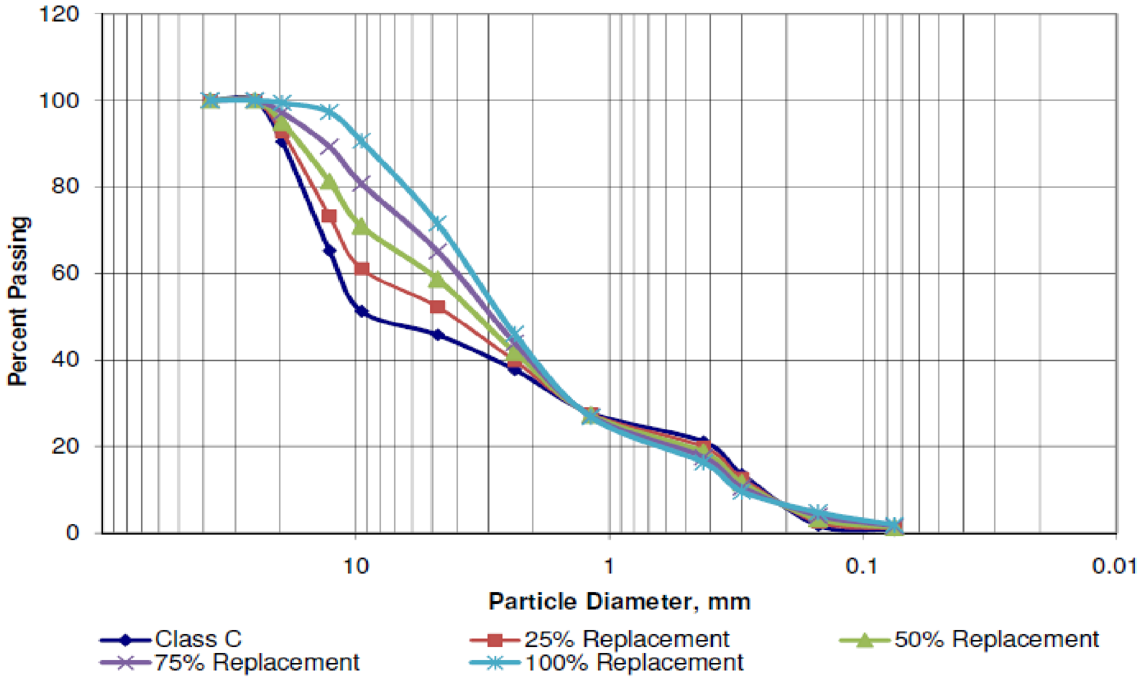


Figure 2: Comparison of replacement mixtures to ODOT Class C paving mixture (Obratil et al., 2009).

The gradation of steel slag as a fine aggregate and a coarse aggregate were examined by Manso et al. (2006) and compared to ASTM C 33. The steel slag as coarse aggregate ranged in size from 4 to 20 mm (0.16 to 0.79 inches) and the fine steel slag ranged in size from 0 to 4 mm (0 to 0.16 inches). It could be seen from the graph of the sieve analysis that the steel slag as a fine aggregate was outside the limits of ASTM C 33 and was considered a poorly graded aggregate. The graph of sieve analysis for the coarse aggregate also showed that the EAF steel slag could meet the requirements of ASTM C 33. Manso et al. (2004) conducted a study on the gradations of steel slag as a fine and coarse aggregate. A sieve analysis was conducted and it was found that the coarse aggregate was able to meet the requirements of ASTM C 33, but the sieve analysis performed on the fine aggregate steel slag resulted in the slag being outside the ranges set by ASTM C 33. There was a lack of the finest particles passing the smallest sieves. The results of the sieve analysis for steel slag as a fine aggregate were also confirmed in a study conducted by Maslehuddin et al. (2003).

A sieve analysis was conducted by Beshr et al. (2003) on an unknown steel slag for use in the testing of the physical properties of high strength concrete containing steel slag. After completing the sieve analysis, it could be seen that the coarse aggregate ranged in size from 19 mm (0.75 inches) to 2.36 mm (0.09 inches) and was within the limits set by ASTM C 33.

3.1.2 Density

The density of a slag aggregate is dependent on the process that produces the slag. Steel slag has a higher density than a natural aggregate, since the iron is infused into the slag. The densities of a particular type of slag, such as EAF slag, will have some variability in its density due to the composition and processing of the slag. An EAF slag will contain more iron oxides, and therefore will have a greater density then a limestone aggregate or even a slag aggregate that is produced from a secondary process like ladle furnace slag. The specific density (specific gravity) of the particles is measured according to ASTM C 127. The specific gravity is the ratio of the mass of a volume of aggregate to the mass of an equal volume of water. Bulk specific density is the mass of a material (including solid particles and any contained water) per unit volume including impermeable and permeable voids in the material (National Stone Association, 1996).

The specific density of calcareous limestone is 2.39 g/cm^3 and a dolomite limestone aggregate has a specific density of 2.54 g/cm^3 (Beshr et al., 2003). Table 2 provides the specific density for some common aggregates reported by the National Stone Association. Table 3 shows the specific density for different steel slags, which have been produced at different steel plants. The EAF, BOF and stainless steel slag all have a specific density that are greater than the limestone aggregates, while the other ladle slag has a specific density that is comparable to a limestone aggregate.

	Granite	Limestone	Quartzite	Sandstone
Specific Density (g/cm^3)	2.60 - 2.76	1.88 - 2.81	2.65 - 2.73	2.44 - 2.61

Table 2: Typical specific density of common aggregates (National Stone Association, 1996).

Specific Density (g/cm^3)			
Specific Density **EAF**	Fine Steel Slag Aggregate	Coarse Steel Slag Aggregate	
Beshr, Almusallam, & Maslehuddin, 2003	3.51	N.R.	Bulk Specific Density
Polanco, Manso, Setien, & Gonzalez, 2011	3.7	3.35	Specific Density
Moon, Yoo, & Kim, 2002	N.R.	3.3	Specific Density
Grieler, 1996	3.2 - 3.8		Bulk Specific Density
BOF			
Moon, Yoo, & Kim, 2002	N.R.	3.39	Specific Density
Grieler, 1996	3.1 - 3.7		Bulk Specific Density
Motz et al., 2001	3.3		Bulk Specific Density
Ladle Furnace Slag			
Polanco, Manso, Setien, & Gonzalez, 2011	2.65	N.R.	Specific Density
Stainless Steel			
De Bock, L. P., & Van den Bergh, H., 2004	3.25	N.R.	Specific Density

Table 3: Specific Density for different types of steel slags.

3.1.3 Porosity

Another important aspect of the steel slag aggregate is the porosity of the particles. Porosity is the percentage of the total volume of an aggregate particle occupied by the pore spaces (National Stone Association, 1996). This ratio is important because the higher the porosity, the more surface area for the cement paste to bond to the aggregate. The porosity of an aggregate can affect the absorption, strength, permeability and the durability of the aggregate. Rocks that have cooled very rapidly will tend to have a lower porosity than those that have cooled from a slower cooling process. Metamorphic and igneous rocks like granite and basalt will have a low porosity while sedimentary rocks like limestone will have a higher porosity. Steel slags that are cooled from the spraying of water in the slag pits will tend to have higher porosity values than if the slag is cooled by emersion into water. Steel slag will generally tend to have a lower porosity than sedimentary rocks like dolomite and sandstone.

The porosity of steel slag from an electric arc furnace that had been weathered for fourteen weeks had a porosity of 9.7% for the coarse aggregate and 13.5% for the fine slag aggregate. Granite has a porosity that ranges from 0.4 to 3.8% and limestone has a porosity that ranges from 1.1 to 31% (National Stone Association, 1996). The porosity of some common aggregates can be found in Table 4. While the porosity of the steel slag does fall into the range of the limestone and sandstone, it is on the low end of the range. The porosity of a ladle furnace slag was reported to have a range of 6.95 to 10.68 % for aggregate that ranged in size from 0.375 to 1.5 inches (9.5 to 38.1 mm), (Manso et al., 2005).

	Granite	Limestone	Quartzite	Sandstone
Range of Porosity (%)	0.4 – 3.8	1.1 - 31	1.59 – 1.9	1.9 – 27.3

Table 4: Average Porosity of common aggregates (National Stone Association, 1996).

3.1.4 Absorption

The absorption of a liquid or gas can be a physical or chemical process. In the case of steel slag and PCC, it is a physical process. The absorption process is the physical bonding of the water and cement to the steel slag particles. The absorption is the amount that the liquid is able to penetrate the aggregate particle, which results in an increase in the weight of the particle (National Stone Association, 1996). The absorption of the water by the aggregate can affect the overall amount of water that is needed to fulfill the workability requirements of the mixture. The amount of water absorbed by the slag aggregate decreases the amount of water that would be available for the reaction with the cement. It was reported that amount of water absorbed by the steel slag is thought to be 2% of the total mass of the slag aggregate (De Bock et al., 2004).

According to the National Stone Association, aggregates having less than 1% absorption minimizes the binder requirements and is preferred in most construction applications. The absorption of water ranges from 0.07 to 0.3 for granite, 2.65 to 2.73 for quartzite, and 1.88 to 2.81 for limestone (National Stone Association, 1996). Aggregates with values greater than 2 to 2.5% are considered to be absorptive (National Stone Association, 1996). The testing of the absorption of an aggregate is done following ASTM C 128.

Table 5 has the absorption percentages for EAF slag particles after aging and prior to the slag aggregate being used in PCC. Table 6 list several absorption values for BOF slag. Table 7 contains the absorption values for concrete mixtures that have EAF slag as a fine aggregate and a coarse aggregate. The first sample in Table 7 contains 50% EAF fine aggregate and 50% dune sand as the remaining portion of fine aggregate. The second sample in the study by Manso et al. (2006) contained 100% EAF slag as both the fine and coarse aggregate.

	EAF Slag Aggregate
(Polanco et al., 2011)	2.88 - 3.65 %
(Luxan et al., 2000)	1.56 – 4.21 %
(Geisler, J. 1996)	0.2 – 1.0 %
(Maslehuddin et al., 2003)	0.85 %

Table 5: Absorption values for EAF slag particles.

	BOF Slag Aggregate
(Geisler, J. 1996)	0.2 – 1.0 %
(Moon, et al., 2002)	1.96 %
(Motz et al., 2001)	1.0 %

Table 6: Absorption values for BOF slag.

Fine aggregate / Coarse aggregate	Control 0 / 0 %	**50 / 100 %**	**100 / 100 %**
(Manso et al., 2006)	Not Reported	6.50 %	12.70 %

Table 7: Absorption values for PCC specimens made with EAF aggregates.

3.1.5 Abrasion Resistance

The resistance of an aggregate to abrasion and impact is an important physical characteristic of an aggregate. The Los Angeles Degradation Test, (ASTM C 131-06: The Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine), is one method for measuring the resistance of a material to abrasion and impact. The results from this method should be used only to indicate the quality of the aggregate with respect to other aggregates with a similar chemical or mineral composition. Since the steel slag is replacing common aggregates like dolomite and limestone aggregate, the slag can be compared in this manner even though the chemical compositions are not the same. The values of abrasion resistance for dolomite range from 18 – 30% and for limestone, they range from 19 – 30% (National Stone Association, 1996). The range of values for abrasion resistance of the steel slag aggregate, found below in Table 8. They are comparable to those of the dolomite and limestone aggregate, but generally tend to be less than the dolomite and limestone, which can provide more resistance to wear in pavement applications. The minimum value reported was 11.6% and the maximum value was 22%.

EAF		
(Manso, Gonzalez, & Polanco, 2004)	---	15 - 20 %
(Beshr, Almusallam, & Maslehuddin, 2003)	---	11.60%
(Maslehuddin, Sharif, Shameem, Ibrahim, & Barry, 2003)	---	18.46%
(Moon, Yoo, & Kim, 2002)	---	25.90%
BOF		
(Moon, Yoo, & Kim, 2002) - converter slag	---	16.80%
(Geisler, et al., 2001)	---	22%

Table 8: Abrasion values (%) of steel slag.

3.2 Mechanical Properties

Concrete made with steel slag as an aggregate must have mechanical properties that are equal to or greater than that of ordinary portland cement concrete. It is important that these properties are not compromised by the replacement of natural aggregates with steel slag. The mechanical properties discussed in this section are compressive strength, tensile strength, flexural strength, elastic modulus and the water penetration of concrete containing steel slag.

3.2.1 Compressive Strength

When evaluating the compressive strength of portland concrete cement, specimens are subjected to various types of tests. In these tests, the specimens are loaded until failure occurs using a uniaxial compressive load. The compression test consists of loading the cylindrical concrete specimens in uniaxial compression and is accomplished by following the procedures of ASTM C 39. The failure of the specimen in compression can occur along one of three failure planes; through the cement paste, along the interface of the cement paste and the aggregate, or directly through the aggregate. The aggregates themselves are generally stronger then the cement paste, so they are of less importance in normal strength concrete but can become a greater factor in high strength concrete due to the relatively high strength of the cement paste relative to the strength of the aggregate (Mindess et al., 2003).

Most chemical admixtures have little effect on the strength of the concrete unless they are water-reducing super plasticizers, which can provide an increase in the strength from the greater cement hydration. This results from the improved dispersion of the cement particles and the elimination of large pores that can act as flaws on the internal structure (Mindess et al., 2003). Air entraining admixtures can affect the strength of the concrete since they can effect the water to cement ratio which can effect the porosity of the concrete. For concrete designed for workability with the addition of an air entraining admixture, the concrete strength might actually increase due to the low cement content (Mindess et al., 2003).

The compressive strength of concrete that contains steel slag as an aggregate has been reported on in many studies. These studies have examined the compressive strength with different percentages of steel slags as a replacement of the natural aggregates. The EAF slag used in this study by Manso et al. (2006) was weathered, homogenized through periodic over turning of the pile of slag for a minimum period of 90 days. The water to cement ratio was less than or equal to 0.6 and no admixtures were used in this study. The

28 day compressive strength of concrete cubes ranged from 3000 psi (20.6 MPa) for specimens that contained 100% fine and 100% coarse EAF slag aggregate to 5100 psi (35.3 MPa) strength for specimens that contained 50% limestone and 50% steel slag as fine aggregate and 100% steel slag coarse aggregate. The control specimen which contained un unspecified limestone aggregate reached a compressive strength of 5600 psi (38.5 MPa). No correleation between the amount of steel slag in the concrete and compression strength could be seen from the results of this study.

In conducted by Polanco et al., (2011), the compressive strengths of concrete containing various amounts both EAF slag and ladle furnace slag as a fine aggregate were investigated. The EAF slag was used for 100% of the coarse aggregate in all test specimens. The water to cement ratio ranged from 0.6 for the control specimen which contained 25% limestone sand fine aggregate and 25% EAF slag fine aggregate (by total weight of the concrete) to 0.8 for the specimen with 25% EAF fine aggregate and 25% LFS fine aggregate (by total weight). The 28 day compressive strength of the control reached a strength of 6750 psi (46.6 MPa) while a specimen which contained 37% EAF fine aggregate and 25% LFS fine aggregate reached a strength of 8700 psi (60.4 MPa). The lowest compressive strength was 4570 psi (31.5 MPa) for concrete which contained fine aggregate in quantities of 25% for each of the EAF and LFS. This mixture had a w/c of 0.8. The results of this study showed that as the percentage of EAF and LFS increased, the compression strength also increased.

Comparable results were also achieved by Maslehuddin et al. (2003). In this study the 28 day compressive strength ranged from 4500 psi (31.4 MPa) with 45% coarse steel slag aggregate to 6200 psi (42.7 MPa) with 65% steel slag aggregate. While results vary slightly, the compressive strengths of the concretes prepared with the steel slag increased as the percentage of slag increased and were comparable to those prepared without the slag.

In work conducted at Cleveland State University (Obratil et al, 2008 and Obratil et al 2009), the compressive strength of concrete mixtures containing EAF slag as a replacement for coarse aggregate was studied and compared to ODOT Class C specification 499.03. The minimum compressive strength allowed by the ODOT specifications is 4000 psi (28.0 MPa) at 28 days. In the 2008 study various percentages of the coarse and the fine natural aggregate were replaced with steel slag to study the effects on the compressive strength. The compressive strength for the specimes with the replacement of the 0.75 inch (19mm) aggregate had an average compressive strength that ranged from 4200 psi to 5500 psi (29 MPa to 38 MPa) at 28 days. The specimens with the 0.5 inch (12.5mm) steel slag aggregate as a replacement had an average compressive strength of 4300 psi to 5600 psi (29.6 MPa to 38.6 MPa) at 28 days. When the “C” fines were replaced in the concrete the average compressive strength ranged from 3300 psi (22.8 MPa) for a 10 % replacement to 5400 psi (37.2 MPa) for 40% replacement at 28 days. All the specimens were able to meet the minimum ODOT specification for Class C paving concrete with the exception of the 10% replacement of the “C” fines. The 0.75 inch (19mm) aggregate showed no trends relating the percentage of slag aggregate to the compressive strength while the compressive strength decreased as the amount of 0.5 inch (12.5mm) slag aggregates increased. In the study of compressive strength for the “C” fines the percentage replaced ranged from 10% to 40% and the strength increased as the percentage of slag increased.

The specimens in the 2009 study at Cleveland State University contained steel slag ranging from 0% to 100% replacement of the coarse natural aggregate. All of the specimens containing the steel slag were able to achieve a compressive strength greater then the minimum specified by ODOT at 28 days. The control specimen reached a compressive strength of aproximately 5600 psi (38.6 MPa) at 28 days and the specimens with the slag ranged from 4200 to 5100 psi (29 to 35.2 MPa). This study showed that the ODOT specification for Class C concrete paving mixures could be obtained when steel slag is used as a replacement for natural coarse aggregates. The maximum compressive strength of the steel slag concrete was achieved when 50% of the natural coarse aggregate was used, but no correleation could be observed between the percentage used and the compression strength obtained.

High strength concrete is considered to have a compressive strength greater than 6000 psi (41 MPa) and researchers have found that the hardened strength-limiting paste and the transition zone are no longer the limiting factor, but that it is the mineralogy and strength of the coarse aggregate that will control the ultimate strength of the concrete.

A high strength concrete containing steel slag as a coarse aggregate in percentages of 25% and 100% resulted in compression strengths of 47.1 and 54.1 MPa (6800 and 7850 psi) which were both higher then the control compression strength of 39.3 MPa (5700 psi). The water to cement ratio was 0.5, and it could be seen from this study that the compression strength increased as the percentage of steel slag increased (Etxeberria et al., 2010).

In a laboratory testing of steel slag (type unknown) as a coarse aggregate in high strength PCC, dune sand was used as the fine aggregate along with a cement to water ratio of 0.35 and a cement content of 759 lbs./yd^3 (450 kg/m^3) with a coarse to fine aggregate ratio of 1.63. The type of weathering of the slag was not stated in this study. A naphthalene-based super plasticizer was used in the mixture to improve the workability of the mixture. This test compared three different limestone aggregates (calcareous, dolomitic and quartzitic), and one steel slag aggregate. The 28 day compression strengths of the specimens were found to be 6200 psi (43 MPa) for the calcareous specimen, 6500 psi (45 MPa) for the dolomite aggregate specimen, 6800 psi (47 MPa) for the quartzitic specimen. The highest was the steel slag specimen at 7800 psi (54 MPa), (Beshr et al., 2003).

3.2.2 Splitting Tensile Strength

The tensile strength of a concrete cylinder can be is determined indirectly by the split tensile test. ASTM C 496 gives the procedures for determining the split tensile strength. Table 9 shows the splitting tensile strengths for PCC specimens that were composed of fine dune sand aggregate with varying percentages of coarse EAF aggregates. The mixtures had a water to cement ratio of 0.40. The splitting tensile strength ranged from 840 psi (5.79 MPa) with a replacement of 45% of the coarse aggregate to 921 psi (6.35 MPa) with the replacement of 65% of the coarse aggregate. The splitting tensile strength of the steel slag specimens were, on average, slightly below the control specimen, which was prepared using a coarse limestone aggregate. The control specimen had a splitting tensile strength of 918 psi (6.33 MPa). While some of values are slightly below the control, the values were comparable. The splitting tensile strengths of all the concretes in this study were above the normal range of 5 to 10% of the compressive strength. The concrete containing 45% slag had the highest percentage of compressive strength, which was 18% and the lowest percentage was in the 65% slag concrete, which was the same as the control's percentage of 15%.

Percent of coarse aggregate replacement	45%	50%	65%	units
(Maslehuddin et al., 2003)	5.79	6.06	6.35	MPa
	(840)	(880)	(920)	psi

Table 9: Split tensile strength for PCC specimens.

The splitting tensile strength was also examined in a study by Etxeberria et al. (2010), which used the steel slag as a course aggregate. The splitting tensile strength of the control concrete, which contained all natural aggregates, was 3.6 MPa (522 psi) and the splitting tensile strengths of the concretes that contained 25% and 100% steel slag was of 3.3 MPa (478 psi). The compressive strength of the control was 39.3 MPa (5700psi), the compressive strength of the 25% steel slag concrete was 47.1 MPa (6800 psi) and the 100% steel slag concrete compressive strength was 54.1 MPa (7850 psi). While the splitting tensile strength of all the specimens had similar values, the resulting percentages were quite different. The control's splitting tensile strength was 9.1% of the compressive strength, the 25% steel slag concrete was 7.0% of the compressive strength and the 100% steel slag concrete was 6.1 % of the compressive strength. The results showed that as the percentage of steel slag increased, the splitting tensile strength decreased. These values were still in the normal tensile strength of concrete range of 5 to 10% of the compressive strength.

The mechanical properties of concrete containing steel slag as a replacement for both the fine aggregate and the coarse aggregate was completed in a study by Obratil et al. (2008). The results of the testing showed an average splitting tensile strength for the replacement of the 0.75 inch coarse aggregate at 28 days ranging from approximately 390 psi to 500 psi (2.7 to 3.4 MPa). The splitting tensile strength for 0.5 inch aggregate replacement had an average 28 day splitting strength ranging from 480 psi to 600 psi (3.3 to 4.1 MPa). When the "C" fines were replaced the average strength of the concrete ranged from approximately 350 psi to 510 psi (2.4 to 3.5 MPa) for a replacement of 40% of the "C" fines. In a separate study conducted by Obratil et al. (2009), the natural limestone coarse aggregate was replaced by steel slag ranging from 25% to 100%. The control reached a splitting tensile strength of approximately 610 psi (4.2 MPa), while the steel slag specimens ranged from 500 psi to 550 psi (3.4 to 3.8 MPa).

In a study of high compressive strength PCC, four different types of coarse aggregates were used in test to compute the splitting tensile strength. In this study, the steel slag aggregate achieved higher splitting tensile strengths then a calcareous limestone, a dolomite limestone and a quartzitic limestone aggregates. A water to cement (w/c) ratio of 0.35 was used and a coarse to fine aggregate ratio of 1.63. This study used limestone as the fine aggregate and along with the coarse aggregates mentioned above. The steel slag specimen achieved the highest 28 day splitting tensile strength of 580 psi (4 MPa) verses a tensile strength of 348 psi (2.4 MPa), 450 psi (3.1 MPa) and 464 psi (3.2 MPa) respectively for the limestone aggregates (Beshr et al, 2003).

3.2.3 Flexural Strength

Flexural strength is tested using ASTM C 78. This test is carried out on reinforced beams or prisms in order to determine the flexural strength of the concrete. In a study that used a fine dune sand as the fine aggregate and then varied the amount of steel slag as a coarse aggregate, the flexural strength of the specimens was calculated and determined to be comparable to that of a limestone aggregate (which contained 60% coarse aggregate) and had a flexural strength of 574 psi (3.96 MPa). The flexural strengths of the steel slag specimens can be found below in Table 10. It can be seen that as the percentage of steel slag aggregate increased, so did the flexural strength. The mixture that contained 65% coarse aggregate achieved a flexural strength of 610 psi (4.21 MPa).

Percent of Coarse EAF aggregate	45%	50%	65%	units
(Maslehuddin et al., 2003)	3.47	3.61	4.21	MPa
	(503)	(523)	(610)	Psi

Table 10: Flexural Strength of PCC specimen with EAF coarse aggregate.

Similar results for flexural tensile strength were obtained by Qasrawi et al. (2009). The EAF steel slag was used as a fine aggregate in this study in porportions that ranged from 0% to 100%. These laboratory results showed an increase in the strength of 1.4 to 2.4 times the strength of normal concrete. The optimim strength occurred when the sand was replaced by 30 – 50% of slag. A replacement of 100% slag resulted in a lower strength then that of normal concrete.

The flexural strength of concrete containing steel slag as a coarse aggregate was also studied at Cleveland State University (Obratil et al., 2009). The aggregate was replaced by volume ranging from 0 to 75%. The beams were tested following ASTM C – 78 using 3 point testing method and were tested at 7 days. The control specimens achieved a strength of approximately 700 psi (4.8 MPa) while the specimens with the steel slag aggregate had an average strength of 640 psi (4.4 MPa) and did not vary much from the 25% replacement to the 75% replacement of coarse aggregate.

3.2.4 Elastic Modulus

ASTM C – 469 gives the procedures for the testing of concrete specimens in order to determine the Modulus of Elasticity. The modulus of elasticity is related to compressive strength and the density of the concrete (Mindess et al., 2003). The factors affecting the modulus of elasticity are the porosity of the concrete, the water to cement ratio and the aggregates within the concrete. As the water to cement ratio is increased, the effects on the modulus of elasticity of the concrete become apperant and the modulus of elasticity decreases. The modulus of elasticity of normal weight concrete (2320 K/m^3, 3915 lb/yd^3) ranges from 2 to 6 x 10^6 psi (14 to 42 GPa) and the modulus of elasticity for light weight concrete (3105 lb/yd^3 , 1840 kg/m^3) ranges from 1.5 to 2.5 x 10^6 psi (10 to 18 GPa), (Mindess et al., 2003).

The modulus of elasticity was determined at 28 days and found to be 5.2 x 10^6 psi (36 GPa) for a specimen containing 25% EAF slag and for a specimen containing 100% slag (Etxeberria et al, 2010). These values were approximately the same as the control specimen, which had a 28 day modulus of elasticity of 5.3 x 10^6 psi (36.4 GPA).

Pellegrino et al. (2009) examined the modulus of elasticity of specimens containing an EAF slag and compared them to reference specimens and the theoretical modulus of elasticity. The calculated theoretical modulus of elasticity was 4.7 x 10^6 psi (32.1 GPa) for the EAF concrete and 4.3 x 10^6 psi (29.6 GPa) for the control's. The steel slag concrete had an average experimental modulus of elasticity of 4.5 x 10^6 psi (30.7 GPa), while the control's modulus of elasticity was 3.5 x 10^6 psi (24.1 GPa). The EAF concrete resulted in a higher modulus of elasticity and a lower variation from the theoretical modulus of elasticity.

The values for the modulus of elasticity for concrete specimens containing steel slag were also reported in work done by Beshr et al. (2003). In this study, the modulus of elasticity was calculated for two types of limestone aggregates, a quartzitic and one steel slag aggregate specimen. The specimens were tested in a uniaxial compression at a constant loading rate at 742 lbf/sec (3.3 KN/sec) with a w/c ratio of 0.35%. The steel slag specimen's modulus of elasticity was calculated to be 4.3 x 10^6 psi (29.6 GPa), which was the highest of the different aggregates tested in this study and fell within the range for normal weight concrete. The calcareous limestone aggregate had the lowest modulus of elasticity, which was 3.1 x 10^6 psi (21.6 GPa). The dolomitic limestone had a modulus of elasticity of 3.6 x 10^6 psi (24.5 GPa) and the quartzitic aggregate had a modulus of elasticity of 4.2 x 10^6 psi (28.8 GPa).

3.2.5 Water Penetration

The depth of water penetration into concrete can be a factor in the long term durability of the concrete. If there is too much penetration this can become a factor in the concretes ability to withstand the effects of freezing and thawing and wetting and drying. The testing of concrete specimens containing steel slag in percentages of 25% and 100% coarse aggregate were studied to see the effects of the steel slag on the depth of water penetration into the conrete. The control had a water depth penetration that ranged from 0.79 to 1 in (20 to 25 mm). The 25% coarse aggreagte concrete had a water pentration range 0.6 to 0.79 in (15 to 20 mm) and the concrete containing 100% coarse aggregate had a water penatraion that ranged from 0.4 to 0.6 in (10 to 15 mm). It can be seen that as the content of the slag increased the depth of water penetration decreased in this study completed by Pacheco et al. (No Date).

The penetration of water into concrete containing steel slag as a fine and coarse aggregate was studied by Manso et al. (2004). The concrete specimens had a content of slag that ranged from 0% fine and 0% coarse to 100% fine and 100% coarse. All specimens except for the control concrete contained 100% EAF slag as the coarse aggregate. The control concrete had a maximum water penetration of 1.97 inch (50mm) and an average of 1.26 inch (32 mm). Concrete containing fine aggregate in percentages of 50% limestone, 50% EAF slag had maximum water pentration of 0.43 inch (11 mm) and an average of 0.2 inch (5 mm). Concrete containing fine aggregate in percentages of 25% limestone, 75% EAF slag had a maximum water pentration of 1.4 inch (35 mm) and an average of 1 inch (25 mm). Specimens that contained 100% steel slag as a fine and coarse aggregate had total water penetration of the concrete. The results of this study showed that as the percentage of slag increased so did the depth of water penetration. The specimens that had 25% limestone and 75% steel slag as fine aggregates had comparable results for the depth of water penetration.

3.3 Durability of Steel Slag Concrete

The durability of concrete is its ability to with stand the effects of the environment. The effects of the environment may not show its impact on the concrete until years later. In order to test the durability of concrete, methods have been developed to accelerate the effects of the different environmental conditions on the concrete. The following section reviews the effects of freeze and thawing, wetting and drying, and high temperature exposure on concrete containing steel slag as an aggregate.

3.3.1 Freeze and Thawing Test

The freeze and thawing test follows ASTM C 666 / C 666M - 03(2008) standard. The resistance to freezing and thawing is the ability of an aggregate to resist the deterioration due to the repeated exposure to freezing and thawing cycles (National Stone Association, 1996). Cracking and flaking can occur due to the expansion of the water trapped in the particles pores. After being cured for 28 days in a moist room, the specimens are subjected to cycles of freezing and thawing. The specimens are then evaluated on appearance, and compressive strength as well as the variation in their weight. Proper care needs to be taken to ensure the air is properly entrained throughout the mixture.

The freezing and thawing test was completed with varying amounts of fine and coarse aggregates that ranged from 0.0 % steel slag aggregate to specimens that contained as much as 60 % fine aggregate and 100 % coarse aggregate. The w/c ratio was less than or equal to 0.6 and there were no admixtures. The results of this testing can be found below in Table 11. The control specimen had the least loss of compressive strength (15 %) while the specimens that contained 60 % fine and 100 % coarse aggregate had the maximum loss, which was a 48 % loss. The specimen that had 50 % fine aggregate and 100 % coarse aggregate showed slight damage, but the samples that had 60 % fine and 100 % coarse aggregate resulted in one of the samples cracking. The variance in weight ranged from a loss of -0.27 % to -1.18 % for the samples with the steel slag aggregates, while the control specimen had a loss of -0.14 %. The superficial appearance of the control was good while two of the mixtures had noteworthy damage and one sample cracked.

Compressive Strength			Percentage of aggregate substitution	Superficial appearance
Before	After	% loss		
38.5 MPa (5600 psi)	32.7 MPa (4700 psi)	15	Control 100% limestone	Good
33.7 MPa (4900 psi)	20.6 MPa (3000 psi)	39	0% Fine and 100% Coarse	Noteworthy Damage
35.3 MPa (5100 psi)	27.2 MPa (3900 psi)	23	50 % fine and 100% coarse	Slight damage
30.2 MPa (4400 psi)	17 MPa (2500 psi)	44	50 % fine and 100% coarse	One sample Cracked
30.7 MPa (4550 psi)	16.0 MPa (2300 psi)	48	60% fine and 100% coarse	Noteworthy Damage

Table 11: Loss in compressive strength as a result of freeze thaw cycles (Manso et al., 2006).

Polanco et al. (2011) also completed freezing and thawing testing and published the results of the study, which used LF and EAF slag as a fine aggregate and 100% EAF coarse aggregate. The result from this study showed losses in compression strength that ranged from -78.4% to a gain of 10.4%. The control specimen, which contained a fine limestone aggregate and 100% EAF slag, had the 7.5% loss. All surface appearances were acceptable except for the mixture that had the 78% loss which had cracking damage. This mixture also had a high w/c ratio of 0.8 and had percentages of 25% EAF and 25% LF slag for the fine aggregate. There were no admixtures used in this concrete, but the author did note that careful attention was paid the gradation of the slag for use as a fine aggregate.

In a similar experiment that used 0% fine steel slag aggregate and 100%, coarse steel slag aggregate in PCC was conducted by Pellegrino & Gaddo (2009). The traditional concrete and the steel slag concrete contained an air-entraining admixture. The average compressive strength before the freezing and drying test was reported to be 6440 psi (44.4 MPa), and after the testing the average strength was 6000 psi (41.2 MPa), which was a loss of 7.28 %. The control specimens in this study showed a gain from 4400 to 4900 psi (30.4 to 33.9 MPa) which was an 11.53 % gain. The difference between the slag concrete and the control concrete was possibly due to the higher porosity of the slag or due to the hydration of free oxides contained in the slag concrete, according to the authors.

The resistance to freezing and thawing can also be measured by the durability factor. The testing of freezing and thawing is conducted up to 300 cycles or when the relative dynamic modulus of elasticity falls below 60, and measured at increments of 25 cycles. The durability factor is calculated using the relative Dynamic Modulus of Elasticity at N cycles of freezing and thawing divided by the total number of cycles completed to be completed (usually 300). The durability factor is used as a method to measure the distress of the specimen on the exterior as well as on the interior of the specimen, which cannot be seen.

The durability of concrete was studied by Patel (2008) at Cleveland State University using specimens that contained steel slag as a coarse aggregate ranging from 0% aggregate to 100% aggregate by volume. The results from this test showed a wide range of durability factors for the various specimens. Three specimens that contained 100% steel slag aggregate failed the test before 50 cycles, which was attributed to the air content of those specimens being comprised mostly of entrapped air instead of entrained air. The study then mixed new specimens with 100% steel slag and included air entraining admixture and the testing was repeated. The new specimens with 100% steel slag had an average durability factor of 85.8. The control specimens and the specimens containing 75% steel slag aggregate both had a durability factor of 100 upon completion of the 300 cycles. The mixture containing 25% replacement had an average durability factor of 96 while the 75% specimens had an average durability factor of 75.7.

3.3.2 Wetting and Drying Test

The wetting and drying test uses specimens that have been stored in a moist room for 28 days, and then the specimens are subjected to cycles of wetting and drying. Resistance to wetting and drying is the ability of the aggregate to resist cyclic wetting and drying without cracking or breaking down (National Stone Association, 1996). The variation in weight, loss of compressive strength and appearance are all characteristics that can be monitored in this experiment.

Table 12 shows that the specimens that contained the steel slag as a coarse aggregate had the larger variance in weight compared to the control specimen. The loss in compressive strength of the specimen containing 100% steel slag as a coarse aggregate had the least loss in compressive strength of 30.18 %, and the control specimen had the largest loss of 52.9% in compressive strength resulting from the wetting and drying test. A superplasticizer, which consisted of vinylic modified copolymers and organic mineral agents, was used in the mixtures containing the EAF slag to improve the workability of the mixtures. The control specimen had a w/c ratio of 0.57, the specimen containing 25% slag had a w/c ratio of 0.58, and the specimen containing 100% slag had a w/c ratio of 0.6.

% Slag	var. in Wt. %	Compressive Strength		
		Before test	After test	% loss
0%	-1.28	39.3 MPa (5700 psi)	18.51 MPa (2700 psi)	52.90
25%	-3.6	47.1 MPa (6800 psi)	28.36 MPa (4100 psi)	39.79
100%	-3.16	54.1 MPa (7800 psi)	37.77 MPa (5500 psi)	30.18

Table 12: Variance in weight and percentage loss in compression strength from the wetting and drying test (Pacheco et al., No Date).

In a study that used steel slag as a fine and coarse aggregate in concrete specimens, the loss in compressive strength ranged from 30% to 49% for the steel slag samples. The control specimen had a loss of 2.9% and the specimen that contained 60% fine steel slag aggregate and 100% coarse aggregate had a loss in compressive strength of 49%. The variance in weight ranged from -0.12 % loss to -0.28% loss in the specimens that contained the steel slag aggregate while the control specimen had a loss in weight of -0.08 % (Manso et al., 2006). Table 13 shows the compressive strengths of the concrete specimens before and after the wetting and drying test. The superficial damage to the specimens was considered acceptable by the author.

Compressive strength			Percentage of aggregate substitution	Superficial appearance
Before	After	% loss		
38.5 MPa (5600 psi)	37.3 MPa (5400 psi)	2.9	Control 100% limestone	Good
33.7 MPa (4900 psi)	19.9 MPa (2900 psi)	41	0% Fine and 100% Coarse	Slight damage
35.3 MPa (5100 psi)	24.7 MPa (3600 psi)	30	50 % fine and 100% coarse	Good
30.2 MPa (4400 psi)	16.6 MPa (2400 psi)	45	50 % fine and 100% coarse	Slight damage
30.2 MPa (4400 psi)	17 MPa (2500 psi)	49	60% fine and 100% coarse	One sample cracked

Table 13: Loss in Compression strength from wetting and drying test (Manso et al., 2006).

Polanco et al. (2011) examined the use EAF and LF slag as fine aggregate in varying percentages, along with EAF slag as coarse aggregate with no admixtures. The results from this study showed excellent durability characteristics for the specimens that only contained steel slag as a coarse aggregate. Specimens that contained percentages of EAF and LF slag below 25% for each type also showed acceptable surface appearance and loss in weight. Mixtures containing 25% EAF, 12.5% limestone and 12.5% LF fine aggregate and mixtures containing 25% EAF and 25% LF had excessive loss in compressive strength.

Similar results to both the Manso et al. (2006) study and the Pacheco et al. (No Date) study were reported by Pellegrino & Gaddo (2009). The specimens were subjected to 30 days of wetting and drying cycles. There was no notable surface damage to the specimens on the exterior of the specimens. The density of the control was 2.33 t/m^3 prior to the aging and was 2.4 t/m^3 after the aging, which was a 2.92% gain. The EAF slag concrete only showed a gain of 0.79%. This lower gain was attributed to the higher CaO and MgO that is in the EAF slag. This higher content could have led to expansion in the specimens. The steel slag specimens showed a loss in compression strength of 26.52% versus the control's loss of 5.68%.

3.3.3 High Temperature Exposure

The effects of exposure to high temperature were studied by Etxeberria et al. (2010), in which specimens were exposed to a temperature of 800 °C for 4 hours. The portland cement was a high strength and rapid-harding cement. The compressive strengths of the concrete cubes prior to exposure were 8800 psi (60.8 MPa) for the control, 9253 psi (63.8 MPa) for the specimen containing 25% coarse aggregate and 10,900 psi (75.1 MPa) for the 100% coarse aggregate. After completing the testing the control had a loss of strength of 62% while the steel slag specimens had losses of 48% and 56% for the 25% and 100% specimens. The results showed that the steel slag specimens were more durable in this test.

3.3.4 Chloride Diffusion Test

The ability of concrete to resist attack from chloride ions from the environment is an important aspect of the durability of concrete, because if it is unable to do so it can lead to the corrosion of the reinforcement within the concrete, which can ultimately lead to the failure of the concrete. This penetration of chloride from the environment into the concrete usually takes place over a long time. The chloride diffusion test is performed according to ASTM C 1556 – 11a.

The testing of concrete containing an EAF slag by means of the chloride diffusion test was completed by Pacheco et al. (No Date). The natural coarse aggregate in the concrete was replaced in percentages of 25% and 100% and compared to the control, which contained no slag aggregate. The concentration of chloride after nine months of testing was the highest in the slag concrete that contained 100% EAF coarse aggregate. The concentration of the 25% replacement concrete was slightly higher than the control, but obtained similar values. The total concentration of chloride increased with time, and was attributed to the capillary suction and diffusion process resulting from the porosity and the chloride binding with the slag (Pacheco et al., No Date). The transportation of chloride through the concrete increased as the percentage of slag increased and was the highest in the 100% slag concrete. The potential durability of the concrete was considered low compared to the control.

3.4 Workability

The slump and workability of the concrete can be affected by the addition of the steel slag into the mixture. As the percentage of the steel slag in the concrete increases, the workability of the mixture decreases. Concrete mixtures that contain 50% slag aggregates or less seem to be affected only slightly, while the mixtures containing 100% slag aggregates were sticky rather than dry and is attributed to the higher absorption of water by the steel slag aggregate (Qasrawi et al., 2009). If an aggregate like steel slag has a higher absorption value greater than common aggregates like a limestone aggregate then this must be taken into account when designing the concrete because the higher absorption will affect the cement to water ratio. As stated earlier it was reported by De Bock et al. (2004) that the additional water needed due to the absorption of the steel slag accounts for approximately 2% of the total mass of the slag aggregate. The decrease in the workability of the concrete can also be due to the effect that the steel slag particles are more angular.

It was demonstrated in a study by Qasrawi et al. (2009) that as the percentage of slag was increased from 0% to 100 % that the slump of the concrete decreased. The average slump of the control specimens was 4.7 inches (12 cm). A replacement of 30% of the fine aggregate resulted in an average slump of 3.9 inches (10 cm) and a replacement of 50% resulted in an average slump of 3.5 inches (9 cm). Finally, a 100% replacement resulted in an average slump of 1.2 inches (3 cm).

Similar results were achieved in a study in which a coarse aggregate was replaced by steel slag. A superplasticizer, which consisted of a vinylic modified copolymers and organic mineral agents, was used in the mixtures containing the EAF slag to improve the workability of the mixtures. The control specimen had a w/c ratio of 0.57 with no additive, the specimen containing 25% slag had a w/c ratio of .58 with 0.65% additive, and the specimen containing 100% slag had a w/c ratio of 0.6 and 1.6% additive. The 25% EAF resulted in a slump of 3.7 inches (9.5cm) and when the coarse aggregate was replaced by 100% steel slag aggregate the workability of the mixture was noticeably reduced and a slump of 2.16 inches (5.5 cm) was obtained (Etxeberria et al, 2010).

In a recent study, the workability of concrete was studied using an EAF slag as the coarse aggregate and then varying the amount and type of fine aggregate. The fine aggregates used in this study were limestone sand, EAF slag, and LF slag. The control mixture consisted of 25% EAF slag and 25% limestone sand as a fine aggregate which was based on the total mass of the concrete, these replacements were based on previous work conducted. The water to cement ratio used in the mixture was 0.6. An expected slump based on the plastic consistency of the concrete would have been 1.2 to 2.4 inches (30 to 60 mm) but a slump of only 0.8 inches (20 mm) was achieved. This low slump was attributed to the steel slag’s absorption of the water (Polanco et al., 2011). The second mixture replaced half of the limestone sand with ladle furnace slag and the w/c ratio was increase to 0.7. The slump achieved by this mixture was the target slump, which was 1.2 to 2.4 inches (30 to 60 mm). The third mixture replaced the remaining limestone sand with EAF slag and the w/c ratio was 0.65. The slump decreased to 0.2 inches (5mm) which was attributed to the addition of the EAF slag. The fourth mixture used equal amounts of EAF and Ladle furnace slag as the fine aggregate and the w/c ratio was increased to 0.8. An acceptable slump was achieved from this mixture and was 1.8 inches (45 mm). The final mixture contained 75% EAF slag and 25 % LFS as a fine aggregate which was the same as mixture 3 but the w/c ratio used in the mixture was increased from 0.65 to 0.7. The cement used in this mixture was decreased from 22 pounds (10 kg) to 17.6 pounds (8 kg). The resulted slump from this mixture was the same as mixture 3, which had a slump of 0.2 inches (5 mm).

This author also conducted work on the mechanical properties of concrete containing EAF slag in 2004, (Manso et al., 2004). The mixtures in this study only contained steel slag from an electric arc furnace, had a w/c ratio of 0.6, no admixtures and had a target slump of 2.4 to 3.5 inches (60 – 90 mm). While the control specimen which contained no steel slag achieved a slump of 2.8 inches (70 mm), the specimen that contained 100% EAF slag as both a fine and coarse aggregate collapsed. A mixture containing limestone as the fine aggregate and EAF as the coarse aggregate had a slump of 2 inches (50 mm) which was below the target slump. A mixture that contained 50% limestone and 50% EAF slag as the fine aggregate and 100% EAF slag as the coarse aggregate as well as a mixture which contained 25% limestone fine aggregate and 75% EAF slag fine aggregate along with 100% EAF slag as a coarse aggregate both achieve the same slump as the control mixture which was a slump of 2.8 inches (70 mm).

In work conducted at Cleveland State University (Obratil et al., 2008), the workability of mixtures containing steel slag was studied using mixtures that ranged from 0% slag to 100% slag. This study was conducted to see if the concrete containing the steel slag could meet ODOT material specifications for a Class C concrete paving mixture. According to section 499.03-1 of the ODOT Construction and Material Specifications Manual, the slump of the concrete must be in a range of 1 to 3 inches (25 to 76 mm). The slump of the specimens ranged from 0.25 to 2.5 inches (6 to 64 mm). All of the specimens were able to meet the ODOT specification for slump except for one of the specimens containing 100% slag. The specimen that was unable to meet the criteria was the only specimen that had a water-reducing admixture. This study demonstrated that a concrete paving mixture containing steel slag could meet the ODOT requirements.

Another possible concern with the use of the steel slag and its workability is the ability to pump the concrete that contains the steel slag aggregate. This concern is valid since the slag concrete tends to be less viscous due to the absorption of the water by the slag. Steel slag is also denser than a limestone aggregate, which in turn makes the concrete have more weight, which could also make it harder to pump to the appropriate location. It has been demonstrated, in two separate instances, that concrete containing steel slag aggregate can maintain enough workability and low enough slump to be pumped into place. A mixture called Ferroform, which will be discussed later in Chapter 8, has been successfully used in pumping applications and with a delivery rate of 2119 ft^3/h (60 m^3/ h). The slump was high, 8.7 in (210 mm), but did not cause any separation problems (Matsunaga et al., 2009). Another example of pumping concrete containing steel slag is the Tecnalia Kubik Building in Madrid Spain. 4944 ft^3 (140 m^3) of concrete was pumped into the reinforced foundation slab and the reinforced walls of the building (Chica et al., 2011).

3.5 Conclusions

The possibility of using steel slag in concrete pavement applications will depend on its ability to meet the same physical, mechanical and durability requirements that natural aggregates achieve when being used in concrete. The gradation of steel slag aggregate is an important aspect, since improper gradation of an aggregate can cause voids between the cement and the aggregate, which can decrease the overall integrity of the concrete. The gradation of steel slag was examined in a number of studies, and showed that the slag could meet the requirements for coarse aggregates set by ASTM Standards. The studies reviewed in this research also demonstrated that this is not always the case for steel slag when it is used as a fine aggregate. Sieve analysis was conducted on steel slag at Cleveland State University and compared to the ODOT Class C requirements for aggregates. The replacement of 25% percent of the natural coarse aggregates resulted in gradations that were the closest to the requirements.

The density of EAF slag is higher than natural aggregate, which is a result of the iron being infused within the slag. Since the density of the slag aggregate is higher than that of a calcareous limestone and a dolomite limestone, it results in a heavier and denser concrete. The specific density ranged from 1.92 to 2.08 oz./ in^3 (3.2 to 3.7 g/cm^3) for the EAF slag and 1.76 to 2.24 oz./in^3 (3.1 to 3.9 g/cm^3) for the BOF slag. The ladle furnace slag had a density of 1.6 oz./in^3 (2.65 g/cm^3) which was comparable to the density of natural aggregates in Table 2. The stainless steel slag, which is a type of LFS, had a density of 2.88 oz./in^3 (3.25 g/cm^3).

The porosity of the EAF slag was in the low range of a limestone aggregate. The porosity of a ladle furnace slag ranged from 6.95 to 10.68%, which increased as the size of the slag decreased. Concrete made with steel slag tends to have a higher absorption of water, which can affect the workability of the concrete if no admixture is used. Aggregates with absorption greater than 2 to 2.5% are considered an absorptive aggregate and the range of values reported in this report ranged from 0.2% to 4.21% for an EAF slag. The absorption for BOF slag ranged from 0.2 to 1.96% while the ladle furnace slag had a range of 1.68 to 2.88%. The additional water needed, due to the absorption of the steel slag, accounts for approximately 2% of the total mass of the slag aggregate (De Bock et al., 2004). The absorption values for concrete that contained steel slag were considered to be within the normal range.

The abrasion values for an EAF slag ranged from 15 to 25.9 %. The abrasion values for BOF slag ranged from 16.8 to 22%, which were lower than that of a limestone aggregate that ranges from 19 to 30%. The abrasion resistance was found to be generally lower than the natural aggregates, which will provide a greater resistance to deterioration of the concrete pavement.

The 28 day compressive strength of concrete with steel slag was comparable to the strengths of the control concrete. In work conducted at Cleveland State University it was demonstrated that concrete containing steel slag in various percentages could meet the ODOT requirement of 4000 psi (27.6 MPa). When specimens containing both EAF slag and ladle furnace slag were used together in the same mixture, the compressive strengths of the concrete outperformed the control specimens. The maximum compressive strength of the concrete containing steel slag is generally obtained when the percentage of slag is approximately 50% of the natural aggregates. In studies that used both fine and coarse slag aggregate, there was no correlation between the strength of the concrete and the percentage of slag and this could be attributed to the slag's ability to achieve proper gradation for the fine aggregate. In studies that used the slag in high strength mixtures, it was observed that the compressive strength increased as the percentage of steel slag increased.

The splitting tensile strengths of concretes made with steel slag were comparable to those of the control in the study by Obratil et al. (2008) and in the study by Maslehuddin et al. (2003). In the study conducted by Beshr et al. (2003) on high strength concrete, the slag aggregate had a higher tensile strength then that of a quartzitic, calcareous and dolomite limestone. The splitting tensile strength generally decreased as the percentage of slag increased. The splitting tensile strengths of concrete containing steel slag were within the normal range of 5 to 10% of the compressive strength.

The results for the flexural strength showed that concrete containing slag could obtain strengths that were comparable to that of the control concrete. Some studies showed an increase in flexural strength as the percentage of slag increased, while other studies did not show the same trend. The maximum flexural strength was generally obtained with 50% replacement of the natural aggregates.

The modulus of elasticity of the specimens containing the steel slag aggregate in concrete was comparable to the control specimens with varying amounts of EAF slag. In a study by Beshr et al. (2003), the steel slag had a higher modulus of elasticity than that of the dolomitic limestone and calcareous limestone. The studies examined during the course of this research showed that the modulus of elasticity for concrete containing steel slag was within the range of normal weight concrete.

The depth of water penetration was examined to study the effect of the replacement of natural aggregates with steel slag in the study completed by Pacheco et al. (No Date). It could be seen that the concrete containing steel slag as a coarse aggregate had penetration depths that were less than the control and as the percentage of slag increased the depth of penetration decreased. The depth of penetration was also examined by Manso et al. (2004), which used steel slag as a fine and coarse aggregate. These results showed that as the percentage of slag as a fine aggregate increased the depth of penetration increased and specimens with 100% fine and coarse aggregate there was total penetration. Concrete that had 25% limestone and 75% steel slag as fine aggregates and 100% steel slag coarse aggregate had comparable results for the depth of water penetration.

The durability of concrete is another important criterion for the feasibility of the use of steel slag as an aggregate in concrete. The durability of concrete containing steel slag was examined in testing that included freeze and thawing, wetting and drying, high temperature exposure and its ability to resist attach from chloride ions from the environment. The surface appearance of the steel slag specimens showed some damage in a study conducted by Manso et al. (2006) for concretes containing EAF and LF slag as a fine aggregate along with 100% EAF coarse aggregate. The steel slag specimens all showed losses in strength that were greater than the control. This study did not use any admixtures.

In work conducted by Polanco et al. (2011), the effects of freezing and thawing were examined. The concrete in this study did not contain any admixtures as well but greater attention was paid to the gradation of the fine aggregates. The surface appearance of the concretes was acceptable except for one mixture that had a w/c ratio of 0.8. Compressive strength losses were considered high, except for the control, which contained 100% fine limestone aggregate and 100% steel slag coarse aggregate. The addition of LF slag into the mixture seemed to have adverse effects on the durability of the concrete. The results from the Pellegrino and Gaddo (2009) study showed that the durability of concrete containing steel slag as a coarse aggregate were comparable to that of the control specimen. In work conducted at Cleveland State University by Patel (2008), the durability of the specimens containing 25% had a durability factor of 96 and the specimens with 100 % slag had a durability factor of 100 after completing the 300 cycles. This concrete in this study did use an air entraining admixture. The durability of concrete from the effects of freezing and thawing was considered good.

The overall results of the durability studies showed that concrete containing just steel slag as a coarse aggregate had comparable durability results. It also showed that the addition of an air entraining admixture improves the durability of the concrete with steel slag. The addition of LF slag had adverse effects on the durability of concrete with respect to freezing and thawing.

The results of the wetting and drying test varied slightly from study to study but the overall results from the testing showed that when the steel slag is used in concrete the surface appearance is acceptable and the weight loss is also acceptable. The compression losses seen in concretes with steel slag tend to be higher than the control’s loss of compression strength. This could indicate some internal damage taking place within the concrete that could be resulting from possibly the hydration of free lime or periclase that is present in the slag.

The durability of concrete from high temperature exposure was examined by Pacheco et al. (No Date). The concrete containing steel slag in percentages of 25% and 100% both had loss of compression strength less than the control concrete. This was the only study found during this research that examined the effects of high temperature exposure, but this test is not relevant for pavement applications.

The effects of attach from chloride ions was studied in the chloride diffusion test by Pacheco et al. (2008). The results after completing the testing for nine months showed that the concentration of chloride increased with time and was attributed to the porosity and chloride binding with the slag. The transport of chloride through the concrete could be seen to increase as the percentage of slag increased. The durability of the concrete containing steel slag was considered low. This was the only study that examined the transport of chloride in steel slag concrete. Most pavements do not use rebar; therefore, the chloride ions should not affect the durability of concrete pavement.

The workability of concrete is affected by the addition of the steel slag by both the higher angularity of the particles and the higher absorption of the slag. The results of studies showed that as the percentage of slag in the concrete increased the slump of the concrete decreases. The addition of admixtures improves the workability of the concrete and it was demonstrated that a slump in a desired range could be achieved. Work conducted by Obratil et al. demonstrated that concrete containing steel slag could meet the ODOT specifications for Class C paving mixtures when the percentage of steel slag was below 100%. The 100% steel slag as a coarse aggregate was 0.25 in (0.6 cm) which was well below the 1 in (2.54 cm) minimum slump. It was also demonstrated in two separate cases that concrete containing steel slag could maintain enough workability to be pumped into place.

The physical and mechanical properties of portland concrete cement made with steel slag aggregate could produce specimens that have comparable physical and mechanical properties to those specimens made with accepted aggregates like a limestone aggregate. Proper care needs to be taken to ensure that the desired strengths of the concrete are achieved through the testing of the mixtures prior to being used in an application since the composition of slags will vary depending on the slag's origin. The results of the durability testing of concrete containing steel slag varied from study to study. The results of freezing and thawing showed acceptable surface appearance and loss in weight, but the loss in compression strength was greater than the control, and this was attributed to the fine steel slag not having the proper grading. The addition of admixtures in the study by Patel (2008) showed positive results for the durability of concrete containing steel slag for freezing and thawing test. The wetting and drying test results were similar to that of the freeze and thawing in that the surface appearance was acceptable for most specimens. Loss of compression strength was generally higher in steel slag concrete. The use of steel slag in concrete can achieve the desired slump and meet the requirement of ODOT, but the addition of admixtures could offset some of the cost saving from its use.

CHAPTER IV

CHEMICAL COMPOSITION AND PROPERTIES

The chemicals and minerals found in the steel slag are leftover components from the production of the steel. The slag produced from the production of the steel contains the impurities that have been removed from the molten steel. The actual chemical compounds found in the slag are dependent on the type of steel production plant and the type of flux used in the process. For example, a ladle slag will have different ranges of chemical composition than that of a slag from an EAF steel plant, which will have different ranges in composition from a BOF plant. The chemical properties of steel slag produced at different plants using the same process, such as an EAF will probably have different chemical compositions from one another. This is because the scrap metal being refined is different and the types and amounts of fluxing agents will be different. The chemical composition of the steel slag at any particular plant will not usually have a large variation from day to day or year to year. The three types of steel slag discussed in this chapter are BOF slag, EAF slag and LF slag.

4.1 Determining the Chemical and Mineralogical Composition

The chemical and mineralogical analysis of steel slag can be accomplished by the following methods: X-ray fluorescence method, X-ray powder diffraction, Electron probe micro analysis and X-ray diffraction method (XRD). The chemical composition of the steel slag is provided in many studies. The methods for determining the chemical and mieralogical composition of the slag were not always stated. The most common analysis used in the studies was XRD, and for this reason it will be described in the following section. The method for determining the content of free lime by the ethylene glycol method is also discussed.

4.1.1 X-Ray Diffraction Testing

XRD is used in order to determine the chemical and mineralogical composition of a rock, soil or slag aggregate. According to Mitchell, et al. (2005) X-ray diffraction is the most widely used method for the determination of fine-grained soil minerals and the study of their crystalline structure. As the X-rays penetrate the crystal, small portions of them are absorbed by the atoms, which cause them to oscillate. This results in some waves that are in phase, which can then be detected as waves that have resulted from a reflection of the incident beam. The direction of the parallel planes of the crystal structure, which are relative to the direction of the incident beam, at which the radiations are in phase depends on the wavelength of the X-rays and the spacing between atomic planes (Mitchell, et al., 2005). Since no two minerals have the same spacing of the interatomic planes in three dimensions, this method can be used to identify the mineral. This particular method cannot detect the presence of the crystalline CaO but it can detect the presence of hydrated lime, which can show that free lime was present in the material prior to treatment. The presence of MgO in steel slag can be detected by X-ray diffraction using the main reflection peaks located at 78°, 62.3°, and 42.91°. The most important peak of 2θ is located at 78°, and if this peak is not present, then MgO content is less than 20% and is difficult to differentiate from the baseline. The presence of some minerals in the steel slag can also make it difficult to detect MgO because minerals such as Larnite overlap and hide the reflection peaks of MgO (Rojas & Rojas, 2004).

4.1.2 Ethylene Glycol Test

This test is generally used to determine the types of minerals that are contained within a sample. The ethylene glycol and glycerol is applied to the mineral, and some of it is absorbed on the surface of the mineral. The amount of glycol retained can be used to determine the type of clay mineral, since different clay minerals have different specific surface areas (Mitchell, et al., 2005).

The ethylene glycol test is currently being used to determine the presence of free lime in steel slag. In Germany, samples of the molten steel slag are taken while it is still in the converter (Motz et al., 2001). Once the slag has been analyzed, the slag is then poured into different slag pits depending on the content of the free lime. One of the reasons the sample is taken at this point in the processing of the steel slag is that the ethylene glycol test does not differentiate between hydrated lime (Calcium Hydroxide) and free lime. Once the steel slag has been aged and allowed to come into contact with moisture, additional testing is required on the slag to find the free lime content. The slag now needs to be tested by thermo-gravimetric analysis, which is able to find the amount of $Ca(OH)_2$ by the weight loss of the sample at a temperature of 842 to 1022 °F (450 to

550 °C). This method for analyzing the steel slag was discussed by Yunxia et al. (2008) and Gumieri et al. (No Date).

In the study conducted by Gumieri et al. (No Date), a BOF slag that had been granulated by quenching in water was tested for presence of free lime. The percentage of free lime as tested by the ethylene glycol test was determined to be 1.4%. The percentage of $Ca(OH)_2$ was 0.31% which was found by thermo-gravimetric analysis. This means that the remaining percentage of 1.09% was the actual free lime content present in the steel slag sample. The presence of periclase was not detected in the slag sample, which was analyzed using XRD.

This method was used to find the free lime of a BOF slag in a study by Yunxia et al. (2008). The study was able to establish a relationship between the amount of free lime and the cracking ages of mortar bars. It was shown in a graph of the free lime content versus the cracking age of slag samples that as the content of free lime increased, the number of days until the specimens cracked decreased. The powder ratio of samples was compared to the content of free lime contained in the samples. It was shown that as the content of free lime increased so too did the powder ratio. The ethylene glycol test was also used in this study to examine the effects of weathering on steel slag to determine the effectiveness of different treatment processes and is discussed later in section 4.6.

4.2 Chemical and Mineral Properties of Steel Slag

The chemical and mineral composition of steel slag is dependent on the type of processing being used during the smelting and refining of the steel. BOF slag is produced in the furnace that has smelted iron ore from a blast furnace preloaded in the furnace before scrap steel is loaded into the furnace. Oxygen is then blown into the molten steel, which causes oxidation and purifies the steel. EAF slag is produced from scrap steel only, and uses an electric arc to melt the steel. Ladle furnace slag is produced from the further refining of BOF or EAF steel, and alloys are added which produce the high alloy steels. The following sections examine the chemical compositions of steel slags produced by the different steel making processes.

4.2.1 Basic Oxygen Furnace Slag

The chemical composition of 6 steel slags produced by basic oxygen furnaces are given in Table 15. The main components of the BOF slags are calcium oxide (CaO), silicon dioxide (SiO_2), iron oxides in the form of FeO or Fe_2O_3, aluminum oxide (Al2O3), magnesium oxide (MgO) and manganese oxide (MnO). These main components ranged from 80% to 95% of the total composition of the slag. The sum of the iron oxides, silicon oxide, and calcium oxide account for 67 to 79% of the total composition of the BOF slags. The minimum reported iron oxide was 15.97% and the maximum was 24.73% with a median of 20 and a standard deviation of 2.83. The calcium oxide had a median of 40.98%, a minimum of 36.31%, a maximum of 45.68% and a standard deviation of 3.49. The magnesium oxide had a range of 2.6% to 10.88% with a median of 7.75% and a standard deviation of 3.24. Ranges of BOF slags that have been suggested by other authors can be found in Table 16. The ranges for iron oxides from Table 15 are comparable to the ranges in Table 16. The calcium oxide ranges in Table 15 have a minimum that is 7% less than the ranges from Table 18, and the maximum values from the studies reviewed are lower. The silicon oxides and aluminum oxides from Table 15 fit within the ranges from Table 18. The maximum values for magnesium oxide were slightly higher in the studies reviewed than the maximum magnesium oxide values provided in Table 16. The authors of the studies can be found in Table 14.

Etxeberria et al., 2010	2		Faraone et al., 2009	13
Moon et al., 2002	3		Manso et al., 2005	14
Polanco et al., 2011	4		Gumieri et al., Unknown	15
Obratil et al., 2008	5		Yunxia et al., 2008	16
Pellegrino et al., 2009	6		Muhmood et al., 2009	17
Qasrawi et al., 2009	7		Luxan et al., 2000	18
Wang et l., 1991	8		Shi 2001	19
Maslehuddin et al., 2003	9		NSA	20
Al-Negheimish et al., 1997	10		Bohmer et al. 2008	21
A. M. Dunster, Unknown	11			

Table 14: Authors from studies used in the analysis of chemical compositions of the slags.

BOF Slags										
Study	3	14	16	20	21	21				
CHEMICAL	%	%	%	%	%	%	Minimum	Maximum	Median	Stand. Dev.
∑ Fe oxides	15.97	24.73	20.57	20	18.9	20	15.97	24.73	20.00	2.83
SiO_2	14.41	10.24	10.1	15.6	14.7	10.7	10.10	15.60	12.56	2.53
CaO	36.31	40.15	40.65	41.3	45.6	45.3	36.31	45.60	40.98	3.49
Al_2O_3	5.3	1.7	1.7	2.2	2.5	2.5	1.70	5.30	2.35	1.35
MgO	8.6	10.56	10.88	6.9	5	2.6	2.60	10.88	7.75	3.24
MnO	NR	7.16	0.06	8.9	4.5	2.9	0.06	8.90	4.50	3.48
$\sum P_2O_5 + TiO_2 + Na_2O + K_2O + Cr_2O_3 + V2O_5 + SO_3$ + other	NR	5.27	1.28	NR	1.46	1.9				
Free CaO	3.3	NR	3.56	NR	NR	NR				
Free MgO	NR	NR	NR	NR	NR	NR				

NR - Not Reported

Table 15: Typical main chemical properties and ranges for BOF slags.

BOF Slags								
Study	11		12		12		21	
			BOF low MgO content		BOF high MgO content			
	Range		Range		Range		Range	
CHEMICAL	%	%	%	%	%	%	%	%
∑ Fe oxides	27	31	14	20	15	20	18	24
SiO_2	10	12	12	18	12	15	10	15
CaO	42	44	45	55	45	50	36	50
Al_2O_3	1	2	< 3	< 3	< 3	< 3	1	3.5
MgO	5	6	< 3	< 3	5	8	4	8
MnO	3	6	----	< 5	----	< 5	----	5
$\sum P_2O_5 + TiO_2 + Na_2O + K_2O + Cr_2O_3 + V2O_5 + SO_3$ + other	NR		NR		NR		NR	
Free CaO	NR		< 10		< 10		< 10	
Free MgO	NR		NR		NR		NR	

NR - Not Reported

Table 16: Ranges of chemical composition of BOF slag from other studies.

4.2.2 Electric Arc Furnace Slag

The chemical compositions of 18 different electric arc furnace slags can be found in Table 17, and the ranges of percentages of the chemical components can be found in Table 18. The sum of the iron oxides, silicon oxide, and calcium oxide account for 61 to 89% of the total composition of the EAF slags. The minimum iron oxide content was 9.8% and the maximum was 44.8%. The iron oxide ranges from Table 18 show a much greater range of values than the ranges found in Table 19. The range of CaO from the 18 studies was similar to the ranges proposed by other authors in Table 19 and this was true for the ranges of MgO. The maximum value reported for MnO was more than twice that of the maximum reported in Table 19.

The content of iron oxides of the EAF slag are generally much higher than the content in the BOF slag. The median calcium oxide content of 29.5% for the EAF slag in Table 17 is much lower than the median content of 40.98% for the BOF slag from Table 15. The medians for MgO and MnO were comparable for the BOF and EAF slags. The median percentage of aluminum oxide for the EAF slag was triple the median percentage for the BOF slag.

	EAF Slag																
STUDY	1	2	3	4	5	5	5	6	6	8	10	10	10	13	17	18	18
Aggregate	Coarse	Coarse	Coarse	Coarse	3/4"	1/2"	C fines	Medium	Coarse	Coarse	Coarse	Coarse	Coarse	NR	NR	NR	NR
CHEMICAL	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
∑Fe oxides	42.5	37.6	17.94	42	14.4	35.6	37.5	37.2	44.8	22.4	21.56	19.45	20.73	9.8	24.1	27.41	34.36
SiO_2	15.3	18.28	22.26	15.5	15.3	12	10.7	10.1	14.7	18.9	17.71	17.88	17.06	13.2	23.3	6.04	15.35
CaO	23.9	21.77	21.35	24	45.2	30.7	28.6	24.2	29.5	43.3	30.09	32.66	31.52	37.9	30.8	29.11	24.4
Al_2O_3	7.4	8.32	10.65	7.5	4.07	5.84	3.09	5.7	7.2	1.7	8.07	8	7.45.	6.8	6.1	14.07	12.21
MgO	5.1	6.14	12.35	5	10.1	9.95	9.82	1.9	4.6	8.4	12.52	12.31	13.52	11.9	12	3.35	2.91
MnO	4.5	4.43	NR	4.5	3.14	3.99	3.88	5.1	5.7	NR	2.44	2.48	2.46	13.5	1.5	15.58	5.57
$\sum P_2O_5 + TiO_2 + Na_2O + K_2O + Cr_2O_3 + V2O_5 + SO_3 +$ other	1.1	3.45	NR	0.5	0.85	1.89	1.8	2.5	4.1	1	3.35	3.67	3.63	6.9	1.5	3.9	4.85
Free CaO	0.45	NR	0.3	1	NR	NR	NR	NR	NR	NR	3.8	NR	NR	NR	1.4	NR	NR
Free MgO	1	NR	NR	< 0.1	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR

NR - Not Reported

Table 17: Typical main chemical properties compiled from 17 EAF slags.

EAF Slag Statistics				
CHEMICAL	Minimum	Maximum	Median	Stand. Dev.
$\sum$ Fe oxides	9.8	44.8	27.41	10.83
SiO_2	6.04	23.3	15.35	4.32
CaO	21.35	45.2	29.50	6.91
Al_2O_3	1.7	14.07	7.30	3.15
MgO	1.9	13.52	9.82	3.92
MnO	1.5	15.58	4.43	3.98
$\sum P_2O_5 + TiO_2 + Na_2O + K_2O + Cr_2O_3 + V2O_5 + SO_3$ + other	0.5	6.9	2.93	1.73

Table 18: Statistics compiled from EAF slags (Table 17).

EAF Slag Ranges			
Study	12	12	21
	EAF low MgO content	EAF low MgO content	
	Range	Range	Range
CHEMICAL	%	%	%
$\sum$ Fe oxides	18 - 28	20 - 29	10 - 30
SiO_2	12 - 17	10 - 15	10 - 18
CaO	30 - 40	25 - 35	35 - 45
Al_2O_3	4 - 7	4 - 7	3 - 8
MgO	4 - 8	8 - 15	7 - 15
MnO	< 6	< 6	<1
$\sum P_2O_5 + TiO_2 + Na_2O + K_2O + Cr_2O_3 + V2O_5 + SO_3$ + other	NR	NR	NR
Free CaO	< 3	< 3	< 4

NR - Not Reported

Table 19: Ranges of chemical composition of EAF slag from other studies.

4.2.3 Ladle Furnace Slag

Ladle furnace slag is produced when additional alloys and fluxes are added to the ladle to further refine the steel slag to produce special steels such as stainless steel. This addition of fluxes into the molten steel then produces a ladle furnace slag that has different chemical properties from an EAF slag or a BOF slag. Ladle furnace slag is produced at a rate of 66 lbs (30 kg) per ton of steel produced (Manso et al., 2005). Once the slag is exposed to the environment and weathered, the slag breaks down and disintegrates in the first week and is known as the slaking process. The exposure of the slag to rain can speed the process of disintegration up until finally the slag is reduced to a fine powder. This results in a high percentage of fine powder, which makes the ladle furnace slag unsuitable for use as an aggregate in PCC. The fines in a ladle furnace slag can be in a range of 20 – 35% that pass the # 200 sieve. It is during this process that all the free lime and part of the periclase is transformed into the hydroxides portlandite and brucite (Manso et al, 2005).

XRD analysis was performed on three different samples of the ladle furnace slag in a study performed by Shi (2002) (Study number 19 in Table 20). The free lime content could not be clearly identified because to the CaO is not detectible by XRD. The presence of hydrated lime ($Ca(OH)_2$) was identified in trace amounts in all three samples which shows that free lime was at least present before aging of the slag. In a different study conducted by Manso et al. 2005, the hydrated lime, also known as portlandite, was found in a quantity of 18 – 22% and periclase ranged of 4 – 8%.

Table 20 shows the chemical compositions of differnt ladle furnace slags. It can be seen from the Table that the iron content is much lower than that of a BOF slags or an EAF slags. It can also be seen that the content of CaO showed little variation in the ladle furnace slags with a standard deviation of 0.91. The CaO content of the ladle furnace slags accounted for more than 50% of the total composition of the slag. The LF slags have a median percentage for CaO of 57% which is approximately twice the median percentage for the EAF slag and is 30% higher than the BOF CaO percentage. The median percentage for the MgO was 4.2%, which is less than half the median for the EAF slags and close to half that of the BOF slags.

The ranges of chemical compositions of LF slag found in Table 21 are from an aggregates case study conducted by Bohmer et al. (2008). This case study was composed of research on different aggregates and slags from countries in Europe. All CaO contents reported in Table 20 were above the maximum value of the range reported in Table 21. The MgO contents of three of LF slags reported in the studies reviewed in this research were below the minimum of the range reported by Bohmer et al. (2008). The iron oxide content and aluminum oxide content were within the ranges reported in Table 21. The range of silicon oxide contents were much higher compared to the range reported in the study by Bohmer et al. (2008).

Ladle Furnace Slag									
Study	4	14	19						
	Fine	NR	L 100	L 200	L325				
Chemical	%	%	%	%	%	Minimum	Maximum	Median	Stand. Dev.
∑Fe oxides	0.5	NR	3	3.9	4.4	0.5	4.4	3.45	1.73
SiO_2	1	17	26.8	26.9	26.4	1	26.9	26.4	11.23
CaO	58	58	57	56.6	55.9	55.9	58	57	0.91
Al_2O_3	12	12	5.2	4.3	4.7	4.3	12	5.2	3.99
MgO	10	10	3.2	3.9	4.2	3.2	10	4.2	3.43
MnO	NR	NR	1	0.5	0.5	0.5	1	0.5	0.29
SO_3	1	1	1.7	2.4	2.3	1	2.4	1.7	0.68
Free CaO	10 - 20	NR	NR	NR	NR				
Free MgO	3 - 4	4 - 8	NR	NR	NR				

NR - Not Reported

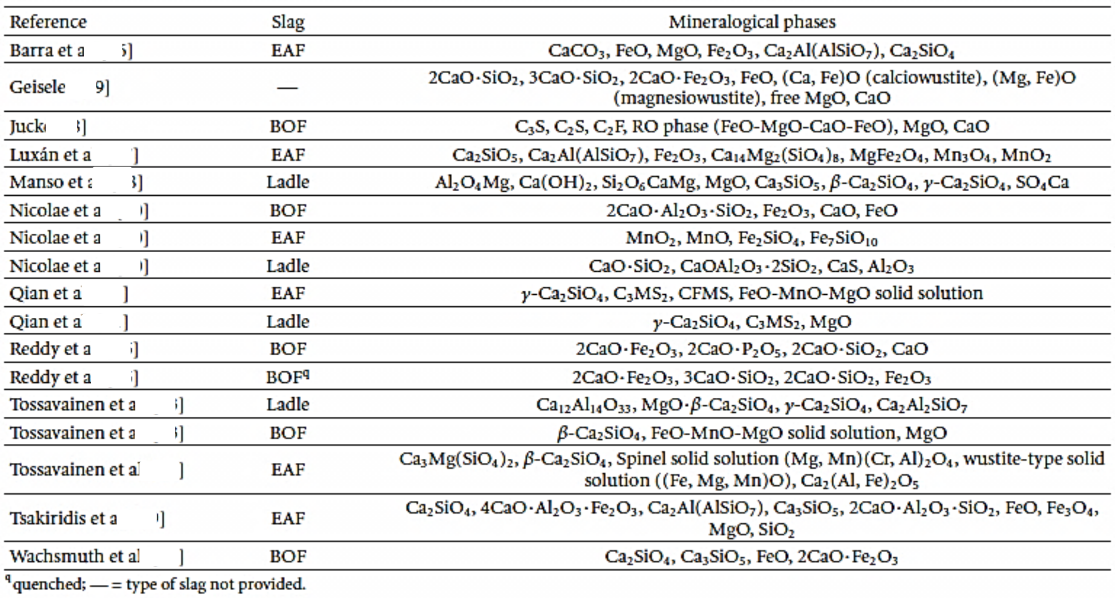
Table 20: Typical main chemical composition for ladle furnace slag.

Ladle Furnace Slag		
Study	21	
	Range	
Chemical	%	%
∑ Fe oxides	2	5
SiO_2	10	20
CaO	30	50
Al_2O_3	3	12
MgO	7	18
MnO	1	5
SO_3	NR	NR
Free CaO	0	< 10
Free MgO	NR	NR

Table 21: Ranges of chemical composition for ladle furnace slag.

4.2.4 Mineralogical Components of Steel Slag

The mineral composition of steel slag will vary from steel plant to steel plant, just as the chemical composition does. The mineral composition is also dependent on the type of process being used to refine the steel and the composition of the steel being recycled. Table 22 shows the mineral composition of different types of steel slags. The most common minerals found in steel slag are CaO (free lime), MgO, FeO, merwinite ($3CaO \cdot MgO \cdot 2SiO_2$), olivine ($2MgO \cdot 2FeO \cdot SiO_2$), ($4CaO \cdot Al_2O_3 \cdot FeO_3$), β-C_2S ($2CaO \cdot SiO_2$), α-C_2S, C_4AF, ($4CaO \cdot Al_2O_3 \cdot FeO_3$), C_2F ($2CaO \cdot Fe_2O_3$), C_3S ($3CaO \cdot SiO_2$), and the RO phase which is a solid solution of CaO-FeO-MnO-MgO (Yildirim et al., 2011). It can be seen from Table 22 that some of these components are reported in the chemical composition of the steel slags previously discussed, but many of them are not listed in the chemical composition since they are such a small fraction of the overall composition of the slag.



Reference	Slag	Mineralogical phases
Barra et a]	EAF	$CaCO_3$, FeO, MgO, Fe_2O_3, $Ca_2Al(AlSiO_7)$, Ca_2SiO_4
Geisele 9]	—	$2CaO \cdot SiO_2$, $3CaO \cdot SiO_2$, $2CaO \cdot Fe_2O_3$, FeO, (Ca, Fe)O (calciowustite), (Mg, Fe)O (magnesiowustite), free MgO, CaO
Juck]	BOF	C_3S, C_2S, C_2F, RO phase (FeO-MgO-CaO-FeO), MgO, CaO
Luxán et a]	EAF	Ca_2SiO_5, $Ca_2Al(AlSiO_7)$, Fe_2O_3, $Ca_{14}Mg_2(SiO_4)_8$, $MgFe_2O_4$, Mn_3O_4, MnO_2
Manso et]	Ladle	Al_2O_4Mg, $Ca(OH)_2$, Si_2O_6CaMg, MgO, Ca_3SiO_5, β-Ca_2SiO_4, γ-Ca_2SiO_4, SO_4Ca
Nicolae et a]	BOF	$2CaO \cdot Al_2O_3 \cdot SiO_2$, Fe_2O_3, CaO, FeO
Nicolae et a]	EAF	MnO_2, MnO, Fe_2SiO_4, Fe_7SiO_{10}
Nicolae et a]	Ladle	$CaO \cdot SiO_2$, $CaOAl_2O_3 \cdot 2SiO_2$, CaS, Al_2O_3
Qian et a]	EAF	γ-Ca_2SiO_4, C_3MS_2, CFMS, FeO-MnO-MgO solid solution
Qian et a]	Ladle	γ-Ca_2SiO_4, C_3MS_2, MgO
Reddy et a]	BOF	$2CaO \cdot Fe_2O_3$, $2CaO \cdot P_2O_5$, $2CaO \cdot SiO_2$, CaO
Reddy et a]	BOF^q	$2CaO \cdot Fe_2O_3$, $3CaO \cdot SiO_2$, $2CaO \cdot SiO_2$, Fe_2O_3
Tossavainen et a]	Ladle	$Ca_{12}Al_{14}O_{33}$, $MgO \cdot \beta$-Ca_2SiO_4, γ-Ca_2SiO_4, $Ca_2Al_2SiO_7$
Tossavainen et a]	BOF	β-Ca_2SiO_4, FeO-MnO-MgO solid solution, MgO
Tossavainen et al]	EAF	$Ca_3Mg(SiO_4)_2$, β-Ca_2SiO_4, Spinel solid solution $(Mg, Mn)(Cr, Al)_2O_4$, wustite-type solid solution ((Fe, Mg, Mn)O), $Ca_2(Al, Fe)_2O_5$
Tsakiridis et a]	EAF	Ca_2SiO_4, $4CaO \cdot Al_2O_3 \cdot Fe_2O_3$, $Ca_2Al(AlSiO_7)$, Ca_3SiO_5, $2CaO \cdot Al_2O_3 \cdot SiO_2$, FeO, Fe_3O_4, MgO, SiO_2
Wachsmuth et al]	BOF	Ca_2SiO_4, Ca_3SiO_5, FeO, $2CaO \cdot Fe_2O_3$

^{q}quenched; — = type of slag not provided.

Table 22: Mineralogical compositions of various types of steel slag (Yildirim et al., 2011).

4.3 Alkalinity

The alkalinity of a liquid or a system quantifies the buffering capacity of the liquid or system, which describes its resistance to changes in its pH when an acid is added (Lackey & Mines, 2009). Rocks like dolomite ($CaMg(CO_3)_2$) and limestone ($CaCO_3$) are high alkalinity carbonates, which can contribute to the alkalinity or buffering capacity of a liquid or substance. Limestone or dolomite are added during the production of the steel as a fluxing agent. Steel slags contain free lime (CaO) which reacts with water to produce slaked lime ($Ca(OH)_2$). This then dissolves into Ca2+ and OH-, which in turn increases the pH (Nippon Slag Association, 2006) . The pH of steel slag generally ranges from 8 to 10 but can be as high as 12. This high pH of the steel slag leachate could be of an enviromental concern when the slag is used in applications where the amount of water the slag is exposed to is limited. The pH could affect organisms and plant life that are exposed to the leachate. When a dilution of 100-fold is obtained, the alkalinity of the leachate from the slag is not anticipated to be of concern (Exponent Inc., 2007).

When the steel slag is weathered, it forms a layer around the slag particle, which is composed of an insoluble calcium carbonate ($CaCO_3$) (Exponent Inc., 2007). This layer of calcium carbonate around the slag particle helps to slow down or prevent the leaching of calcium hydroxide and metals, such as chromium or aluminum, which might be of environmental concern. This layer of calcium carbonate will continue to build up with time, and thus, the longer the slag is exposed to the water the less leaching of metals and calcium hydroxide will occur. This formation of calcium carbonate around the slag particle is known as the “armoring process” (Exponent Inc., 2007).

4.4 Leaching of Heavy Metals – as an aggregate in unbound applications

A concern with the use of steel slag in unbound applications, such as when it is used for the stabilization along a riverbank, is its potential to leach chemicals and metals into the environment. These chemicals and metals can possibly pose a risk to the health of both people and animals. The leaching of metals from the slag can become harmful when the amount of metal leached is greater than the amount found naturally in the soil or water. Some metals contained within the slag that can occur in concentrations higher than those found in the soils of the United States are: antimony, beryllium, cadmium, chromium, copper, manganese, molybdenum, nickel, selenium, silver, thallium, tin, vanadium, and zinc (Proctor et al., 2000). According to Motz et al. (2001), chromium as a mineral component may occur in higher amounts in steel slag, but its concentration in the leachate is low since its ions are bound within the crystalline phases of the slag. Since slag is highly alkaline, this limits the amount of metals leached from the slag (Exponent Inc., 2007). The following sections discuss the human and ecological risk posed by steel slag.

4.4.1 Human Health Risk Assessment

In a risk assessment study conducted in 1998, the use of slag in environmental applications was found to not pose a hazard in most situations to the health of people or the ecology (Exponent Inc., 2007). The most recent study was conducted to update the previous risk studies conducted by Proctor et al. (2000) and Proctor et al. (2002) using the most recent federal and state environmental regulations. This study conducted by Exponent Inc. (2007) assessed the human health risk, as well as the ecological risks. The findings of this report are summarized in the following sections.

The human health risk assessment was composed of the hazard identification, exposure assessment, toxicity assessment, and risk characterization. Metals found in the slag were compared to the levels of that metal found in the soil. If the concentration of the metal was higher than that of the maximum concentration allowed by the state or EPA levels, the metal was considered a constituent of interest (COIs) and was selected for further study. Metals that were found to have concentrations exceeding the allowable levels and considered to be COIs were: antimony, beryllium, cadmium, total chromium, copper, manganese, nickel, selenium, silver, thallium, tin, vanadium and zinc. The human health risk assessment included residential exposure from use in an unpaved driveway or as fill on site, residential exposure from dust generated from an unpaved roadway, and exposure to farmers from use in agricultural applications. It also included exposure to industrial and maintenance workers at an industrial of commercial site, and exposure to the construction workers that are using it as an aggregate for a road base or shoulder.

The “reasonable maximum exposure” (RME) and “most likely exposure” (MLE) were assessed in accordance to the EPA guidelines. This exposure assessment calculated average daily doses for exposures from all pathways and scenarios (Exponent Inc., 2007). Beryllium, cadmium, and certain forms of nickel were the only COIs to be considered potentially carcinogenic. The exposure and toxicity assessments are combined to form the risk characterization, which describes the potential health effects from the different uses of the slag. The theoretical excess cancer risk was calculated to be in a range of 2 in-ten-billion to 8 in- ten-billion for the RME, which is below the range of 1 in-a-million to 1 in-ten-thousand which the EPA considers to be negligible. These calculated risk levels from slag exposure show that under the exposures assessed in this risk assessment the slag does not pose a significant cancer risk to people exposed to the slag.

The hazard index (HI) is calculated based on the potential hazard associated with a cumulative exposure from all pathways. When a total HI is calculated to be larger than one, there is potential for a hazard and more studying of the COI is needed. The HI’s ranged from 0.07 to 1 for the RME scenarios, with the maximum being calculated for a child onsite residential scenario and for the construction worker for an EAF slag. HI’s ranged from 0.01 to 0.5 for the MLE scenarios with the maximum being calculated for the child onsite residential exposure for both EAF and BOF slag (Exponent Inc., 2007). Since all of the calculated HI values are equal to or less than 1, this indicates that the use of slag does not pose a hazard to human health. The uncertainty for the RME onsite residential child and construction worker scenarios, which had a HI of 1 were examined, and the critical toxicity and exposure assessment parameters were likely to have been overestimated according to the report. These over estimates would yield a conservative result and overestimated HI values.

4.4.2 Ecological Risk Assessment

The risk to the environment and animals in the environment is another important aspect of the leaching of chemicals and metals from steel slag. This hazard was assessed in the risk assessment conducted by Exponent Inc. (2007). This assessment used the screening-level approach, and there were no field studies conducted. This risk assessment was non site-specific and therefore some assumptions were made to estimate the level of metals that could affect the species in the environment coming in contact with the slag. The focus of this study was for unbound applications such as agricultural applications, and bank stabilization along rivers and bodies of water. The ecological risk associated with aquatic invertebrates in freshwater and saltwater as well as terrestrial orginisms that might come in contact with the soil or ingest the soil was assessed. The ASTM water leachate data was used for comparision with the freshwater and salt water screening levels. In order to acount for the dilution of the leachate into the ambient water, a 100-fold dilution factor was used in the analysis of the steel slag.

The maximum aluminum leachate concentrations from EAF slag were found to exceed the acute and chronic Ambient Water Quality Criteria (AWQC). According to Exponent Inc. (2007), a review of the AWQC for aluminum showed that the chronic criterion for aluminum is likely to be over estimated. The EPA acknowledges the questionable nature of the chronic criterion, since many high-quality waters in the United States exceed the chronic criterion for aluminum. The EPA chronic criteria is based on a pH of 6.5 to 6.6, and data cited by the EPA has demonstrated that aluminum is substantually less toxic at a higher pH. Therefore the EPA criteria is likely to be over conservative (Exponent Inc., 2007). It is therfore recommended that a site specific study be conducted in aquatic applications when the dilution of the slag leachate is limited.

The maximum barium concentration for chronic criterion for EAF slag exceeded the AWOC. According to Exponent Inc., the AWQC for barium was constructed from a limited toxicity database. Suter and Tsao (1996) showed that the levels in the AWQC for barium have been lowered due to the use of a "unusually sensitive non-native snail." The use of different organisms such as daphnids and gammarid amphipods would result in the AWQC for barium being higher, and therefore the leachate from the steel slag would be within the limits of the AWQC.

None of the slag leachate levels exceeded the allowable limits for saltwater. However the allowable screening levels for saltwater sediments was exceeded by total chromium for BOF and EAF slags. In order to meet the 95% upper confidence limit (UCL) for metal concentrations, a dilution factor of 10 would be needed. In most typical saltwater scenarios, a dilution factor of greater than 10 would probably be achieved, which would result in adequate dilution to achieve levels below the accepted limits. Conditions for the dilution of the leachate should be studied on a site by site basis.

The freshwater screening levels were exceeded for aluminum, barium, total chromium and hexavalent chromium, lead, selenium, silver, and vanadium for undiluted steel slag leachate. If a dilution factor of 40 is used, this would result in the 95% UCL metal concentrations of the steel slag that would not exceed the allowable sediment screeening levels (Exponent Inc., 2007). This is again site-specific, and it is assumed that at most sites eroision scenarios would meet the a dilution factor of more than 40. Table 7 of Proctor et al. (2000 and 2002) compares the toxicity characteristics leaching procedure (TCLP) slag leachate concentrations to the TCLP criteria with a 95% UCL leachate concentration. Arsenic, barium, cadmium, chromium VI, chromium total, lead, mercury, selenium, and silver were the nine metals examined. It can be seen that the nine metals shown in the table, none exceed the 95% UCL.

The findings of the ecological risk assessment by Exponent Inc. (2007, page xvi) state: "The results of the initial screening-level evaluations indicate that, when plausible environmental conditions and application scenarios are considered, in which slag particles or leachate are naturally diluted by ambient water, sediment, or soil particles, no significant haxard to ecological receptors is anticipated. The only potential caveat involves the need for sufficient dilution in scenarios where the slag is applied next to freshwater bodies due to the potential aluminum concentrations." It is recommended that site specific investigations be conducted when the slag-to-water ratio is low and the dilution of the leachate is questionable or when the possiblity of aluminum concentration could affect the ambient water.

The leachate from steel slag has been investigated in a number of studies and compared to the standards of the country in which the slag was tested. All of the studies reviewed in this research found that the leachate from steel slag does not pose a risk. These studies include but are not limited to:

- Greisler, J. (1996) – The leachate from steel slag was investigated using the tank leaching test and it was determined that the leachate from steel slag into the environment contained insignificant elements and did not pose an impact on the environment. This includes chromium due to the fact that the ions are bound within the stable crystiline form (Greisler, J. 1996).

- Leaching test were also conducted in another study by Pellegrino & Gaddo (2009) on an EAF slag aggregate in order to establish the leaching of toxic compounds from an EAF slag. These values were then compared to limits of the Italian standards. The slag was found to have leaching values below the limits and is acceptable for use as an aggregate in concrete based on this criteria. The leaching of slag has been examined in a number of different studies, and the results from these studies have all suggested that the leachate from steel slag does not pose a risk.

- Manso et al., 2006 (Spain) – Leachate from concrete containing EAF slag showed results that all values for Sulphates, Fluorides and Cr_{tot} were below limits set by local legislation.

4.5 Free CaO and Free MgO – Origin, Content and Limits

The chemical composition of steel slag is dependent on the type of process used to produce the steel, and the amount and type of scrap steel that is being smelted. It can be seen from the chemical compositions of the steel slags that were shown section 4.2 that the chemical composition can be very different between slags. The type and amount of flux that is used during the steel making process is also another key aspect to its chemical composition. Steel that is produced using dolomite will tend to have higher concentrations of magnesium oxides, and steel that is produced using lime will tend to have higher concentrations of calcium oxide. The following sections cover the origin of free lime and free magnesium in the steel slag, and examine the limits on the content of CaO and MgO for current applications that have been discussed in research studies.

4.5.1 Free Lime and Free Periclase

The feasibility of using steel slag in a concrete pavement depends on its physical and mechanical properties as well as its volume stability. The amount of calcium oxide and magnesium oxide are very important components that need to be examined, since they are the main components that are responsible for volume instability.

Many of the studies reviewed in the course of this research mention the potential expansion problems that arise from the chemical components of free lime and free periclase, but very few studies tested for the compounds when completing the chemical analysis or discussed the how the free lime and free periclase forms in the steel slag. Free lime originates from residual undissolved lime or from the dissociation of tricalcium silicate (Makikyro, 2004). The chemical equation for the dissociation of tricalcium silicate is:

$$3CaO * SiO_2 = 2CaO * SiO_2 + CaO_{free}$$

The volume stability depends on the amount of free lime and free periclase that is present in the steel slag. When the free lime and free periclase in the slag are exposed to water, they hydrate and this hydration is what causes the expansion of the slag. The volume stability and expansion of steel slag are discussed in Chapter 6. Free lime can be present in the slag in two forms, as a precipitated free lime and as a residual free lime. According to Makikyro (2004) and Greiseler (1996), the precipitated free lime does not have any major impact on the volume stability of the slag, but the residual free lime does. The residual free lime can be separated into two categories, granular free lime that has a particle size of 3 to 10 µm, and spongy free lime that has a particle size of 6 to 50 µm. The spongy free lime is the most important factor in the volume stability of the slag (Makikyro, 2004).

The presence of free magnesium is also a factor in the long-term stability of the steel slag. The free magnesium in the slag originates from undissolved slag or is due to the saturation of the slag with MgO (Makikyro, 2004). Steel slags that have a high content of MgO will generally have higher contents of free MgO. The form of MgO that is of concern is the magnesio-wusite form when concentrations reach or are above 70%.

4.5.2 Limits on the Content of CaO and MgO

The following statements and limits are from articles reviewed during this research. Some authors documented where these limits came from and some did not. The validity of these statements may or may not be based on experimental results and are declarations of the authors.

Before using a BOF slag as building aggregate, a thorough classification has to be made of the slag and determined if the content of free CaO is over 7 %. If it is determined that the slag contains a free lime content greater than the 7% limit, it cannot be used as a building aggregate (Bohmer et al., 2008).

The expansion of cement is harmful when the free CaO exceeds the limit of 2% (Gumieri et al., No Date). This limit was originally proposed in the book ‘The chemistry of cement and Concrete, 3rd edition’ by author Edward Arnold Ltd., London in 1970.

In Germany, the steel slag is separated by sampling the steel slag while it is still in the molten stage. The free lime content is determined by the ethylene glycol method or statistical formulas, and the slag is then separated based on the test. A limit of 4% free lime is used as the separation limit. This method for separating the slag is only used if dolomite is not used as a fluxing agent (Motz et al., 2001). Experience in Germany has also found that a content of up to 7% of free CaO may be used in unbound layers and up to 4% of free CaO in asphalt layers.

Limits on the content of MgO have also been established using the German steam test, which is discussed in Chapter 6. The limits were developed by a task group in Europe and were based on 10 years of testing when this study was published in 2001. Table 3 on page 290 (Motz et al., 2001), shows standards that have established the requirements for MgO content based on the intended use of the slag, which limits the maximum allowable expansion percentage of the aggregate using the steam test, and states the required testing time for the aggregate using the steam test. A ladle furnace slag with an MgO content of less than 5% has to be tested for 24 hours and ladle furnace slag that has a MgO percentage greater than 5% have to be tested for 168 hours. EAF slags have to be tested for the 168 hours due to the content of MgO usually being larger than that of LF slag. Category V_A is for use in unbound layers and asphalt layers while category V_D there is no necessity to test the slag’s volume stability, if the experience conforms to a satisfactory performance record (Motz et al., 2001).

4.6 Effects of Aging / Treatment on the Chemical Composition

The main components attributed to the problems of the expansion of the steel slag aggregate are the free CaO and the free MgO in the slag. Once the slag is removed from the furnace, it can be cooled by a number of different processes, which are discussed in Chapter 5. For many years the main way of allowing the slag to cool was by pouring the liquid slag into a slag pit and spraying it with water. This process is considered to be a slow cooling process, and produces a solid slag in a crystalline form.

In a study conducted by Gumieri et al. (No Date), the effects of cooling the slag rapidly by the quick quenching method with a BOF slag was examined. This method cools the slag very rapidly, which improves the slag's hydraulic properties and stabilizes the slag by reducing the amount of free lime in the slag. It is reported that this method not only reduces the amount of free lime in the slag, but also reduces the amount of MgO because the MgO combines with FeO and MnO and forms a solid which is not of the form of periclase. X-ray diffractogram was used to analize the BOF steel slag sample and periclase was not detected using this method. Electron probe micro analysis of the sample showed that the MgO phases were distributed throughout the sample and had low concentrations of crystals in the form of periclase (Gumieri et al., No Date). The amount of free CaO reported was reported to be 1.4%, and was determined by the ethylene glycol method. The instant chilled method of cooling the slag rapidly, which is discussed in Chapter 5, also reported low amounts of free lime and periclase in the slag. In this study, the free lime ranged from 2 to 4% and periclase was not detected in the steel slag

(Montgomery et al., 1991). The method used for the analysis was not documented in the study.

The effectiveness of treatment methods to stabilize the steel slag by means of hydration of the free lime was examined by Yunxia et al. (2008). This study used four treatment processes on a BOF slag and compared the results by testing for the free lime content that remained in the slag. The steel slag samples were tested using the ethylene glycol test and the thermo-gravimetric analysis test. The control BOF slag sample had a free lime content of 3.56%. The first treatment process was exposing the steel slag to steam treatment for eight hours. The second treatment process was steam for twelve hours. The free lime content was 1.07% for the eight-hour treatment and was 0.94% free lime percentage for the twelve-hour steam treatment. While the twelve-hour treatment hydrated more free lime the difference between the two steam processes is not very significant for the additional time. The eight-hour steam treatment was able to reduce the free lime content by 60%. In the third process, the slag was treated in the autoclave for 3 hours at 419 °F (215°C) at 290 psi (2.0 MPA). The free lime content was 0.31%, which is a 90% reduction in the steel slag.

The authors of the paper do not discuss the fourth method used to treat the steel slag. At the beginning of the paper, it is mentioned that the BOF slag was aged for twelve months outdoors prior to being used in the laboratory testing. They used this aged slag as the control specimen to compare the results to. As stated earlier, the free lime content of the control slag was 3.56%. While the content of the free lime was unknown when the slag was removed from the converter, this clearly shows that the weathering of slag outdoors does not remove all the free lime from the slag.

4.7 Conclusion

The chemical and mineral composition of steel slag is dependent on the type of process being used to refine the recycled steel and the amount and types of steel that is added to the furnace. Steel slag is comprised of the impurities and components that are left over from the steel making process. The type of flux used in the steel refining process also has an effect on the final composition of the steel slag.

The most common method for determine the composition of the slag is XRD, which is able to determine the composition of the slag, since no two minerals have the same spacing of interatomic planes in three dimensions. There are some difficulties in establishing some of the components of the steel slag due to the overlapping of the main diffraction peaks. If there is less than 20% MgO present, in the slag then it is difficult to establish its presence since it is hard to differentiate from the base line. The ethylene glycol test may be used along with thermo-gravimetric analysis to find the amount of free lime contained in the steel slag. Ethylene glycol extracts both hydrated lime $(CaOH)_2$ and free lime at the same time. For this reason, thermo-gravimetric analysis is used to find the amount of calcium hydroxide. Then the un-hydrated free lime can be obtained by subtracting the amount of calcium hydroxide from the amount determined by the ethylene glycol test.

The chemical compositions of three types of steel slags were examined in this research. They were BOF slag, EAF slag and LF slag. The main components of BOF slag accounted for 80 to 95% of the total composition with iron oxide, silicon oxide, and calcium oxide accounting for 67 to 79% of the total composition. Most of the studies examined in this research did not report the amount of free CaO or free MgO content in the slag, but the two studies that did reported a free CaO content of approximately 3.5%.

There were 18 studies that reported the chemical composition of EAF slag reviewed in this research. The sum of the iron oxide, silicon oxide, and calcium oxide accounted for 61 to 89% of the total composition of the slag. EAF slags have higher iron oxide content than BOF slags and they had a larger range of content for CaO. The median content for CaO was 10% lower than that of the BOF slag. The CaO ranged from 21.35 to 45.2% and the MgO content ranged from 1.9 to 13.52%.

Ladle furnace slag is prone to disintegration and the fines produced from the slaking process can account for 20 to 35% of fines that pass the number 200 sieve. The iron oxide content of LF slag is very low compared to BOF or EAF slags and account for 0.5 to 4.4% of the total composition. The CaO content of the LF slags showed very little difference between the five slags, with a standard deviation of 0.91, and accounted for more than 55% of the total composition of the slags. The mineral composition of different slags was also examined. The most common components were CaO (free lime), MgO, FeO, merwinite ($3CaO \cdot MgO \cdot 2SiO_2$), olivine ($2MgO \cdot 2FeO \cdot SiO_2$), ($4CaO \cdot Al_2O_3 \cdot FeO_3$), β-$C_2S$ ($2CaO \cdot SiO_2$), α-C_2S, C_4AF, ($4CaO \cdot Al_2O_3 \cdot FeO_3$), C_2F ($2CaO \cdot Fe_2O_3$), C_3S ($3CaO \cdot SiO_2$), and the RO phase which is a solid solution of CaO-FeO-MnO-MgO.

The alkalinity of steel slag is its ability to resist changes in pH, and fluxes like dolomite and lime can contribute to the alkalinity of the slag. When slaked lime dissolves, it produces Ca2+ and OH- and this increases the pH. The pH of steel slag ranges from 8 to 10, but can be as high as 12. This high pH can affect organisms and the environment when exposed to the leachate from the slag if a dilution of 100 fold is not obtained.

The leachate from steel slag in unbound applications was also examined in this research, even though the slag is being used as an aggregate in a bound application. This was done primarily to examine the exposure of workers that might be exposed to the slag at the mixing plants. It also was completed to examine the leachate of the steel slag when it is being weathered in slag piles, since this is the most common method used for aging the slag.

The risk assessment conducted by Exponent Inc. (2007) examined exposures from all pathways and scenarios, and determined that beryllium, cadmium and certain forms of nickel were COIs since they occurred in levels that were higher than found naturally in U.S. soils. The calculated risk levels showed the slag did not pose a significant cancer risk to people exposed to the slag. The maximum HI calculated was equal to 1 for a child and this was considered to be a conservative assessment. Since there should not be any children in the concrete mixing plants, the HI for a child would not be considered an issue in this particular instance.

The ecological risk assessment was also conducted by Exponent Inc. The maximum aluminum leachate concentrations exceeded the AWQC limits. According to Exponent Inc. the EPA acknowledges the chronic criteria for aluminum to be overestimated, since many waters in the U.S. exceed the chronic criterion for aluminum. Site-specific studies are recommended when dilution of the leachate from the steel slag is limited. A dilution factor of 40 is needed to ensure sediment screening levels for freshwater are not exceeded by aluminum, barium, total chromium and hexavalent chromium, lead, selenium, silver, and vanadium. The findings of the ecological risk assessment were: when plausible environmental conditions and application scenarios are considered in which the slag particles, and leachate are naturally diluted by ambient water sediments and or soil particles, there is no significant hazard to ecological receptors. The leachate from steel slag was investigated by a number of different studies reviewed in this research, and all studies found that the leachate did not pose a risk.

The content of calcium oxide and magnesium oxide in steel slag is mainly from the flux added during the production of the steel. The free lime in steel slag originates from residual undissolved lime or from the dissociation of tricalcium silicate. The volume stability of the slag depends on the amount of free lime and free periclase present in the slag. The expansion due to the free lime and free periclase is one of the major concerns with the use of steel slag as an aggregate in concrete. Free lime can be present in the slag in the form of precipitated free lime and as residual free lime. The residual free lime can then be separated into granular free lime, with a particle size of 3 to 10 µm and spongy free lime with a particle size of 6 to 50 µm. The spongy free lime is the component that is mainly responsible for the short-term volume instability of steel slag. The free periclase originates from undissolved slag or saturation of the slag with MgO. Magnesio-wusite form of MgO is the component that is attributed to the long-term volume stability of the steel slag. The volume stability attributed to free lime and free magnesium will be discussed in more detail in Chapter 6.

In order to ensure the volume stability of slag so it can be used as an aggregate in concrete, limits of the content of free CaO and free MgO need to be established. Limits on the content of CaO and MgO have been suggested in some studies. The limit of 7% of free CaO for a building aggregate was cited by Bohmer et al. (2010), but it was not directly stated if this was for bound or unbound applications. The content of free CaO is limited to less than 2% for cement or the expansion of the cement, due to the free lime, can become detrimental. In Germany, the steel slag is separated into piles depending on the content of free lime being before being aged. The limit of 4% is used as the criteria for separation. This method is only used when dolomite is not used as a fluxing agent. If the content of free CaO is less than 7% than experience in Germany has found it is suitable for unbound applications and a limit of less than 4% free lime ensures it is suitable for applications in asphalt. The limits on MgO content were established by a task group in Europe and were based on ten years of testing. The limits were established for the amount of MgO that is allowed to be present in the slag depending on the intended application and it established the time required to test the slag depending on the type of steel slag. If steel slag can be shown to have the physical, mechanical and volume stability that meet the requirements that are necessary so it can be used in portland cement concrete than it will be imperative to establish guidelines for testing and limits on the content of free lime and MgO.

The effects of different treatment process were discussed on the chemical composition of steel slag for their ability to reduce or eliminate free lime and free periclase from the slag. The quick quenching method is reported to reduce the free lime content in the slag, but it also reduces the free MgO content, because the MgO combines with FeO and MnO and forms a solid that is not of the form of periclase. The periclase that was found in the BOF sample was in the form of crystals and was distributed throughout the slag sample and the free lime content was reported to be 1.4%.

The effectiveness of reducing the free lime content using different treatment processes was also examined by Yunxia et al. (2008). The treatment of the BOF slag by steam for eight hours showed a reduction of free lime from 3.56% for the control specimen to 1.07%, which is a 60% reduction. The additional treatment of the slag for four more hours only reduced the free lime content to 0.94%, which suggests the additional time and money that would be necessary to treat the slag might not be cost effective. The treatment by the autoclave method was the most effective and reduced the free lime content by 90%, and only took three hours to age the slag. All the slag used in this study was aged outdoors for twelve months prior to being used in the study. While the original free lime content prior to being aged outdoors is not stated, this example clearly demonstrates that the aging of steel slag in stockpiles is ineffective at removing or hydrating the free lime. If steel slag is to be used as an aggregate in PCC, then testing on the slag aged by this method will need to be conducted to ensure the free lime has been hydrated.

CHAPTER V

TREATMENT OPTIONS - TECHNIQUES FOR THE STABILIZATION OF THE STEEL SLAG

The expansion is an important aspect to the possible use of steel slag in concrete and so is the proper treatment of the slag to eliminate the expansion. The aging of steel slag by stockpiles outdoors and spraying has been used by the slag industry for some time now and is generally accepted for reducing the expansion. The treatment of the steel slag prior to cooling is also a possibility. This accomplished by the addition of silica sand and the blowing of oxygen into the slag while it is still in its molten state. Some other new methods that have recently been developed are quick quenching of the slag, steam aging, and autoclave aging of the slag. One final possible treatment of the slag is to chemically treat the slag to remove the chemical components that are responsible for the expansion.

5.1 Aging by Spraying with Water

The process of cooling the slag outside in areas that are covered or not covered has been used by slag companies for treating the slag aggregate since sometime in the early 1980's. The slag is brought outside in the slag pot and then it is poured into a slag pit and allowed to cool. Depending on the company and the intended use of the slag, the slag pits can be sprayed with water. The spraying of water initially helps to cool the hot molten slag faster and helps to fracture the slag as it is cooled. This type of cooling is considered a slow cooling process. Once the slag has cooled completely, the continued spraying of the slag with water accelerates the aging process of the slag by the hydration of the free lime and periclase. The slag remains outdoors, exposed to the natural elements, and is occasionally turned over to insure all the slag is aged properly. The slag should remain outside for a period of 90 days prior to being used as an aggregate in unbound applications such as a road base. According to the National Slag Association (1984), tests have indicated that aging in stockpiles after the processing and the use of coarser aggregate sizes tends to limit the potential expansion of the steel slag. It is also noted that aging the slag in large piles or pieces is not very effective, since the steel slag needs to be directly exposed to the weathering or it can remain expansive for a long period of time. The frequency of the overturning of the piles of slag is not discussed.

5.2 The Addition of Silica Sand Combined with Oxygen Blowing

This process takes place in a separate slag ladle so the process does not affect the quality of the steel. The molten slag is poured into a separate ladle where dry sand and oxygen are injected into the molten slag. The CaO / SiO_2 ratio is reduced, and the free lime is chemically bound and thus the free lime content is reduced (Motz et al., 2001). This process can also be used to chemically bind the free magnesium as well. The addition of the silicious material into the molten slag reduces the free MgO content by the hydration of the periclase during the high hydrothermal condition, which then reduces the expansion by reducing the amount of free MgO content (Yunxia et al., 2008). This process was introduced into a converter line of Thyssen Krupp Stahl, Duisburg in 1996 and has been operating successfully. The slag produced using this process is reported to have a free lime content of less than 1% by weight (Motz et al., 2001). The free MgO content of the slag produced from this process is not given but it was stated that the reaction works the same for the free MgO.

5.3 Quick Quenching Methods

The instant chilled slag process is comprised of four basic stages. The first stages consist of the cooling of the molten slag on shallow plates, which results in a thickness of the slag of approximately 4 inches (100 mm). The molten slag is cooled for approximately 4 minutes before it moves on to the next stage. The second stage of the cooling process consists of continuously spraying the slag with water for approximately 20 minutes until a temperature of 932 °F (500 °C) is reached. The slag is then transported to the 3rd cooling stage, which sprays the slag for an additional 4 minutes and cools the slag to a temperature of 392 °F (200 °C). The slag is finally placed into a pool of water and cooled to a temperature of 140 °F (60 °C) and the slag is now ready for further processing such as magnetic screening. This process of treating and cooling the slag produces slag with a free lime content ranging from 2 – 4%. No periclase exists in the slag and the particle sizes of the slag ranges from 1.2 to 2 inches (30 – 50 mm), (Montgomery & Wang, 1991).

Another process of rapidly cooling the slag is by quickly quenching the molten slag in water. This is accomplished by allowing the liquid slag to leak out from the converter into a slag pot that contains water, which produces a granulated slag. This process of granulating the slag produces a slag with a lower free CaO content then if the slag was cooled by air (Gumieri et al., No Date). The steel slag used in this study for cooling the slag rapidly had a CaO of 40.15%, MgO content of 10.56%, and free lime content of 1.4%. There was no detection of free MgO. There was no expansion testing done in the study.

5.4 Other Treatment Processes

Some other treatment processes using some form of water that are mentioned in different references are not described in detail. This may be because they are relatively new and the processes are still being perfected, or it might be because these processes are patented and proprietary to a certain company. One of these methods is the hot water aging process. Hot water aging is accomplished by submerging the steel slag aggregate into hot water at a temperature of 176 ± 37 °F (80 ± 3 °C) for 1 to 3 days (Moon et al., 2002). Another aging process is the aging or processing of the slag accomplished by exposing the aggregate to 212 °F (100 °C) steam for a period of over 3 days under 1 atm of pressure (Moon et al., 2002). Treatment of the steel slag in an autoclave device has also been mentioned in literature, but the details were not discussed. Aging the slag by steam at 212 °F (100 °C) is accomplished without pressure, and experimental processing times range from 3 hours to days in steam is another example. A final method of steam processing covers the slag with large tents and steams the slag in the tents for a period of a few days.

5.5 Chemical Treatment of Steel Slag

All the treatment processes discussed up to this point have focused on the treatment of the slag using some form of water. Another possibility is to use some type of chemical process to eliminate the components of the steel slag that cause the expansion. One possibility of treating the steel slag is the use of an acid, which will react with the calcium and or the magnesium. In a study conducted by Eloneva et al. (2008), the removal of calcium from a BOF slag was investigated to examine the possibility of producing pure calcium carbonate by mineral carbonization that then could be sold and used in other industries.

Since the BOF slag contains many different elements, a process for removing and separating just the calcium is needed, so the final product after carbonation will be pure form calcium carbonate with little or no impurities. The steel slag used in this study was air cooled, which produced a coarse grained crystalline slag. The CaO content was 46% by weight, and the MgO was 3.7% by weight, which was measured by XRD. The concentration of Ca was 30.1% and the concentration of Mg was 2.8 %, which were measured by Inductively Coupled Plasma – Atomic Emission Spectrometry (ICP-AES) analysis. Manning et al. (pages 1-19, 1997) defines ICP-AES as: “Inductively Coupled Plasma-Atomic Emission Spectroscopy is one of several techniques available in analytical atomic spectroscopy. ICP-AES utilizes plasma as the atomization and excitation source.” ICP-AES is used to identify and quantify the concentrations of chemicals and minerals in a substance. Two separate methods were used in the study by Eloneva et al. (2008) to remove the calcium from the slag, by dissolution or by precipitation.

5.5.1 Dissolution Method

The removal of the calcium from the slag by the dissolution method was conducted by using acetic acid and distilled water, with varying concentrations of the acid. The experiment used a glass reactor, which was surrounded by a heated water bath. Ten grams of slag with a particle sizes ranging from 125 to 250 μm were used in the acid. The concentrations ranged from 0 to 8 M of acetic acid at 86 °F (30°C). The solution was monitored at intervals to observe the dissolution. The experiment was repeated at temperatures of 122 °F (50°C) and 158 °F (70°C) to study the effects of temperature on the dissolution process. 10.6 oz (300 grams) of slag was also put into a solution of acetic acid solution (1M in 1.5 L) and stirred at 86 °F (30°C) to study the effects on the slag. The slag was removed from the acid, oven dried, and examined using XRD and SEM analysis.

The calcium was reported to have leached from the slag rapidly within 2 to 4 minutes in every solution of acid, with the stronger concentrations of acetic acid removing more of the calcium. The weakest solutions of acetic acid dissolved the calcium in a range of 25 to 30% while the stronger acid dissolved the calcium more effectively and provided 86 to 90% removal. The analysis of the solutions was completed by ICP-AES. The weaker solutions of acid dissolved the calcium but did not dissolve the other elements in high concentrations that were present in the slag. The stronger acid was more effective at removing the calcium, but also dissolved some other elements at higher concentrations from the slag, including Fe, Si, Mn, Mg, V, and Al. Analysis by XRD showed that all the lime and calcium hydroxide had been completely dissolved. This was confirmed by SEM analysis, which was performed on the slag prior to the treatment and after the treatment. Using the weaker acetic solution, the lime and calcium hydroxide were removed more selectively from the slag. Pictures of the BOF slag prior to the treatment, and after the treatment by the dissolution method, show the cubical particles of lime and calcium hydroxide can no longer be seen in the slag after treatment.

5.5.2 Precipitation Method

The second method for treating the steel slag for the production of calcium carbonate was the precipitation method. The experiment was done by dissolving 10.6 ounces (300 grams) of the slag into 0.4 gallons (1.5 liters) of 1 M of acetic acid solution at 86 °F (30 °C) for 2 hours. Then the slag was removed by sedimentation and the solution was filtered. The solution was then separated into eight batches so multiple experiments could be performed.

Part of the solution of acid and slag was placed in a glass reactor with a condenser and heated (solution A). Nitrogen gas was pumped into the solution at a rate of 1.06 gallons (4 liters) per minute during the heating stage of the experiment. Then carbon dioxide was bubbled into the solution at a rate of (4 liters) per minute, for 30 minutes and finally, the heating was increased for the remaining time of 90 minutes to a temperature of 136°F (58 °C). The solution was filtered and the precipitate was dried and analyzed the next day by XRD and SEM. The result from this experiment yielded approximately 3% of the total theoretical calcium carbonate.

A number of other trials were completed in the same procedure as solution A with the remainder of the original solution (solution B). The difference is that a specific amount of aqueous sodium hydroxide, NaOH, was added to the solutions in amounts of

5, 10, 15, 20 ml to see if improvements could be made in the amount of the precipitation of calcium carbonate from the addition of NaOH. The effects of temperature were also studied by increasing the temperature to 158 °F (70 °C) in one study and the effects of varying the flow rate of the carbon dioxide at 0.5, 1, and 2 liters per minute was also studied. The effects of combining the carbon dioxide and the nitrogen gases at various concentrations were also examined. As in the other studies, the precipitate was filtered, oven dried overnight and then examined by XRD and SEM analysis.

Without the use of sodium hydroxide, the production of acetic acid occurred at the same time as the calcium carbonate, which did not allow most of the calcium to precipitate. With the addition of NaOH, the pH of the solution remained higher for a longer period of time, which would allow more carbon dioxide to dissolve in the solution and allow the precipitation of the calcium carbonate. The result of increasing the amount of NaOH in the solution showed clearly an increase in the amount of precipitate formed. The study that examined the effects of varying the concentrations of gases that were bubbled through the solution showed that the stabilization time of the pH was increased as the carbon dioxide concentration was decreased. The concentration of the CO_2 did not seem to affect the amount of precipitate formed. The stabilization time of the solution was affected by the flow rate of the carbon dioxide, but the results were not discussed. The result of using sodium hydroxide in the solution produced calcium carbonate in the pure form of calcite. The calcium carbonate in the form of calcite ranged from 99.5 to 99.8 % weight. The conversion rate of the calcium from the solution ranged from 31 to 86% (Eloneva et al., 2008).

The amount of calcium carbonate produced from the chemical treatment of steel slag from one steel plant in Finland could amount to 10% of Finland's precipitated calcium carbonate needs. Since the free lime has been removed from the slag it may be more stable, and therefore it could be used as a construction material (Eloneva et al., 2008).

5.6 Conclusion

The aging / treatment processes discussed in this chapter all have one purpose, and that is the hydration of the free CaO and free MgO, which is the cause of the expansion of the steel slag. The treatment of the slag by methods of outdoor aging has been used for several decades now and is effective in the hydration of the expansive components of the slag. However, it does not always hydrate all the free components, and residual free lime and free periclase can still remain in the slag. It would appear that the weathering outdoors of the slag is fairly effective at the hydration of free lime, but free periclase can still remain due to the slow reaction time of the periclase.

The treatment of the slag while it is still in the molten stage by the addition of silica sand and injected oxygen reduce the free components by binding them chemically which produces a slag with a low content of free CaO and free MgO. Expansion testing of slag produced from this treatment process was not found during the course of this research. The cooling of the steel slag by rapidly cooling the slag is reported to produce slag that has a range of free lime of 2 – 4 % and no free periclase is reported to exist in the slag. This type of processing could be useful, since the periclase is the cause of long-term expansion and is not easily hydrated by the weathering in outdoor stockpiles. If there is no free periclase in the slag then the slag could be treated to remove the free lime by a process such as outdoor aging and this should then stabilize the slag. Some other treatment processes discussed were the aging of the steel slag by methods that involved the steaming of the slag after cooling. Another method was the hot water aging process, which submerges the slag in hot water for a period of 1 to 3 days. All these processes involved the use of some form of water. Chemically treating the slag may also be a possibility.

One possibility discussed was the treatment of the slag with an acid, which reacts with the calcium and produces calcium carbonate. Two methods discussed for this possible treatment were the dissolution method and the precipitation method. The dissolution method was studied by the use of a weak acid and a strong acid to see the effect on the removal rate of the calcium and the purity of the calcium carbonate. The weak acid was not as effective at removing the calcium, but it produced a more pure product, while the stronger acid was more effective at removing the calcium but also removed other components from the slag. The final product contained some impurities. The chemical treatment of the slag by the precipitation method proved to be more effective than the dissolution method. The addition of NaOH along with higher CO_2 concentrations affected the stabilization times of the solution, which allowed for more calcium carbonate in the form of calcite. The calcite ranged from 99.5 to 99.8 % purity. These methods may be able to the free lime from the slag, to help prevent volume instability. While this treatment of the slag might prove to be effective, the cost might offset the additional revenue from selling the steel slag as an aggregate for PCC. The cost of treating the slag could possibly be reduced by the revenue produced from the sales of the calcium carbonate, which is produced from the treatment process. The treatment of the steel slag will be the key to success if the slag is to be used in pavement applications. This treatment can either take place while the slag is still in a molten stage, while it is cooling or after it has cooled.

CHAPTER VI

EXPANSION CONCERNS, TESTING METHODS AND EXPANSION TESTING

One of the biggest concerns with the use of steel slag as an aggregate is its volume instability. The history of steel slag applications are well documented, and so are its successes and failures. While steel slag has had some success as an aggregate in unbound applications, it has also had some failures. These failures are what have made it difficult to gain acceptance for use in PCC applications. Many of the documented failures of the use of steel slags as an aggregate occurred prior to when it became a standard practice to age or weather the slag. The aging and weathering of the steel slag became standard practice and was implemented sometime in the mid 1980's.

According to the USGS MYB (2009, page 69.2), "Steel slags containing large amounts of dicalcium silicate are prone to expansion and commonly are cured in stock piles for several months to allow for the expansion and leaching out of lime." It then later states that steel slags are used mainly for a variety of aggregate applications but because of the expansion problems, it finds little use in applications requiring a fixed volume like concrete.

The following quote is for a warning regarding the use of steel slag due to its tendency to expand is provided by Harsco Metals, “Despite any amount of weathering or re-weathering, steel slag aggregate retains the potential to expand. Steel slag aggregate should therefore under no circumstances be used in rigid structures (such as concrete structures) or as a fill material beneath or adjacent to rigid structures. Any expansion within, beneath or adjacent to the rigid structure could result in the structure losing its integrity or being weakened or failing” (February 15, 2010).

The use of steel slag in asphalt concrete applications has been banned by the Ministry of Transportation of Ontario, Canada several years ago (Shi, 2002). One example of the expansion of an EAF slag aggregate can be seen in a picture of an asphalt shoulder (Figure 8, of Erlin & Jana, 2003). The expansion took place in an asphalt shoulder flanking a concrete pavement which expanding laterally. This expansion was attributed to electric arc furnace slag aggregate that contained free lime and periclase in an econocrete subbase (concrete lean in portland cement) (Erlin & Jana, 2003).

The statements by the USGS (MYB) and Harsco Metals demonstrates the view and reputation steel slag has, and the example of the expansion problems shown by Erlin & Jana (2003), gives valid reasons for reluctance to use the aggregate in a bound application like PCC. While both the statements from the USGS MYB and Harsco Metals are true, recent laboratory results that have been conducted over the past decade shows that concrete containing steel slags that have been aged properly can be within allowable limits for expansion. Laboratory experiments have demonstrated that the expansion of the steel slag aggregates is below the allowable limits set by ASTM when tested as an aggregate, and when it has been tested as a constituent in portland concrete cement.

6.1 Expansion

The expansion of steel slag is the major concern for use in bound applications such as a concrete pavement. The expansion of an aggregate can cause unwanted internal stress that could become large enough to lead to a failure of the concrete. The chemical components that are mainly responsible for the expansion of the steel slag are free lime and free magnesium. The expansion of steel slag can be separated into two separate phases, short-term expansion from the free lime and long term expansion from free magnesium.

6.1.1 Short-Term Expansion

The short-term expansion problems of steel slag originate from the reaction of free lime and water. The hydration of the free lime can cause expansion stresses within bound applications such as concrete. These stresses have been calculated to be in excess of 30,000 psi (200 MPa) (Erlin & Jana, 2003). The Japanese have used this expansion force to their advantage in demolition by packing the free lime along with some type of moisture into specific locations of the concrete columns in a structure. The expansion of the free lime created enough expansion forces to cause the columns to fail and implode the structure. They have also used the hydration of the free lime in concrete applications to create shrinkage- compensating concrete by controlling the hydration and expansion of the free lime (Erlin & Jana, 2003). Free lime hydrates rapidly and can cause large volume changes over a relatively short period of time. A solid reactant of 17.25 cm^3 /mole of free lime combines with the water and the hydration of the free lime results in a product of 33.07 cm^3 /mole. This hydration of the free lime shows an increase in volume of 91.7 %. The hydration of free lime usually occurs within a few days if it is directly exposed to water. If the free lime is encased within the slag, than the hydration process can be delayed or not occur at all if it is not exposed from a crack in the slag particle. The free lime is hydrated at the surface and this hydration produces the calcium hydroxide, which can encase the remainder of the free lime. As the hydration process continues, the calcium hydroxide is forced away from the surface by newly forming calcium hydroxide, until the calcium oxide is consumed or it is encased by the hydroxide and the water can no longer reach the calcium oxide. The encasement causes the increase in volume, and it is this that causes the buildup of stress in the concrete, which can lead to micro cracking, macro cracking and pop-outs (Erlin & Jana, 2003).

The free CaO can also be infused within the slag aggregate, and this can result in unexpected expansion if the slag aggregate is crushed after the aging or treatment process has been completed. The formula for the hydration of free lime is shown below. The hydration of the free lime produces calcium hydroxide (Epizet).

$$CaO + H_2O \longrightarrow Ca(OH)_2$$

6.1.2 Long-Term Expansion

Slags that are produced from the steel making process that has used dolomite instead of lime as a fluxing agent generally will have a higher MgO content. MgO is produced from the calcination of magnesium carbonate at 2102 °F (1150 $^{\circ}$C) (Gao, et al., 2007). The long term expansion of the slag is caused from the hydration reaction of free MgO and water, which takes place over a long period of time, sometimes years. In Germany, experience has found that a content of up to 7% of free MgO may be used in unbound layers and up to 4% of free MgO in asphalt layers (Motz et al., 2001). The magnesia (periclase) reacts with water and the hydration of the magnesia produces magnesium hydroxide (brucite). A solid product of periclase in the amount of 11.25 cm^3 / mole produce 24.71 cm^3 / mole of solid product which is an increase of 119.6 % (Erlin & Jana, 2003). As in the case of the hydration of free lime, the increase in volume causes an increase in the stress, which can cause the cracking of the concrete. The formula for the hydration of free magnesium can be found below.

$$MgO + H_2O \longrightarrow Mg(OH)_2$$

6.2 Limits on Expansion, Free lime and Free Magnesium

ASTM C – 33 provides specifications for the use of blast furnace slag in concrete, but there is no ASTM specification for the use of steel slag as an aggregate in cement concrete. The limits listed below are for the expansion of an aggregate, concrete containing the potentially expansive aggregate or a mortar that contains the potentially expansive aggregate. A more in depth explanation of the ASTM standards reviewed during this study can be found in Appendix A.

- ASTM C – 227 – 03: Potential Alkali Reactivity of Cement – Aggregate combinations (Mortar-Bar Method) – Aggregate Combinations: expansion of greater than 0.05% at 3 months or 0.10% at 6 months when high alkali cement is used. Combinations of aggregate and cementitious materials have produced excessive expansion should be considered potentially reactive.
- ASTM C – 1260 - 07: Potential Alkali Reactivity of Aggregates (Mortar bar Method) –this method is an accelerated method for detection of reactions that develop deleterious expansion slowly over a long period of time. An expansion of less than 0.10% at 16 days means the specimen's reaction is harmless and an expansion of greater than 0.20% shows the specimen is revealing potentially deleterious expansion.
- ASTM D – 2940 - 03: Standard specification for graded aggregate materials for bases and subbase for highways or airports. The expansion limit is less than 0.5% tested at 7 days according to the procedures of ASTM 4792 - 00.
- ASTM D – 4792 - 00: The Potential Expansion of Aggregates from Hydration Reactions – The potential expansion of the slag can be evaluated by this procedure, which is the standard testing method for the potential expansion of aggregates from hydration reactions. The expansion limit is less than 0.5% tested at 7 days.
- Limits by PennDot Test-The maximum expansion must be less than 0.50% (Pennsylvania Department of Transportation, 2011).

6.3 Testing Methods for Expansion

Since steel slag produced at one plant will not necessarily have the same chemical composition as slag produced from another plant, it will be imperative that testing be performed on all slag sources prior to use in bound applications. The development of tests that are reliable and fairly quick to perform is another aspect that needs to be addressed if steel slag is to be used in concrete applications such as pavements. Some methods are currently accepted to test for the expansion like the PennDot test described below. Other methods like the autoclave test, the steam test, and the boiling test have been developed to test for the expansion due to the hydration of the free lime and free magnesium. This section also discusses the testing of the slag for possible expansion that can result from alkali-silica reactions. The final testing method reviewed is the delayed autoclave test, which is used to test for expansion in concrete resulting from high levels of MgO.

6.3.1 PennDot Test

The need for the monitoring of the possible expansion of the steel slag requires a quick and easy test so that the possible expansion of a slag aggregate can be determined prior to its use. The PennDot test for the expansion of the steel slag aggregate is PTM 130, (2011). The testing of the steel slag is as follows: Three representative samples totaling approximately 45 kg (100 pounds) of material per sample should be obtained from each stockpile, obtained at a random location from each of three separate faces of the stockpile. The samples should not be taken from the exterior of the piles but should be taken from the interior. The test specimens are immersed in a water bath at 71 ± 3 °C for 7 days in a perforated standard Proctor mold, which allows for the movement of moisture. The vertical expansion of the slag aggregate is monitored and recorded. The stock pile is accepted if the expansion is less than 0.50%. If the stockpile meets the requirements, the stockpile should be reworked, soaked with water, and then kept moist in the pile for a period of six months. If the steel slag fails to meet the expansion criteria, the stockpile is rejected, and an additional 2 months of curing is required prior to it being sampled and tested again. It clearly states under section 703.2 (a) 4 Steel Slag, "Aggregate manufactured from steel slag is not acceptable for pipe or structure backfill or in cement concrete. Steel slag may be used for subbase, selected granular material, shoulders, selected material surfacing, and in bituminous surface courses, if accepted."

6.3.2 Autoclave Test - Modified

The autoclave test is used to detect the expansion of compounds such as free lime and free manganese in portland concrete cement and is conducted using testing procedures from ASTM C-151. This test has been modified to test the durability of concrete containing steel slag. The pressure and time from the original autoclave test have been modified. Concrete cube specimens are cured in a moist room for 28 days prior to the testing. The autoclave is warmed up for 1 hour at 290 psi (2 MPa) and then maintained at that pressure for a period of 3 hours. The pressure is then increased to 580 psi (4 MPa) in a secondary warming stage and then is maintained at that pressure for 2 hours. The specimens go through a cooling stage and then immersion into water at a temperature of 194 °F (90°C). The concrete cubes are then cooled at room temperature, followed by a weathering period of 90 days being protected from the rain and direct sunlight.

After being cooled to room temperature the autoclaved concrete is first evaluated on it appearance for cracking. The specimen's compressive strength is tested prior to the autoclave test, tested after the autoclave test, and the loss in strength is calculated. The steel slag concrete is then compared to the loss in compression strength of the control specimen. According to Manso et al. (2006), if there were any expansive compounds in the concrete cubes, it would have caused the specimens to be compromised, which would be shown in its physical appearance and its loss in compression strength should be larger than the control's loss. The following study uses the process described to test durability of the concrete containing steel slag aggregate.

In a laboratory experiment, specimens that contained an EAF slag as a fine and coarse aggregate were subjected to an autoclave test. The EAF slag used had been weathered for 90 days prior to its use in this experiment. The specimens ranged from having no slag as a fine aggregate and 100 % slag as a coarse aggregate to having 100% fine and 100% coarse aggregates. After completing the test, the control specimen showed a 52% loss in compressive strength while the specimen that contained 100 % coarse and 0% fine showed a loss of 38% compressive strength and the specimen that contained 50% fine and 50% coarse showed a loss of 33% in compressive strength. All specimens showed some superficial cracking after 90 days, including the control specimen, which contained 100 % limestone aggregate and no slag as an aggregate. The superficial cracking was considered to be within an acceptable range, and it was determined that the specimens were not expansive in nature. The compression strength of the concretes containing steel slag showed the least loss in strength. The results from this test demonstrated that PCC can be made using EAF slag when the slag is properly aged prior to its use (Manso et al., 2006).

6.3.3 The Steam Test

The steam test, also known as the accelerated swelling test or the German steam test, is conducted at 100 ^{0}C and ambient pressure and the steam is supplied to a compacted slag aggregate with a grain size distribution of 0 to 0.87 inches (0 to 22 mm). The steam test allows sufficient moisture for the reaction of the hydration of the CaO and MgO to take place. After the predetermined time, the volume expansion of the slag aggregate can then be read off the dial. This testing method has been used in Germany since 1980 and is considered a routine testing method (Motz et al., 2001).

The steam test has been incorporated into the European aggregate standards as a test method for steel slag aggregate. The steam test can then be used to generate expansion curves and used to predict the final volume increase of the slag. These curves are dependent on the specific type of slag aggregate being tested, but can be used to generate a formula that can be used in the prediction of the expansion. The limits of expansion were developed by a task group in Europe and were based on 10 years of testing when this study was published in 2001. These limits were correlated with the MgO content and were discussed in section 4.5.2.

6.3.4 Accelerated Aging Test

The accelerated aging test is used to test for the expansion of free lime and free manganese. This particular test uses an indirect approach to determine if expansion is occurring, by comparing the compressive strength prior to the test to the compressive strength after the test. The percent gain or loss is calculated. The appearance of the concrete is observed and the percent of mass lost or gained is calculated. The testing of the concrete cube samples follows the methodology of ASTM D-4792 (Manso et al., 2006). After the specimen has been kept in a moist room for 28 days, the specimens are then submerged under water and kept in 70 C^o water for 32 days to facilitate the expansion of the free lime. The specimens are then exposed to the weather outside for an additional 90 days in a moist atmosphere. The weathering outside is to be an indirect weathering, which means the specimens are not exposed to the sun or rain directly. This process is to facilitate the long-term expansion of the periclase.

The compressive strength of the concrete is tested and recorded before performing the accelerated aging test, and will be considered the control strength. The results of the accelerated aging test results are then compared to the control. The water to cement ratio in this study by Manso et al (2006) was less than or equal to 0.6%. Table 23 shows that the mixture with 50 % EAF slag as fine aggregate and 100 % EAF slag as coarse aggregate showed the greatest strength gain, and the control specimen that contained no slag aggregate had the least strength gained. The remaining fine aggregate portion of the mix was limestone sand. The strengths of the EAF concrete specimens are very close to the control specimen. The specimens that had a change in mass of -0.7 and -0.9% showed some flaking on the surface, while all other specimens had a good surface appearance. The steel slag concrete specimens had similar strengths to that of the control, and therefore it was concluded that the steel slag aggregate showed no significant differences in this test. The results in Table 23 are after the completion of both the 32 day portion and the 90 day portion of the experiment.

Change in Weight %	Strength before	Strength After	% gain	
-.026	38.5 MPa (5075 psi)	39.6 MPa (5740 psi)	2.78	Control 100% natural aggregate
-0.70	33.7 MPa (4900 psi)	35.9 MPa (5200 psi)	6.53	0% fine and 100% Coarse
-0.90	35.3 MPa (5120 psi)	39.4 MPa (5700 psi)	11.6	50 % fine and 100% coarse
-0.60	30.2 MPa (4380 psi)	33.5 MPa (4860 psi)	10.9	50 % fine and 100% coarse
-0.80	30.7 MPa (4450 psi)	34.1 MPa (4945 psi)	11.07	60% fine and 100% coarse

Table 23: Compressive strength before and after accelerated aging (Manso et al., 2006).

In work conducted by Polanco et al. (2011), the previous study was repeated with a few variations. Instead of using limestone sand as the fine aggregate along with the EAF as a fine and coarse aggregate, a ladle furnace slag was introduced as a fine aggregate. There were five separate mixtures used in the study. All contained the EAF as the coarse aggregate, but the amount and percentages of the fine aggregate were changed in the mixtures. The water to cement ratio was also varied in the mixtures to study the effect it had on the overall properties. Following the same procedures as before, the accelerated aging testing was completed on the five concrete specimens.

The control concrete that contained 25% steel slag and 25% limestone sand as fine aggregate, and 100% EAF slag as a coarse aggregate. The control's compression strength prior to testing was 6759 psi (46.6 MPa) and after was 6686 psi (46.1 MPa). It had a compression strength loss of -1.1% and a mass loss of -0.28%. The compression strengths prior to testing ranged from 4570 psi to 8760 psi (31.5 to 60.4 MPa) with mixture three having the maximum strength, which contained 37% EAF fines and 13%

LFS fines with a w/c ratio of 0.7. Mixture four had the lowest strength of 4570 psi (31.5 MPa) prior to testing.

Mixtures two and three, which contained LFS and EAFS as the fine aggregate in varying proportions, had strength losses of -8.7% and -3.1% respectively, and weight gains of 1.05 and 1.53%. Mixture four contained 25% LFS and 25% EAF slag as the fine aggregate and it had the highest water to cement ratio of 0.8. Mixture four had a strength gain of 6.0% and mixture five had a strength loss of -3.2%. Mixture four also had the highest mass gain of 2.4% and mixture five had a mass gain of 1.8%.

The increase in strength of mixture four after performing the accelerated aging test was attributed the mixture containing the highest LFS percentage. Research on LFS has shown that it has some cementitious properties, which could account for the strength gain in specimen four (Shi, 2002). The results of the testing showed that the losses in strength were acceptable. All five concrete samples had an acceptable surface appearance after completing the test and were reported to have had a linear expansion below the allowable limit of 0.2%.

In a similar study conducted in Pellegrino & Gaddo (2009), specimens consisting of 100% medium and coarse EAF steel slag aggregate and an unspecified natural fine aggregate were tested using the accelerated aging test. The steel slag was stored and weathered outdoors. The water to cement ratio was 0.52, and the mixture contained a fluidifying admixtue and an air entraining admixture. The 74 day compression strength of the concrete that contained 100% natural aggregate was 4400 psi (30.4 MPa) prior to testing, and the steel slag sample had a strength of 6440 psi (44.4 MPa).

The concrete samples compression strength was tested after 7, 28 and 74 days of being immersed in water at 158 °F (70 °C) for 32 days. The results from this part of the accelerated aging test showed that specimens with the steel slag aggregate lost more than 5% of their compressive strength, while the control specimens that contained no slag aggregate had a 9% gain. Both specimens, but mainly the steel slag specimens, showed some white powder on the surface of the specimens. This powder was comprised of calcium and magnesium hydroxides. A second set of specimens were subjected to the 32 days of accelerated aging and then were then exposed to 90 days of indirect weathing outside. The results of the long term weathering showed a slight decrease in average compressive strength of the specimens from 6440 psi (44.4 MPa) to 6290 psi (43.4 MPa), which is a loss of -2.37%. The control specimens showed an average strength gain from 4400 psi (30.4 MPa) to 4770 psi (32.9 MPa), or a gain of 8.35%.

While the steel slag specimens resulted in higher losses in compressive strengths, the overall compressive strengths of the specimens with the steel slag aggregate were ultimately still higher than the specimens with the natural aggregate. The affects of the additional weathering outside for the 90 days seemed to stabilize the specimens, which resulted in compression strengths closer to those prior to the accelerated aging test. The results for the testing showed that the steel slag in concrete as an aggregate could have the same durability as concrete containing natural aggregates.

6.3.5 The Boiling Test

Steel slag is used as an aggregate in the production of a stone called Armour stone. This stone is used in applications in hydraulic structures such as decorative waterfalls. Since the stone is being subjected directly to the water, this could cause a chemical reaction between the CaO, MgO and water. This application of the steel slag aggregate prompted the development of a new test called the boiling test.

This test was developed by the Expert Group "Armourstone," and was based on a similar test that has been used in the Netherlands. A sample of the slag that is to be used in the stone is sorted, and then twenty individual pieces are weighed. The twenty pieces of slag have a range in diameter of 2 to 6 inches (50 – 150 mm). The pieces are put into boiling water and left there for 8 hours and the loss in mass of the slag is recorded. This loss in mass was then used by the Expert Group Armourstone to establish the requirements for their stones. Category A allows a maximum of four of the twenty pieces tested to show more than a 0.5% loss of mass and category B limits the total loss to be less than 5% of the total mass (Motz et al., 2001). The boiling test method is described in prEN 13383-2 Armourstone –Specifications and prEn 13383-2 Armourstone – Test methods.

6.3.6 Alkali-aggregate Reaction Test

The alkali-aggregate reaction test is used to test steel slag components for alkali-silica reactions that could result in internal expansion. This test is important for aggregates that react slowly. It is important to verify that the expansion is due to a reaction from the alkaline and silicates, and not from another component of the specimen that is being tested. EAF slag contains silicates such as larnite and merwinite, which are stable by themselves when in contact with alkalis. EAF slag can contain a glassy phase, which can have a chemical reaction with the alkalis in cement. The procedures for completing this test follow the ASTM C-1260 standard and were compared to the limits.

Laboratory testing of the alkali-aggregate reaction of an EAF slag that had been weathered for 90 days prior to its use in the portland concrete cement was performed. The steel slag had chemical component percentages by weight of: CaO – 23.9 %, MgO - 5.1%, SiO_2 - 15.3%, free CaO – 0.45%, free MgO – 1% and a glassy phase of less than 5%. The cement used had a chemical composition by weight of: SiO_2 of 21.9 %, CaO – 64.2%, MgO – 0.9%, and the free lime and free MgO was not reported. The specimens had an average expansion of 0.14% at 16 days and 0.15% at 28 days (Manso et al., 2006). This expansion of the concrete demonstrated that there were reactions taking place between this EAF slag and the cement and this expansion could be due to the free CaO content of 0.45% and free MgO content of 1.0% by weight. The expansion of 0.16% was below the maximum allowed by ASTM C-1260.

6.3.7 Expansion Force Test

This test was developed to find the expansion force generated by steel slag particles during the hydration process (Wang, 2010). In order to determine the expansion force, the steel slag is tested by the autoclave disruption test and the expansion force test. The autoclave disruption test evaluates the volumetric stability of a single coarse steel slag particle. The slag is examined petro-graphically after the slag has been separated into size fractions, and 50 or 100 pieces of each size fraction are tested in the autoclave for testing. The autoclave is set to 3.5 atm (357 kPa) and 279 °F (137 °C) for 1 hr. The disruption ratio (R) is given by the number of slag particles that cracked (N_c) divided by the total number of particles used in the test (N_t), shown as equation 1 in Table 24.

$R = N_c / N_t$	Eq. 1
$f_{ex} = F_{ex} / V_{sl}$	Eq. 2
$F_{ec} = f_{ex} / V_{sc}$	Eq. 3
$V_{se} = R^* \phi * V_{sc}$	Eq. 4
$f_{eus} = (F_{ec} / V_{se}) = (f_{ex} * V_{sc}) / (R^* \phi * V_{sc}) = f_{ex} / (R^* \phi)$	Eq. 5
$V_{ss} = \pi^* d^3 / 6$	Eq. 6
$F_{ss} = f_{eus} * V_{ss} = (f_{ex}{}^* \pi^* d^3) / (6^* R^* \phi)$	Eq. 7
$F_{ss} = (F_{ex} / V_{sl}) * (\pi^* d^3) / (6^* R^* \phi)$	Eq. 8

Table 24: Equations for calculation of the force produced by a slag particle (Wang, 2010).

The expansion force test determines the expansion force that is generated by a known volume of coarse slag aggregate. The steel slag is sieved and separated into particles that range in size of 16 to 20 mm (0.63 to 0.79 inches). The samples are placed in the expansion-testing mold and compacted in three layers at 56 blows per layer. The mold has a perforated bottom to allow water to flow through the mold when it is immersed into the testing container. The testing container is then filled with water of temperature 165 ± 37 °F (74 ± 3 °C) which will be maintained throughout the testing period. The testing container is placed into the testing unit and a preload of 10 N (2.25 lbf) is applied. Readings from the load cell attached to the testing unit are read every 24 hours until the hydration process is complete and the force generated from the expansion does not change.

The expansion force of unit volume (f_{ex}) can be calculated from the measured force (F_{ex}) divided by the volume of the steel slag (V_{sl}), equation 2. Knowing the volume of steel slag aggregate in 1 m^3 of concrete(Vsc) and knowing the expansion force per unit volume, the expansion force produced by the steel slag in 1 cubic meter of concrete can be calculated (F_{ec}), equation 3. The original compacted volume of slag has voids and based on the slag particles being generalized as spherical particles, ϕ will represent the solid volume of the spheres in the compacted volume (67%). Assuming only the percentage slag particles that hydrated during the disruption test will contribute to the measured expansion force, the actual volume of hydrated slag (V_{se}) in the concrete is equal to the disruption ratio (R) times the solid volume of the slag (ϕ) times the volume of steel slag in 1 cubic meter of concrete (V_{sc}), equation 4. The expansion force from the steel slag in a unit volume of concrete (f_{eus}) can now be calculated using equation 3 and equation 4. The volume of a single slag particle (V_{ss}) is equal to π times diameter of the slag particle cubed, divided by 6, equation 6 in Table 24. Finally, the expansion force of a single slag particle (F_{ss}) can now be calculated by the expansion force in a unit volume of concrete times the volume of a single slag particle, equation 7. Using substitution the force of a single slag particle can be calculated by the expansion force produced per cubic meter of concrete times π times diameter of the particle cubed divided by 6 times the volume of a single slag particle times the disruption ratio times the actual solid volume of the slag, equation 8.

Three BOF steel slag samples were tested to determine the expansive forces generated by the steel slag (Wang, 2010). The cooling process and weathering of the slag was not noted in the study and the range of CaO was 35.1 to 40.6 %, while the range of MgO was 8.8 to 11.3%. The slag particles ranged in size from 0.63 to 0.8 inches (16 to 20 mm), and were tested using the process described earlier in this section. The disruption ratios were calculated to be 3%, 2%, and 1%. The calculated expansion force of a single particle on the first day was 3 N (0.64 lbf), 52 N (11.7 lbf) and 26 N (5.8 lbf) for the 3 samples respectively. The testing of the slag was completed when the measured expansion force stopped increasing. The first BOF sample had a calculated expansion force for a slag particle of 805 N (181 lbf) on the 20th day. The second BOF sample had a calculated expansion force for a slag particle of 556 N (125 lbf) on the 14th day and the third BOF sample had a calculated expansion force for a slag particle of 1609 N (362 lbf) on the 26th day.

Concrete samples were made using the three steel slag samples and were subjected to the autoclave test at 357 kPa (3.5 atm) at 137 °C for three hours. The results from this testing resulted in surface pop-out on the third BOF concrete sample, but the other concrete samples containing BOF sample 1 and BOF sample 2 showed no signs of distress. The surface tension stress generated in the three BOF slag concrete samples was calculated using the expansion force for each slag sample and the surface area of the nominal particle size and were 0.64 MPa (93 psi) for BOF sample 1, 0.57 MPa (83 psi) for BOF sample 2 and 1.28 MPa (186 psi) for BOF sample 3. The tensile strength of the portland cement mortar being used in the study was 3 MPa (435 psi).

The results of this type testing may be able to be used in the future to develop the maximum expansion force allowed based on the stress that is created by the expansion from the steel slag. This could be used along with the tensile strength of the cement that is being used to develop a safety factor that could then be employed to evaluate the steel slag sample (Wang, 2010). This testing method could also be applied to test a sample of slag to determine if it meets the expansion force criteria prior to being used in the concrete. This testing method may prove to be a very valuable method in the future for testing the expansion of steel slag.

6.3.8 Delayed Autoclave Test – Possibility for use in the testing of concretes containing steel slag

The following testing method is for the testing of concretes that contains MgO and fly ash. There was no steel slag used in this study, but it is relevant since steel slag is known to contain MgO. It might be possible to use this testing method for the testing of the expansion of concretes containing steel slag.

The delayed autoclave test was introduced in response to criticism of the autoclave test. The main criticisms of the autoclave test are that the expansion values of cements do not agree with concretes, the hydration process of MgO is accelerated, and that this hydration process is different from that which would occur in normal curing of portland concrete cement. Finally, the autoclave expansion value of cement should not be the measure for the soundness evaluation of concrete (Gao et al., 2007).

The delayed autoclave test was designed to test the expansion and strengths of concrete containing MgO. Concrete specimens are mixed and molded into 3 x 3 x 11 inches (75 x 75 x 285 mm) size. After being placed in a fog room for 48 hours, they are then removed from the molds and their lengths are measured. The specimens are cured in water at 176 ± 36 °F (80 ± 2 °C) for a period of 24 hours. The specimens are then placed in the autoclave in which the pressure is raised to 290 psi (2 MPa) and the temperature is raised to 421 °F (216 °C) over a period of 45 to 75 minutes. The specimens are left in the autoclave with these conditions for a period of 2 to 10 hours. The specimens are then measured again and the change in linear dimensions is calculated. The concrete specimens in this study contained portland cement, fly ash, MgO expansive agent, granite aggregate that ranged in size from 0.4 to 0.8 inches (10 to 20 mm) for the large aggregate, granite aggregate ranging in size from 0.1 to 0.4 inches (2.5 to 10 mm) for the small aggregate and silica sand fine aggregate.

It was determined from the testing of concrete specimens containing MgO, that the expansion values increase as the content of MgO increases, and that an increase in the amount of fly ash, decreases the expansion values. When the amount of MgO ranged from 4% to 8%, the increase in expansion was obvious. When the amount of MgO ranged from 8% to 12%, the specimens cracked and disintegrated (Gao, et al., 2007). While this test is intended test for the expansion of concretes containing fly ash and MgO as an expansive agent, the delayed autoclave test might be used to study the expansion of steel slag containing MgO.

6.4 Testing the Expansion of Steel Slag as an Aggregate

Concrete specimens containing steel slag as an aggregate in PCC have been tested in laboratories over the past decade. Many of these studies have been completed using EAF slag as fine aggregates, coarse aggregates or both. This section discusses the results of studies that tested the expansion of concrete resulting from the expansion of the steel slag as an aggregate in the concrete and studies conducted on steel slag as an aggregate.

6.4.1 Steel Slag as an Aggregate in Concrete Cement

Specimens in one study contained EAF slag as a coarse aggregate with percentages ranging from 25% to 100% were tested for expansion. The CaO content was 21.7 % and the MgO content was 6.14% by weight. All specimens were submerged in water for a period of 12 to 56 weeks and all specimens, including the control that contained no steel slag, experienced approximately the same length change at 12 weeks. The length of the specimens then remained constant for the remaining duration of the study. The results of the testing showed an expansion of 1.5% at 12 weeks for the control and the slag specimen containing 50% coarse aggregate. The steel slag was considered a non-expansive material. It was not noted if the slag had been aged prior to its use in the concrete (Etxeberria, M. et al., 2010).

Three samples of ladle furnace slag were tested for a period of 170 hours according to the testing methods of ASTM D 4792. The ladle furnace slag contained CaO of 58% by weight and MgO of 10.0% by weight. The results of this test showed a maximum expansion of 0.28%, which is below the maximum expansion of 0.5% set by ASTM D 2940 (Manso et al., 2005). The initial expansion of 0.22% occurred in the first 20 hours and was attributed to the presence of free lime and the second period of expansion took place from 20 to 170 hours and was attributed to the hydration of the periclase.

Specimens were tested for dimensional stability in a study by Patel (2008). The EAF steel slag was aged out doors in stock piles and sprayed with water which provided a uniform moisture content for a period of not less than 3 months. The CaO was 30.7%, MgO was 9.95% and the free CaO and free MgO was not reported in this study. The study used proportions of steel slag aggregate that ranged from 0% to 100% of the total coarse aggregate. The specimens were tested according to ASTM C 157 in a lime bath for a period of 120 days. The two control specimens showed a slight linear expansion of 0.034% and 0.016% while the two specimens that contained 25% slag aggrgate had linear expansion values of 0.0% and 0.024%. The two specimens that contained 100% slag aggregate showed an average decrease in linear length of -0.161%. The maximum linear expansion was in the specimen that contained 50% steel slag aggregate and it was 0.034%, which was the same as the control. No corelation could be observed between the amount of steel slag and the change in length of the specimens.

In a study conducted by Maslehuddin et al. (2003), the expansion of an EAF slag was studied as a course aggregate in cement motars. The weathering of the slag was not noted in the study, and the chemical composition pertaining to the amount of CaO, MgO, free Cao and free MgO was not given. The cement content was 675 lb/yd^3 (400 kg/m^3) with a water to cement ratio of 0.4 in all specimens tested. The ratio of coarse to total aggregates ranged from 0.45 to 0.65% with a maximum aggregate size of 0.5 inches (12.5 mm). The fine aggregate used was a limestone dune sand. The mortar bars were exposed to moisture for a period of 110 days and the expansion was monitored. The results of the study showed a increase in length of 0.034% for the bars containing steel slag while the control specimen comprised of sand aggreagte had a change in length of 0.0%. This expansion was below the limit of 0.05%.

Yunxia et al. (2008) studied the effect of the treatment of steel slag as an aggregate on volume stability of steel slag as a fine aggregate in a cement mortar was studied by. The study was conducted on a BOF slag using three different aging / treatment processes. The chemical analysis of the slag showed a content of CaO of 40.65% and an MgO content of 0.06 % by weight. The steel slag was naturally cooled and aged outdoors for 12 months prior to any testing. The three different methods of treatment of the slag used in the study were the autoclave treatment under 290 psi (2.0 MPa) for 3 hours, steam treatment of the slag at 212 °F (100 °C) for 8 hours, and steam treatment for 12 hours. The rate of linear expansion test was conducted by immersing the cement mortor bars into 176 ± 34 °F (80 ± 3°C) water. Measurements of the specimens were then taken on a daily basis.

The change in length of the specimens was then plotted versus the aged date so the treatment methods could then be compared. The expansion of the mortar bars was separated into three stages based on the results. The first stage showed a slight increase of the expansion, the second stage of expansion was when the rate of expansion is approximatley zero and the third stage showed a rapid increase in the expansion rate. The initial expansion of the mortar bars was approximately 0.1% for all three treatment methods, while the slag being used as the control was slightly higher on day 1 after the immersion into the water. The non-treated slag showed a slightly higher expansion rate from day 2 through 9, while the treated slag remained fairly constant. From day 10 to day 15 the nontreated slag showed an exponential growth rate which was almost vertical by day 15. The 8 hour steam treated slag's expansion rate remained constant through day 12, and then showed exponential growth rate of expansion until day 19. The 12 hour steam treated slag ramained fairly constant through day 15, at which time it began to show a exponetial rate of expansion as well. The 8 hour and 12 hour steam treatment of the slag showed that it only delayed the expansion of the slag and did not prevent the expansion. The autoclave treated slag on the other had showed an initial expansion of approximately 0.1% on day 1 just as the other treated slags but in this particular case the expansion rate of the slag mortar bars remained approximately zero indicating that the treatment of the slag by the autoclave method was superior to the other methods.

An analysis of the chemical composition of these slags from this study was conducted and discussed previously in Chapter 4, but will be briefly discussed again. The original free CaO content of the non-aged slag was 3.56% and after treatment it was 1.07% for the 8 hour steam treatment, 0.94 % for the 12 hour steam treatment and 0.31 % for the autoclave treated slag which clearly shows why the autoclave test expansion rate was approximately zero. Chemical analysis by X-ray diffraction showed small amounts of $Ca(OH)_2$ for the steam treated slags, but a much higher diffraction peak for a material subjected to the autoclave 3 hour treatment. Xray diffraction of broken points also showed the main phase in the slag was periclase.

The correlation between rate of linear expansion, the content of the free lime and free periclase, and the time at which the linear expansion occurred could be observed in the graphs. The initial expansion was due to the hydration of the free lime, and the exponential rate growth was due to the hydration of the free periclase. The key to this conclusion is that the BOF slag had been aged outdoors prior to any treatment processes, and the hydration of the free lime occurs rapidly versus the hydration of the free periclase, which is a much slower process. Since the slag had been aged outdoors for twelve months prior to any treatment, it is likely that the hydration of most of the free lime had already taken place. This would indicate that the rapid expansion seen in stage three of the steam treated slags would be attributed to the free periclase. This would also indicate that the autoclave treatment was effective at removing the expansive nature free periclase by hydration. More laboratory studies will need to be conducted to verify if this is indeed the case.

6.4.2 Expansion of Steel slag as an Aggregate and the Effects of Aging

Manso et al. (2004) tested an EAF slag for expansion to examine the effects of the aging process. The sample's chemical composition included CaO that ranged from 23.0 to 32.0%, an MgO content that ranged 4.8 to 6.6 %, and a free lime content that ranged from 0 to 4.0%. The free periclase content was not given. The steel slag aggregate was tested according to ASTM C – 4792. Four samples were tested prior to treatment, and the results from that testing showed an expansion that ranged from 0.25 to 2.1% at a time of 150 hours. The EAF slag was aged using the outdoor aging process for 90 days, and included the permanent wetting of the slag and the overturning of the slag pile. After the aging process was completed, the slag was tested again, and the maximum expansion of the specimens was 0.33% with an average expansion of 0.26% for the four specimens being tested. This expansion value was half that set by ASTM D-2940.

In a study conducted on EAF slag, the expansion of the aggregate was examined. The steel slag used for the study was sampled prior to and after the aging process. The aging process consisted of wetting and overturning of the pile for a period of not less than 90 days. The composition of the slag contained CaO of 23.9%, MgO of 5.1%, free lime of 0.45% and free MgO content of less than 1%. After the crushing process has been completed, and prior to aging the EAF slag, the expansion of the slag ranged from 0.5% to 2.5%. With the proper weathering of the slag, the expansion was reduced to 0.15% to 0.40% (Manso et al., 2006). The expansion of the slag was tested according to ASTM D 4792.

The testing of expansion using a stainless steel slag aggregate was tested using the steam test, which was discussed earlier in this chapter. The testing was to study the effects of the aging process on the expansion of the slag aggregate. The free lime content of the coarse size aggregate, 0.25 to 0.78 inches (7 to 20 mm), was less than 0.2%. The free lime content of the finer aggregate, 0 to 0.28 inches (0/7mm), ranged from 0.5 to 1%. After combining the aggregates and prior to aging, an expansion test was performed on the slag and the volume increased 1.5% after seven days. The linear expansion was tested using the accelerated swelling test, and was calculated to be 0.7 to 1.5% for size fractions 0 to 0.28 inches (0 / 7 mm) and 0.3 to 0.6% for the 0.25 to 0.78 inches (7 to 20 mm). After aging the slag for three months, a linear expansion of approximately 0.5% was calculated for the 0/7 mm slag and 0.2% for the coarser slag. The amount of MgO contained within the slag is not discussed in this article (De Bock et al., 2004).

In a study conducted in Korea by Moon et al. (2002), the effects of different aging processes of steel slag as a course aggregate was studied to see the effects of the processes on the expansion of steel slag. The slag was tested by the immersion test, which was not described. The chemical content was obtained by XRF. The chemical content of CaO for the EAF slag was 21.35% and 36.31% for the BOF slag. The chemical content of the MgO was 12.35% for the EAF slag and was 8.6% for the BOF slag. The free lime content of the EAF slag was 0.3%, and the free lime content for the converter slag was 3.3%, which was determined by loss of ignition at 1022 °F (550 °C). The authors did not comment on the amount of free MgO. There were four different aging processes examined in this study. They were steam aging, air aging and hot water aging for 1 day and hot water aging for 3 days. This study was conducted on an EAF slag and a converter slag, and the results were then compared in graphs of the expansion ratio (%) versus the age (days), for the four treatment processes for both types of slag.

The hot water aging immersed the slag in water of 176 °F (80°C) and the steam aging exposed the slag to steam that had a temperature of 212 °F (100°C). It can be seen in the graph for the EAF slag samples, that the hot water aging and the steam aging for three days had the greatest reduction in the expansion of the steel slag. The expansion ratio for the 3 day steam treatment and the 3 day hot water treatment was 0.06% at 10 days. There was a 62.5% reduction in the 10 day expansion of the specimens steam and hot water aging for three days. The aging in air for 1 month showed a reduction in expansion of 43.75%. Increasing the time of aging from 1 day to 3 days for the hot water aging process decreased the expansion by approximately 0.01%, suggesting the additional time of aging might not be significant enough to warrant the additional time (Moon et al., 2002).

In the graph for the converter slag, the non-aged converter slag had an expansion of approximately 1.6% at 10 days, which was above the Korean limit on expansion. It was noted by Moon et al. (2002) that in Korea, the standard prohibits use of steel slags in concrete. The hot water 1 day aging and the 3 days steam aging showed approximately the same results for reducing the expansion of the slag aggreagte. The expansion ratios for these methods at 10 days were approximately 0.1%.

The expansion of the EAF slag was significantly lower than that of the converter slag, and could be seen when the two graphs were compared. The expansion of the non aged converter slag was 10 times greater than that of the non aged EAF slag at 10 days. It can also be seen from comparing these figures that the expansion of the EAF slag from 3 day steam and 3 day hot water aging was 0.05% and the 3 day steam streament for the converter slag was 0.1%, which is twice the EAF expansion at 10 days.

6.5 Conclusion

The possibility of dimensional instability caused from the expansion of free lime or periclase is cause for concern, and the expansion of the steel slag aggregate would be detrimental in bound applications like PCC. The short-term expansion from the hydration of free CaO has shown an increase in volume of over 90% and the long-term expansion from the hydration of free MgO has shown volume increase over 100%. The expansion of steel slag in the econocrete subbase below the asphalt pavement is an example of the effects of the expansion of steel slag.

The hydration of free lime occurs rapidly and is the cause of the short-term expansion. The hydration of the free lime occurs on the surface and produces calcium carbonate. The hydration process continues until the water can no longer reach the surface of the free lime, or the free lime is totally consumed by the reaction. The buildup of the calcium carbonate on the surface of the free lime is known as the armoring process. It is this armoring of the free lime or periclase that results in the increase of volume, which can intern increases the internal stress within the concrete. The long-term expansion is a result of the hydration of free periclase, and high amounts of MgO are a result of using dolomite in the steel making process.

The testing methods used to determine the expansion of the steel slag aggregate have continued to be developed over the past years. The testing of the expansion of the steel slag must be reliable for predicting the final expansion, and must be performed in a reasonable time. The testing methods used to test for the expansion of the steel slag discussed in this section were the PennDot test, the autoclave test, the steam test, and the accelerated aging test. Some other tests that were discussed were the boiling test, Alkali-aggregate test, the expansion force test, and the delayed autoclave test.

The PennDot test is used to determine the expansion of the steel slag as an aggregate and has an expansion limit, which is the same as ASTM C 4792. The autoclave test can also be used to test for the expansion of steel slag aggregate resulting from the hydration of free CaO and free MgO. The autoclave test has also been modified to test for the expansion in concrete specimens by testing the durability of the concrete containing the slag aggregate. When expansion occurs in the concrete, it results in lower compression strength, cracking of the concrete, and can cause surface pop-outs. The results of the study examined in this research showed that the steel slag aggregate had the least strength loss and sufficient volume stability to be used in PCC.

The steam test is widely accepted throughout Europe to predict the expansion of steel slag. It is used to generate an expansion curve, which can be used to predict the final expansion of the aggregate. It is currently used to test the steel slag in Europe for use in bound applications such as bituminous mixtures and for unbound applications. Since the chemical composition of the slag is different at each plant, expansion graphs would have to be generated for the slag originating from each of the different slag processors. These graphs then could be used to predict the expansive characteristics of that particular slag. The testing of the slag for expansion would only have to be performed on a routine basis to verify the expansion, since the chemical composition of each plant does not vary much from batch to batch. The steam test can test for the expansion within 24 to 168 hours depending on the content of MgO present in the slag.

The accelerated aging test uses the same principles as the autoclave test, which focuses on the durability of the concrete by comparing the compressive strength before and after aging. If the concrete containing the slag has strengths that are comparable to the control, and the surface appearance of the concrete is comparable to the control, then it has passed the test. There were no limits discussed in any literature. Some type of ranges will need to be established before this could be used as a reliable test.

The study conducted by Manso et al. (2006), which used EAF as a fine and coarse aggregate, showed a strength gain that was larger than the control after the testing. It also showed that when the amount of the slag increased, so too did the final compression strength of the concrete. This shows that concrete containing the slag is as durable as concrete containing natural aggregates. In the study conducted by Pellegrino et al. (2009), the slag concrete was tested after the first part of the accelerated aging test. The slag concrete had compression strength loss of 5% while the control had a 9% gain. The study was conducted again, but the specimens were placed outside for additional weathering time of 90 days after completing the accelerated aging test. This seems to stabilize the slag concrete and the results of the durability testing showed that the slag concrete had similar compression strengths as the control.

The testing of steel slag concrete by the accelerated aging test was completed by Polanco et al. (2011), but this time LFS was included in the mixtures. The results of this testing showed that concretes containing EAF and LFS were as durable as the control concrete. It was also seen that the addition of LFS increased the compressive strength, which was attributed to the ladle furnace slag's cementitious properties.

The boiling test is used by a company that manufactures decorative stones for use in waterfalls. These stones contain steel slag as an aggregate. This testing method uses the loss in mass of the individual slag particles to determine if the slag is acceptable for use in their stones. Category A allows for a maximum of four out of the twenty pieces tested to show more than a 0.5% loss in mass and Category B limits the total loss to less than 5% of the total mass. No other documentation on this testing method was obtained. This testing method could prove to be a cheap and valuable testing method for testing of steel slag for applications in portland concrete cement. It may be possible to conduct testing and use the results to establish guidelines for the loss in mass for PCC applications. The testing would also have to be done on slags from different processors to make sure the limits were applicable for all slags.

Most papers focus on the expansion of the free CaO and free MgO, but it is also possible for the steel slag components to have reactions with the alkali-silica present in cement, which would also lead to unwanted expansion. In a study conducted by Manso et al. (2006), an EAF slag was tested according to ASTM C -1260. The results of the testing showed a maximum expansion of 0.15% at 28 days, which was below the allowable expansion of 0.2%. This demonstrated that this slag could be used in a bound application. The free CaO and free MgO content of the slag were very low, 0.45% and 1% respectively. The expansion shows there was some activity between the cement and the slag. Some of the expansion could have been from the free CaO and free MgO, but it was still below the allowable limit.

The expansion force test was developed to find the expansion force of a steel slag particle during the hydration process. In order to determine the expansion force, the slag must be tested using the autoclave disruption test and the expansion force test. It is possible to determine the forces generated by the volume of slag in one cubic meter of concrete and then determine the force generated by a single slag particle once it has hydrated. Three BOF slag specimens were tested and the forces generated from the expansion of the slag were calculated. The third BOF sample had the highest calculated force of 1.28 MPa (186 psi). This was then compared to the tensile strength of the cement mortar being used in the study, which was 3 MPa (435 psi). While the force calculated was less than half of the tensile strength of the cement, the concrete suffered cracking when it was tested in the autoclave test. In making the calculations for the force generated, some simplifications were made when calculating the volume of the slag in the unit for testing the forces generated. The slag particles were assumed spherical in order to determine the void ratio in the unit. The dimensions of the particles were also simplified when calculating the surface area of the slag particle. These simplifications could account for the discrepancy between the force generated by the slag and the tensile strength of the cement. Once more testing has been completed and the forces generated by the slag can be confirmed, it may be possible to predict if a particular slag is suitable for use in a bound application. If enough testing on steel slag is done, it may also be possible to set a limit on the forces generated. This limit would allow for the testing of samples from slag piles to see of the slag aggregate is acceptable for use.

The delayed autoclave test was developed due to criticisms of the autoclave test, which were discussed earlier in this chapter. The criticisms focused on the hydration of MgO and this accelerated hydration process is different from what would occur in normal curing of portland concrete cement. This test was designed to test the strengths and expansion of concrete containing MgO and fly ash. In the study discussed earlier, the MgO was added as an additive to help compensate for the shrinkage of the concrete. This testing method may be able to be used in the testing of the expansion of concrete that contains steel slag, since the steel slag contains MgO. The results of the expansion then could then be compared to the results from other testing methods to determine the effectiveness of using this method for the testing of concrete containing steel slag aggregate.

The expansion of concretes and cement mortars discussed in this chapter was studied by multiple laboratory studies such as Etxeberria et al. (2010), Manso et al. (2005), J. Patel (2008) and Maslehuddini et al. (2003). In all four studies, the expansion of the specimens containing steel slag was similar to the control and was below the expansion limits, which were dependent on the type of cement or mortar being tested. In the studies that reported expansions for the specimens that contained different amounts of steel slag as an aggregate, no correlations were made between the amount of steel slag and the total expansion of the specimens.

Yunxia et al. (2008) studied the effects of the aging processes on BOF slag prior to its use in cement mortar bars. The slag used in the study had been naturally cooled and aged outdoors for twelve months prior to being used in the study. There were 3 treatment processes used in this study. They were 8 hour aging by steam, 12 hour aging by steam, and aging by the autoclave under pressure for 3 hours. All specimens showed an initial expansion of approximately 0.1% on day 1, but the autoclave treated slag was the only treatment that did not experience any further expansion after the initial expansion. The initial expansion was probably due to the free lime still present in the slag. The values of the free lime that were present in the slags were the highest in the “non-aged” slag and were the lowest in the autoclave treated slag. The main phase that was reported by X-ray diffraction was periclase. The initial expansion was due partially to the hydration of the free lime and periclase, and the exponential rate of expansion was due to the expansion from the free periclase. The BOF slag had been aged outdoors prior to the study and therefore it is most likely that the hydration of most of the free lime had already taken place. This would also indicate that the rapid expansion seen in stage three of the steam treated slags would be attributed to the free periclase. The results of this study also indicated that the autoclave treatment was effective at removing the expansive nature of free periclase and free lime more effectively than the aging by steam. More laboratory studies will need to be conducted to verify if this is indeed the case.

The expansion of an EAF slag was studied by Manso et al. (2004, 2006). The expansion of the steel slag was tested prior to and after it was aged. In the 2004 study, the expansion of the specimens ranged from 0.25 to 2.1%. After the weathering outdoors for 90 days, the expansion of the aggregate decreased to an average expansion of 0.33%. In the 2006 study, the EAF slag was tested prior and after the outdoor weathering to determine the effects of the aging process. Prior to aging the aggregates expansion ranged from 0.5 % to 2.5%, and after aging it ranged from 0.15% to 0.40%. Both of these studies showed a significant reduction in the expansion, and confirm that the aging of the slag can reduce the expansion and that steel slag can meet the expansion limits of ASTM D – 4792, which is 0.5%.

In 2002, Moon et al. studied and compared the effects of some of the different aging processes on an EAF slag and a BOF slag. The aging processes studied were air aging for 1 month, hot water for 1 day, hot water for 3 days, and steam treatment for 3 days. Prior to the study chemical analysis was performed on the slags and the EAF slag had a free CaO content of 0.3% and the free CaO content of the BOF slag was 3.3%. The study measured the expansions of the EAF slags for ten days, and then the expansion of the slag was plotted for all the aging methods. The same process was performed for the BOF slag. It can be seen from comparing the two graphs that the BOF slag had a much higher expansion than the EAF slag. All of the aging methods used on the EAF slag, with the exception of air aging, resulted in lower expansions than any of the methods used on the converter slag. The reduction in expansion by air aging for 1 month resulted in an expansion of half the non-aged slag for the EAF sample and the reduction for the BOF slag was approximately 60%. The steam treatment process and the hot water for three days results were essentially the same and showed the best results for both types of slag. It can be seen that the expansion of the non-aged BOF slag was 10 times as much as the expansion of the EAF non-aged slag. The fact that the expansion was ten times greater in the BOF slag versus the EAF slag is directly related to free lime content in the slags. The free lime content of the BOF slag was ten times that of the EAF slag, which shows a correlation between the expansion of the slags and the content of free lime. This correlation between the free lime content and the amount of expansion definitely warrants further investigation.

While the total expansion of the steel slag was below the limits for unbound and bound applications in the laboratory studies, the expansion could still cause unwanted internal stresses within the concrete. All of the studies examined on the expansion of the steel slag, as an aggregate, when it was used in portland concrete cement, and as a cement mortar, demonstrated that treated steel slag could meet the expansion limits set by ASTM.

CHAPTER VII

STATE DOT SPECIFICATIONS OF MATERIALS

In general steel slag is widely accepted as an aggregate as a base course, shoulders and as a fill material. In recent years, it has gained acceptance as an aggregate in bituminous asphalt concretes. The following sections examine the material specifications for its use in in bituminous applications. No state DOT has approved the use of steel slag in portland concrete cement as an aggregate in pavement applications.

7.1 Ohio Department of Transportation – ODOT

The material specifications for aggregates for ODOT are listed under section 703. Among these specifications are those concerning the use of steel slag as an aggregate. There are many specifications that deal directly with the different types of steel slag. Section 703.14A states recycled slag and crushed slag are not allowed, and section 703.14D that deals with the aging and stock piling of the slag. Fine aggregates and coarse aggregates for Asphalt concrete can be found in section 703.04 for concrete base and section 703.05 for intermediate and surface courses. In both of these sections sand, gravel and air-cooled slag are mentioned, but steel slag is not.

The criteria for the use of steel slag are stated under section 703.01- General. 703.01 E states that OH, BOF, EAF steel slag aggregate must conform to 703.04, 703.05 material specifications. It then states a letter of certification must be provided with each shipment that ensures the quality of the slag as well as quality control documents from the processor. These need to meet the requirements set forth in supplement 1071. Supplement 1071 gives the quality control requirements for steel slag aggregate producer and processors. At the very end of section 703.01E it states; “OH, BOF, or EAF slag is not permitted for coarse or fine aggregate (virgin or recycled) used in any surface course mix or any mix used as a surface course according to 703.05” (Ohio Department of Transportation, 2011). This statement seems to state that steel slag could be used in lower pavement layers. However, section 703.04 list the coarse aggregates for asphalt concrete base as CCS, gravel, or crushed ACBFS, and for fine aggregate for asphalt concrete base as natural sand or manufactured sand from stone, gravel, or air-cooled slag. Steel slag is not mentioned as an approved aggregate in this section.

The material specifications for aggregates in portland cement concrete are outlined in section 703.02 A and B. Section A deals with fine aggregates and section B deals with coarse aggregates. Natural sand and sand manufactured from stone are listed under fine aggregates and washed gravel, crushed carbonate stone (CCS) or crushed ACBFS, are listed under section B for coarse aggregates. Steel slag is not mentioned under this particular section. Since there is no direct mention of the use of steel slag in PCC and there are no references to any other section of the specifications, the use of steel slag in PCC seems not to be allowed.

7.2 Indiana Department of Transportation – INDOT

In chapter 2 of the INDOT material specifications, an artificial aggregate is a by-product of an industrial product and therefore steel slag is classified that way. Chapter 3 of the material specifications deals with the physical, chemical, and general characteristics of aggregate properties. Listed under general characteristics are aggregates for hot mix asphalt and PCC. In the chemical properties section, the mineral content of the aggregates is discussed, and the adverse effects of free lime and free magnesia in industrial products may cause distress in PCC. The characteristics for aggregates are listed for hot asphalt mix and PCC, but the actual types of aggregates are not listed in this section of the specifications.

In chapter 4, section 904 deals with the specifications for aggregates. Section 904.02 deals with the use of fine aggregates. It lists natural sand for PCC in decks and bridges, natural sand, crushed limestone and ACBFS for PCC for other construction. For hot mix asphalt, the specification lists natural sand or manufactured sand, and it says, “Steel furnace slag is permitted only with steel furnace slag coarse aggregate.” Section 904.03 deals with coarse aggregates and lists quality classification. The class of aggregates listed for PCC on grade is class AP, for structural PCC exposed its class A or AP, and for PCC structural non-exposed, its class A or B (Indiana Department of Transportation, 2011).

7.3 West Virginia Department of Transportation – WVDOT

Division 700 is the material section that addresses hydraulic cement, fine aggregate, and coarse aggregates in West Virginia. Section 702 contains regulations for fine aggregates. Section 702.3 states that fine aggregates must meet requirements of ASTM D 1073 for asphalt mixtures. Section 702.5 states that lightweight fine aggregate for structural concrete use the requirements of ASTM C 330. Section 703 provides the specifications for coarse aggregates. 703.3.1-steel slag defines the classification and requirements for the steel slag. It states that the steel slag must be stockpiled, maintained wet for at least 6 months, and be rendered inert to minimize the possible expansion. After six months of aging, an expansion test must be completed before its use.

When the steel slag is used in hot mix asphalt, the expansion test is waived. The mixture may not contain more than 50% by weight of the coarse aggregate and cannot be used as a coarse aggregate in a single mix. The expansion test can be waived when being used in aggregate applications for shoulders and road base stabilizers, where it is not confined. Section 703.3.1 concludes with the statement, “Steel slag shall not be used in any item where the expansion might be detrimental. Such items include, but not necessarily limited to, the following: aggregate for Portland cement concrete, backfill around drainage structures, piers, abutments, walls, etc.” (West Virgina Department of Transportation, 2011).

7.4 Pennsylvania Department of Transportation – PennDOT

Section 703 is the specification section for aggregate uses in Pennsylvania. 703.1 deals with the use of fine aggregates and states that steel slag may be used as an aggregate for bituminous concrete mixtures. It outlines the requirements for stockpiling and weathering as well as the testing in accordance with PTM No. 130. The testing methods for the expansion of steel slag aggregates using PTM No. 130 were discussed in Chapter 5. The maximum volumetric expansion is 0.50%. Section 703.1 also states, "Fine aggregate manufactured from steel slag may not be used in cement concrete or mortar mixtures."

Materials section 703.2 contains the requirements for coarse aggregates. Under section 703.2, item 4 deals with steel slag as a coarse aggregate. One interesting requirement is that the slag is soaked in water before or during the stockpile operation. The slag aggregate is stockpiled and weathered for 6 months before being tested. The slag aggregate can be used for shoulders, selected material surfacing and in bituminous concretes. It is also stated in this section that, "Aggregate manufactured from steel slag is not acceptable for pipe or structural backfill or in cement concrete," (Pennsylvania Department of Transportation, 2011) .

7.5 Michigan Department of Transportation – MDOT

The section of material requirements that deals with aggregates for Michigan DOT is section 902. Steel slag is defined in section 902.02 A-2 as a synthetic by-product from BOF, EAF or open hearth furnaces. Section 902.03 contains the requirements for Portland concrete cement and discusses natural aggregates as well as BFS. In item A - slag coarse aggregates, BFS is allowed to be used if it meets certain requirements but there is no mention of steel furnace slag in this section. Under section 902.04 – Coarse aggregates for HMA mixtures; natural aggregates as well as BFS and steel furnace slag are discussed. Since the steel slag is mentioned in this section as a viable option for an aggregate, steel slag seems not to be allowed as an aggregate in Portland concrete cement since it is omitted in section 902.03, (Michigan Department of Transportation, 2011).

7.6 Illinois Department of Transportation – IDOT

Section 1000 of the Illinois Department of Transportation provides the requirements for the materials for Portland cement and blended hydraulic cement. Section 1004.01 covers coarse aggregates. Some approved aggregates consist of gravel, chert gravel, crushed stone, wet bottom boiler slag, crushed slag from air cooled blast furnace slag, and crushed steel slag from OH, BOF or EAF processes. Section 1004.02 covers coarse aggregates for Portland Concrete. Section 1004.02 states that the aggregates must conform to the requirements of section 1004.01. It also states that the aggregates shall be gravel, crushed gravel, crushed stone, crushed concrete, crushed slag or crushed sandstone. Section 1004.03 lists the types of aggregates that are approved for use in bituminous courses in item A. Some of the approved aggregates are crushed gravel, crushed sandstone, crushed slag and crushed steel slag. Therefore, steel slag seems not to be allowed as an aggregate for Portland Concrete since it is not specified in section 1004.02, (Illinois Department of Transportation, 2011).

7.7 Florida Department of Transportation - FLDOT

Section 901 of the 2010 Standard Specifications for Road and Bridge Constructions Materials covers coarse aggregates. A manufactured coarse aggregate can originate from molten nonmetallic by-products such as air-cooled blast-furnace slag or phosphate slag. According to section 901-3.1 of the manual, slag is not permitted to be used in portland concrete cement. Section 902 contains the specifications for fine aggregates. In section 902-6, the use of local materials is discussed, in which slag is listed as an acceptable fine aggregate, but the type of slag and specific use is not stated.

The materials section that deals with bituminous pavements is section 916. Section 917 covers the composition of mineral filler, and states that the mineral filler needs to be an inert material, which can consist of limerock dust, Portland cement, or slag. Slag screenings may be used as a filler material for an asphalt concrete mixture. This is covered under the provisions specified in 917-3. While slag is permitted as a fine aggregate is some applications, and also as an addition to cement, section 901-3.1 clearly states that slag is not permitted in portland cement.

7.8 Conclusion

Some state DOT's address the use of steel slag as a fine and or coarse aggregate in their material specifications. Most of the state DOT's have requirements for the handling, processing, weathering and the specific testing that is required of the slag before the slag can be used. With the exception of ODOT, steel slag was allowed in bituminous concretes, but it varied as to the level of use. The state DOT's that were examined in this chapter did not allow the use of steel slag in portland concrete cement. Sometimes this was directly addressed and sometimes it was indirectly addressed by omission.

CHAPTER VIII

CASE STUDIES

This chapter examines cases of the use of the steel slag as an aggregate in portland concrete cement. These case studies are from the United States and other parts of the world. The application of steel slag in PCC can be separated into roadway pavement applications, such as an econocrete subbase or a roller compacted cement, and applications in which the steel slag aggregate is used in concrete, such as floor slabs, walls of a building, and harbor and seawall blocks.

8.1 United States

There were two case studies located in the United States that used steel slag as an aggregate in an econocrete subbase for pavements in Florida. The first case study reviews the failure of an econocrete base that failed in part due to the expansion of an electric arc steel slag in Interstate 75 located south of Tampa Florida. The second case study examined in this chapter reviews the catastrophic failure of an econocrete base that was totally replaced in a runway at the Tampa International Airport.

8.1.1 Interstate 75 (Florida)

A section of interstate 75 was replaced by an experimental pavement system in the late 1970’s. This project had eleven sections and was located 40 miles (64 km) south of Tampa Florida. The pavement was constructed of a two layered unbound system which was comprised of a 6-in (150 mm) econocrete subbase and a 9 in (230mm) top layer of concrete. Approximately six months after being opened to the traffic in 1980, a section of pavement showed signs of distress. The concrete pavement began showing transverse and longitudinal cracks. One third of the pavement had cracking in the first two years. In one section of the experimental pavement, longitudinal cracks were 100 feet (30m) long and 2 inches (50mm) wide.

When the test road was investigated, it was observed that there was water between the surface layer of concrete and the subbase. There were also no edge drains, and this allowed entrapped water between the two pavements to be the principal initiator of the mechanisms leading to the premature distress in the pavement (Armaghani et al., 1988). This penetration of water eventually caused the joints to start pumping. The econocrete contained an experimental aggregate steel slag.

The steel slag used in this study was produced from an electric arc furnace produced near Tampa, Florida. Samples of the concrete were tested and found to meet or exceed the design requirements. The compressive strength of the econocrete that contained the steel slag aggregate was 1000 psi (6895 kPa) which exceeded the design strength of 800 psi (5516 kPa). It was found that the expansive steel slag that was used as an aggregate in the econocrete was responsible for the failure of one of the sections of the test road (Armaghani et al., 1988). A chemical analysis performed on the cores found that there were magnesium and calcium oxides present, but the amounts of these oxides were not reported. The weathering of steel slag in stockpiles and other forms of treatment of the slag did not begin in the United States until the mid to late 1980's. It is therefore likely that the EAF steel slag used in this experimental road had not been treated by processes mentioned previously in this report. Due to the duration of time that has elapsed since this test road was constructed and removed, the treatment process used on the slag, if any, could not be confirmed.

In a personal communication with Dr. Armaghani, it was confirmed that the use of the steel slag aggregate resulted in longitudinal cracks that ranged from ½ inch (12.5 mm) to 2.5 inches (60 mm) in one section of the pavement. This case study was also discussed with Michael Bergin of the Florida Department of Transportation and Dr. Armaghani's findings were confirmed.

8.1.2 Tampa International Airport

Another known use of steel slag in portland concrete pavement was at the Tampa International Airport. The steel slag was used as an aggregate in the econocrete subbase for a runway at the airport. This project occurred in the late 1970's or early 1980's. The type of steel slag used in the econocrete is unknown, the percentages of the steel slag aggregate is unknown and the weathering processes used, if any are also unknown. While no documentation could be obtained on its use, Michael Bergin from the FDOT, Dr. Armaghani and Greiner Engineering Company of URS Corporation have acknowledged the use of steel slag in the econocrete subbase. In a personal communication with Ernest Barenberg of the University of Illinois, retired, it was confirmed that the econocrete in this application had the same results as Interstate 75. Dr. Barenberg did an investigation into the longitudinal cracks that resulted from the expansion of the steel slag in the econocrete. The solution to the expansion problem was to tear out and replace the runway.

8.2 International Experience

The first international case study is the Labein-Tecnalia Kubik Building constructed in Spain. This was completed several years ago and there have been no reports of problems. The next two case studies were constructed in Belgium. The first study used a cement bound mixture and in-situ mixing of a base layer that contained stainless steel slag for a storage facility. The second case study in Belgium used stainless steel slag in a roller compacted concrete. The final application discussed in this section is the application of steel slag in a mixture called Ferroform. The Ferroform mixture is comprised of steel slag as the fine and coarse aggregate, GGBFS, fly ash and an alkali activator such as slaked lime and water. This mixture has been used as a basement fill and in the manufacturing of blocks that can be used in the construction of harbor and sea walls. The Ferroform blocks have a higher density and lower abrasion coefficient than conventional normal weight concrete, which makes them ideal for this use.

8.2.1 Application of Steel Slag Concrete in the Foundation Slab and Basement Wall of Labein-Tecnalia Kubik Building

The construction of the Labein-Tecnalia Kubik Building in Madrid Spain, took place between 2008 and 2010. The concrete used in the construction of the concrete basement floor slab and the walls used of 100% EAF slag for the fine and coarse aggregates. The steel slag was stored for one month prior to its use. The slag concrete was used for the basement walls and the reinforced concrete foundation slab. The foundation slab and walls of the building contained 180 yd^3 (140 m^3) of concrete that contain as much as 75% steel slag aggregate. The foundation slab contained 46% fine aggregate and 54% coarse aggregate, while the walls contained 40% fine aggregate and 60% coarse aggregate. The producers of the EAF black slag guaranteed an expansion value of almost 0%, however no standards were stated. The amount of free lime or free magnesium was not reported. The concrete was reported to have been pumped into place and there were no problems reported with the placement.

A cement concrete mixture of 875 lb/yd^3 (375 kg/m^3) was used with a target 28 day compressive strength of 7250 to 8400 psi (50 to 58 MPa). The concrete walls were 11.8 inches (300 mm) thick and 9.8 feet (9 meters) high. The concrete slabs reached a compressive strength that ranged from 7500 to 8260 psi (52 to 57 MPa) at 28 days and ranged from 8260 to 9300 psi (57 to 64 MPa) at 175 days. The basement walls reached a compressive strength of approximately 6800 psi (47 MPa) at 28 days and 8260 psi (57 MPa) at 175 days (Chica et al., 2011). The modulus of elasticity was reported to have an average value of 4786 ksi (33 GPa) and the Poisson's ratio was 0.26. This project demonstrated the possibility that steel slag could be used as an aggregate in portland concrete cement. It is still too early to show if there are any long-term expansion problems, although to date none have been observed.

8.2.2 Application of Stainless Steel Slag in Belgium

In 2004, an article was published that discussed two separate case studies that used a stainless steel slag as an aggregate in portland concrete cement. Both of the case studies were in Belgium, with one application as a subbase layer for a slag storage facility and the other as a roller compacted concrete for a rural road. The stainless steel slag that was used in both of the following studies originated from an electric arc furnace.

8.2.2.1 Cement Bound Mixture, In-situ mixing of base layer

The design of the mixture for this case study incorporated 78% slag aggregate, by mass of the dry mixture, with a particle size of 0 to 0.8 inches (0/20 mm). The cement content was 4 to 6% by mass of the dry aggregates with a water content of 8%. This application was in a pavement for a new slag storage facility, which covered approximately 16,146 yard^2 (13,500 m^2). The system used for paving the site was as follows: an impervious geomembrane was laid down first, a subbase sand layer with drainage was constructed next, a 24 inches (600 mm) thick subbase cement-bounded slag, which was compacted in three separate 8 inched (200 mm) layers, and an asphalt layer consisting of a base and wearing course (De Bock & Van den Bergh, 2004). The base layer for the concrete pavement was a cement-bound mixture with stainless steel slag and natural sand, mixed in place.

The free lime content of the coarse size aggregate 0.25 to 0.78 inches (7 to 20 mm) was less than 0.2% and the free lime content of the finer aggregate 0 to 0.25 inches (0 to 7mm) ranged from 0.5 to 1 %. After combining the aggregates, an expansion test was performed prior to aging. The volume increased 1.5% after seven days. After aging the slag for three months, a linear expansion was reported of approximately 0.5% for the 0 to 0.25 inches (0 to 7 mm) slag and 0.2% for the coarser slag. The amount of MgO contained within the slag was not discussed. After completion of the base layer, in situ samples were taken from three separate places to test the volume stability of the mixture. The stability of the mixture was evaluated using 6 samples at 1 and 7 days using an accelerated swelling test. The results showed a 0.4% increase for 1 day and a range of 1.8% to 2.9% volume increase after 7 days, with an average of 2.3%.

Samples of the mixture were tested in the field laboratory, using the mixture of slag, sand, cement, and water. The specimens were manually compacted in the mold and tested for compression strength. The results were an average strength of 1090 psi (7.5MPa). The range of values for the compression strength was 620 to 1380 psi (4.3 to 9.51MPa). The difference in strengths was attributed to the amount of sand in the mixture. While the reported strengths were low, the mixture was intended to be low strength and used to stabilize the road base. The compressibility was also measured and compared to the Belgian standard of 15 ksi (110 MPa) within 72 hours. The plate bearing test values ranged from 9.3 to 77 ksi (64 to 532 MPa). There were 8 tests performed and 3 of them were below the limit so further compaction of the mixture was needed.

8.2.2.2 Roller Compacted Concrete Pavement

The second case study in Belgium was a roller compacted concrete designed for a low traffic rural road. The design mixture consisted of a stainless steel slag, which was 75% by mass of the dry mixture. The particle size of the slag ranged from 0 to 1.2 inches (0 to 30 mm). The workability of the mixture was satisfactory, and efforts to increase the overall moisture content resulted in the mixture needing more time before it could be compacted. By the end of the day, the mixtures from the mixing plant were reported to be too dry, which was attributed to the weather being hot and dry.

A change in the mixture was made to try and fix some problems of segregation of the mixture at the end of the day. The sand content was increased by 5% and the slag content was decreased by 5%. 5 core samples were taken from the road at 7, 27 and 90 days. The compression strength was determined to be 4350 psi (30 MPa) on average at 7 days, with a range of 3045 to 5800 psi (21 to 40 MPa) and 6100 psi (42 MPa) on average at 90 days, with a range of 3480 to 7700 psi (24 to 53 MPa). One of the cores from one of the locations disintegrated. A large crack had formed in the core and it was determined that a 0.06 in^3 (1 cm^3) pocket of hydrated lime was the cause of the crack in the core and this caused the "pop-out" on the core. The location of the cores where the mixture had been modified, showed very low compression strengths compared to the other four core locations, and therefore was omitted from the average compression strength calculations.

8.2.3 Ferroform

The Ferroform mixture is comprised of steel slag as the fine and coarse aggregate, GGBFS, fly ash and an alkali activator such as slaked lime and water. This material can be used as to construct concrete blocks, natural stones and concrete (Matsunaga et al., 2008). This environmentally friendly mixture has been developed by Japan to conserve on natural resources and reduce the amount of landfill debris. Steel slag is reported to have a 98% recycling rate in Japan.

The mixture is reported to have a modulus of elasticity of 3481 ksi (24 GPa) which is approximately the same as the normal weight concrete (NWC) modulus of elasticity of 3626 ksi (25 GPa). The tensile strength of the Ferroform was 319 psi (2.2 MPa) which is slightly higher than the 276 psi (1.9 MPa) reported for the normal weight concrete. The flexural strength is also slightly higher and was 580 psi (4.0 MPa) compared to 3.4 N/mm^2 for the NWC. The density of the Ferroform mixture is 2.4 to 2.6 t/m^3,which is slightly more than the NWC density of 2.3 t/m^3. The medium pore size is about one quarter that of the NWC, and was reported to be 0.02 µm for the Ferroform compared to 0.09 µm for the NWC and the abrasive coefficient was 0.04 cm^3/cm^2 which is less than half that of the NWC of 0.09 cm^3/cm^2. The compression strength of the Ferroform at 28 days was approximately 4061 psi (28 MPa) and was reported to have increased to over 4360 psi (30 MPa) after 1 year.

The Ferroform mixture has been used in Japan for the filling of a basement floor in 2003, which was pumped into place. The flow rate of the mixture was 78 yd^3/hr (60 m^3 /hr), for a horizontal distance of 164 yards (150 meters) through a 5 inch (125 mm) pipe. There was no separation of the mixture which had a slump of 0.83 inches (21 mm). The average compression strength was 2176 psi (15 MPa) with a coefficient of variation of 5% (Matsunaga et al., 2008).

The Ferroform mixture is also used for blocks, which can be mass produced in a manufacturing plant. The blocks have dimensions of 1.1yard x 1.1 yard by 0.2 yards (1 meter by 1 meter by 0.2 meter) and are steam cured. These Ferroform blocks have been used in the repair and construction of ports and harbors. One example of its use is the Mizushima Port, Japan, which used this environmentally friendly block in the repair of the port wall. Another example was the construction of a sea wall located near JFE Steel's Kurashiki district (Matsunaga et al., 2008). Since the Ferroform blocks have a higher density due to the steel slag, it makes them ideal for use in dynamic applications such as harbor and sea walls. These blocks also have a lower abrasion coefficient than normal weight concrete, which also makes them ideal for applications in water and along the shorelines. The Ferroform blocks that were used below the sea line were reported to have had no negative effects on the plant and animal life and the increase in the pH of the sea water was small.

8.3 Conclusion

The use of steel slag as an aggregate in PCC dates back to the 1970's in the United States and its use in PCC is still being studied in countries throughout the world. The earlier case studies such as the Tampa airport and I 75 reported major failures, and the sections of the econocrete that contained the slag aggregate had to be torn out and replaced. It is unknown how much of the slag was used in the concrete and what proportions of the natural aggregates were replaced by the steel slag. The lack of edge drains along the I 75 might have also contributed to the hydration of the slag since the water became trapped between the concretes. This could have led to excessive penetration of the water into the econocrete, which would have facilitated the hydration of any free lime or free manganese in the slag. It is unknown if the slag was aged prior to it being used.

Some of the more recent concrete applications have reported some success in its use in concrete, such as the Labein-Kubik building in Spain, the roller compacted concrete road application, and the concrete layer for the storage facility in Belgium.

While the Labein-Kubik building is not a pavement, it does demonstrate that the EAF slag can reach good compressive strengths and maintain enough workability to be pumped into place.

The in-situ cement mixture at the storage facility with the stainless steel slag as an aggregate in the base layer showed an average volume expansion of 2.3%, which is high, but no problems were reported due to the expansion. There have been no follow up reports on these applications to date, so it is unknown if there have been any other problems observed. The second case study reported some minor problems with the mixture drying out to quickly and attempts to rectify it with additional water were not successful. The addition of additional water seems to have affected the overall mixture adversely.

The Ferroform mixture demonstrates that byproducts that had been landfilled in the past are now being used in beneficial ways, to not only reduce the amount of landfill, but also to reduce the stress on our natural resources. This mixture has been shown to have physical properties that are essentially equal to that of normal weight concrete. The Ferroform mixture exhibits compressive strength that is comparable to normal weight concrete and has a higher tensile strength and flexural strength, and a modulus of elasticity that is essentially equal to normal weight concrete. The use as a basement fill showed that it could be pumped even though it had a low slump. The compression strength of the concrete was 2176 psi (15 MPa), which can be considered low, but the target strength of the Ferroform was not stated. The compression strength of the blocks showed that it could meet the standards for a pavement mixture.

While the testing on the cores from the applications in Belgium showed that the steel slag concrete can obtain values equal to, or greater than the specified compressive strength, the disintegration of one of the cores from the hydration of free lime demonstrates that the weathering outside for three months prior to its use didn’t remove all of the free lime. This should cause some concern about this type of treatment process. All these applications aged the slag prior to use in the PCC, with the exception of the Ferroform mixture, which did not state if the slag had been aged. It should be noted that none of these case studies used the steel slag as an aggregate in a traditional pavement surface application for a roadway.

CHAPTER VIIII

FINAL CONCLUSIONS AND RECOMMENDATIONS

The objective of this report was to examine the technical properties of steel slag, which included the physical properties of the steel slag aggregate, the mechanical properties of concrete containing the slag as an aggregate, and the chemical compositions of the main types of steel slag. This research also examined the testing methods used for determining the expansion of the steel slag, aging, and treatment methods used to reduce the oxides that are responsible for the volume instability. The results from laboratory studies that examined the expansion of steel slag as an aggregate and concrete specimens that contained the steel slag aggregate were also reviewed. The material specifications from seven state Departments of Transportation were reviewed and several case studies that used the steel slag as an aggregate were discussed.

9.1 Final Conclusions

The feasibility of using steel slag as an aggregate in concrete depends on many factors. The production of steel and steel slag has continued to grow since the 1970's and the production of steel slag increased from 2010 to 2011 by 30%. This continued growth means steel slag should be available for use in areas where steel production remains strong. The use of the steel slag as an aggregate in concrete will also depend on its physical and mechanical properties.

The ASTM gradation requirements can be obtained for steel slag as a course aggregate but there have been some difficulties reported for achieving the requirements for a fine aggregate. The density of the steel slag is higher than natural aggregates commonly used in PCC, but this should not be a factor for use in pavement applications. The porosity and absorption of steel slag are higher than some natural aggregates used in PCC. For this reason there may need to be some corrections to the percentage of water for the design mixture. The higher porosity of the steel slag allows for more surface area for the cement to bond to, and the higher angularity of the particles can cause water to be trapped in the pores of the slag. The higher absorption of steel slag will result in a reduction of water that is available for the hydration of the cement. According to De Bock et al. (2004), the additional water needed to compensate for the water absorption of the steel slag aggregate is 2% of the total mass of the steel slag. The resistance to abrasion of the steel slag aggregate is superior to those of a limestone aggregate and should provide a greater resistance to surface wear of the pavement.

Many laboratory studies have been conducted on the mechanical properties of concrete containing steel slag. The compressive strengths of concrete containing steel slag are comparable to the strength of concrete containing natural aggregates. The maximum compressive strength is usually obtained when 50% of the natural course aggregate is replaced by the steel slag. No trends could be established relating the percentage of natural aggregate replaced to the compressive strength obtained when the steel slag was used as a course and fine aggregate. In work conducted at Cleveland State University it was demonstrated that concrete containing steel slag in various percentages could meet the ODOT requirement of 4000 psi (27.6 MPa). A trend has been established correlating the percentage of steel slag with the compressive strength achieved for the high strength concrete. It was shown that as the percentage of steel slag increases, so too does the compressive strength of the high strength concrete. The split tensile strengths of concrete with steel slag were comparable to those containing natural aggregates and were within an expected range of 5 to 10% of the compressive strength. The split tensile strengths generally decreased as the percentage of steel slag increased. The maximum flexural strength was usually obtained with a replacement of 50% of the course aggregate and the strengths achieved were similar to those of ordinary concrete. The modulus of elasticity of concrete with steel slag increased slightly as the percentage of slag increased and was within the range of concrete containing natural aggregates.

The depth of water penetration decreased as the percentage of course steel slag aggregate increased and was less than the control specimens in the laboratory studies. When steel slag was used as a fine and course aggregate the opposite was true. As the percentages of aggregate increased, the depth of water penetration also increased, and the specimens with 100% fine and course aggregate resulted in complete penetration. When the fine aggregate percentage was decreased to 75% steel slag fines and 100% course aggregate, the depth of water penetration was comparable to the control specimens. The results of the water penetration testing showed that concrete containing steel slag was similar to PCC as long as the percentage of steel slag as a fine aggregate was equal to or less than 75%. The addition of steel slag as a course aggregate had no adverse effects with respect to the depth of water penetration.

The durability of concrete is important and it is crucial that this is not diminished from the addition of steel slag. The results from the freezing and thawing testing showed mixed results. When EAF and LF were used together, the loss of compressive strength was higher than the control, and the surface appearance showed some damage. When only an EAF slag was used as a replacement, with the addition of an air entraining admixture, the results of the freezing and thawing testing showed the concrete containing steel slag was comparable to the control specimens. The surface appearance and loss of mass resulting from the wetting and drying testing were acceptable. The loss of compression strength was higher than the control, which could be an indication that there are some adverse effects of steel slag. This loss of strength could be due to the hydration of free lime and periclase within the concrete, but this was not confirmed in any of the studies. The results of high temperature exposure testing showed the steel slag concrete had a lower loss of strength than OPC, indicating the steel slag concrete was more durable with respect to high temperature exposure but this is not relevant for pavements. The result of nine month testing of concrete containing steel slag to study the effects of attack from chloride ions showed the transport of chloride through the concrete increased as the percentage of steel slag increased. The durability of the concrete was considered low.

The workability of concrete is affected by the addition of steel slag, due to the higher angularity of the particles and the higher absorption of the aggregate. The addition of admixtures can improve the workability. It was demonstrated in several studies that an acceptable slump could be achieved for concrete containing steel slag. It was also shown that the concrete could meet the ODOT specifications for Class C paving mixture (Obratil et al., 2008 and 2009).

The chemical composition of steel slag is dependent on the process used to produce the steel. The content of calcium oxide and magnesium oxide in steel slag is mainly due to type of flux used. The ladle furnace slag contained the highest percentage of CaO, with a median value of 57%. The BOF slag had a median value of 40.98% and the EAF slag had a median value of 29.5% for CaO. The MgO content of the BOF slag and EAF slag were similar, with median percentages of 7.75 and 9.82% respectively, while the LF slag MgO median percentage was 4.2%. The origins of free lime and free periclase were discussed, but the reporting of their content in the steel slag was limited and no correlations could be established between the percentages of CaO and MgO of the slag and the percentages of free lime and free periclase. The pH of steel slag ranges from 8 to 10, but can be as high as 12, and can have adverse effects organisms and the environment if a dilution of 100 fold is not obtained. The calculated risk levels from exposure to steel slag to adults showed the slag does not pose a significant cancer risk. The ecological assessment performed by Exponent Inc. showed a dilution factor of 40 is needed to ensure that sediment screening levels are not exceeded. When plausible environmental conditions and application scenarios are considered, in which the slag particles and leachate are naturally diluted by ambient water sediment and or soil particles, no significant hazard to ecological receptors is anticipated. The leachate from steel slag was found not to pose a risk in the studies reviewed during this research.

Free lime can be present in the form of precipitated free lime and residual free lime. The residual free lime can then be separated into granular and spongy free lime. The spongy free lime is mainly responsible for the short-term expansion of steel slag. The magnesium-wusite form of MgO is attributed to the long-term expansion concerns of steel slag. The limits on the content of free CaO and free MgO for slags used in Germany and in Europe were discussed for unbound applications and applications in asphalt. No limits have been established on the percentage of free CaO and free MgO for steel slag as an aggregate in bound applications. If steel slag is going to be used in concrete as an aggregate, then establishing limits on these contents could help to prevent the volume instability associated with these components.

The expansion of steel slag is the most crucial and important concern of the feasibility of expanding the use of steel slag in PCC. The expansion resulting from the hydration of free lime and free periclase can result in the failure of the pavement, as was shown in several instances throughout this research. The expansion of the steel slag is separated into two components, the short-term expansion from the hydration of free lime, which can occur within days of being exposed to water, and the long-term expansion resulting from the hydration of free periclase, which can take place over a period of years. There are several methods that have been established to test the steel slag for expansion.

The PennDot test is based on ASTM C 4792, and has been used for many years to test for the expansion of the steel slag for unbound applications and bituminous asphalt concrete. The German steam is also another accepted testing method and is used in Europe to test for the expansion of steel slag for use in unbound applications and asphalt.

This testing method is currently being used to generate expansion curves for steel slag, which may be used to predict the final expansion of the slag aggregate. There are several other testing methods that have been developed to test for expansion. They are the boiling test, which was developed by the company Armourstone and the expansion force test, which is used to determine the forces generated by a single slag particle. It may be possible someday to use the expansion force test to establish a limit on the forces generated by the expansion of the slag and this limit would allow for a comparison to the concretes tensile strength to determine if the slag aggregate is acceptable for use. There have also been some testing methods that have been developed to test concrete containing steel slag as an aggregate for expansion. These testing methods include the autoclave test, the accelerated aging test and the delayed autoclave test. The autoclave test and the accelerated aging test determine if there are any adverse effects from the expansion of steel slag by comparing the compressive strength of the concrete prior to the testing to the strength after the testing. The results from all laboratory studies conducted using both of these testing methods showed that the use of steel slag in the concrete had no adverse effects. It was determined in the studies that the treated slag was non-expansive.

The treatment of the steel slag to reduce the free lime and free periclase is a key requirement for the feasibility of its use in concrete. Most methods use water in one form or another to hydrate the two expansive compounds and reduce the expansive characteristics of the slag. The aging of the slag in stockpiles is the most common method used in the United States, but this method does not totally eliminate the expansion. The addition of silica sand and oxygen into the molten slag reduces the free lime and free periclase in the slag, and is currently being used in the production line by a company in Germany. The quick quenching of the steel slag by rapidly cooling the slag is reported to produce slag with a free lime content that ranges from 2 – 4 % and no free periclase. It is also possible to chemically alter the steel slag by treating the slag with an acid, which reacts with the calcium and produces calcium carbonate. The two methods discussed as possible treatment methods were the dissolution method and the precipitation method. The chemical treatment of the slag by the precipitation method was a more effective method then the dissolution method at the removal of calcium oxide.

The expansion testing of concrete or cement mortars with steel slag aggregate resulted in expansion values that were similar to the control specimens and were less than the allowable expansion limits of ASTM in all studies reviewed. In laboratory studies that varied the percentage of steel slag aggregate, no correlations between the percentage of steel slag and the expansion of the cement concrete or mortar could be established.

There were multiple studies that examined the effects of different aging processes on expansion. Several of these studies examined the effects of the aging processes on the steel slag as an aggregate, and some studies examined the processes on cement or mortar bars containing the slag as an aggregate. One study compared four different treatment processes: the aging outdoors for twelve months, 8 and 12 hour steam treatment, and autoclave treatment of the slag. The autoclave treatment was the most effective process of the four, and weathering of the slag outdoors was the least effective at reducing the expansion of the specimens. The weathering of the slag outdoors was examined in two studies for its efficiency at reducing the expansion of the steel slag as an aggregate. The expansion of the steel slag in the first study ranged from 0.25 to 2.1% prior to treatment. After the aging of the slag, the expansion decreased to an average of 0.33%. In the second study, the expansion ranged from 0.5% to 2.5% prior to treatment and from 0.15% to 0.40% after treatment. These studies demonstrated that the weathering outdoors was effective at reducing the expansion of the slag and the expansion of the slags in both studies was below the ASTM limits of 0.50%. The results of this testing confirms that the aging of the slag outdoors does not completely hydrate all the free lime and or free periclase, and there is still some expansion of the aggregate that takes place after the aging process.

One final study examined the effects of four aging processes on a BOF slag and an EAF slag. The four treatment processes were: aging in the air for one month, hot water aging for 1 and 3 days, and the treating of the slag by steam for 3 days. The air aging showed a 50% reduction in expansion from non-aged slag for the EAF slag sample and a 60% reduction for the BOF slag. The treatment of the slag by steam for three days and hot water for three days showed essentially the same results, and had the largest reduction of expansion for both types of slag. The results of the air aging outdoors again showed that that it is effective at reducing the expansion, but it does not totally eliminate the expansion. Prior to conducting the experiments on the two types of slags, a chemical analysis was completed on the slags. It was determined that the free lime content of the BOF slag was 3.3% and the free lime content of the EAF slag was 0.3%. Both slags were also tested for expansion without any treatment, and it could be seen from the expansion curves generated from the testing that the expansion of the BOF slag was 10 times the expansion of the EAF slag. The 10 day expansion ratio was 1.6% for the BOF slag and was 0.16% for the EAF slag. This showed a clear correlation between the expansion of the slag aggregate and the content of the free lime. The treatment processes and their effectiveness at reducing or eliminating the expansion is one of the main factors in the feasibility of using steel slag in PCC.

The material specifications of seven state departments of transportation were reviewed in this study. The specifications for use in bituminous applications, unbound applications and for its use in PCC were examined. Most of the state DOT's have requirements for the handling, processing, weathering and the specific testing that is required of the slag before it can be used in unbound applications and for bituminous concretes. ODOT was the only DOT to not allow the use of steel slag in bituminous concrete surface layers and no state DOT has approved the use of steel slag in portland concrete cement as an aggregate in pavement applications.

The two case studies located in Florida that used EAF slag in an econocrete subbase resulted in failure of the pavements and serve as a precautionary warning to the potential detrimental effects of the expansion of steel slag. It is unknown if the slag had been aged. The Labien-Kubik Building in Spain, which was built between 2008 and 2010, contained 100% steel slag as fine and course aggregates and there have been no reports of problems resulting from any expansion of the steel slag aggregate. The two case studies located in Belgium used a stainless steel slag for a cement mixture and a roller compacted cement pavement. After aging the slag for three months, a linear expansion of approximately 0.5% for the 0 to 7 mm (0 to 0.25 inches) slag and 0.2% for the coarser slag was reported. It was reported that the disintegration of one of the cores acquired for compression testing had resulted from 1 cm^3 (0.06 in^3) of hydrated free lime. While there have been no other reports of problems with the pavement from the expansion of the steel slag, this shows that the aging of steel slag outdoors for three months and spraying the steel slag is not effective at hydrating all the free lime present. No case studies were located in this research that used steel slag as an aggregate in a traditional surface pavement application for a roadway.

In conclusion, the laboratory testing of the physical properties of the steel slag and the mechanical properties of concrete containing steel slag as an aggregate results in concrete with similar properties and strengths to conventional concrete. The durability of the concrete with steel slag aggregate exhibited similar attributes to concrete with natural aggregates when an air entraining admixture was used. The workability of the concrete was improved by the addition of admixtures and an acceptable slump was obtained and was within the limits set by ODOT. The results of expansion testing for both the steel slag as an aggregate and for concretes containing steel slag as an aggregate showed that the treatment of the steel slag was successful at reducing the expansion and were within the allowable limits set by ASTM. Sufficient laboratory testing has been completed on the steel slag to demonstrate that it is feasible to use steel slag as an aggregate in concrete, since the concrete maintains similar properties to concrete with natural aggregates.

9.2 Recommendations

The following recommendations are based on the literature, data and results of laboratory studies reviewed while conducting this research. They are the opinion of the author and are intended to serve as a guide to support the FHWA Office of Pavement Technology, state highway agencies, and steel-slag producers concerning the potential use of steel slag as an aggregate in concrete for paving applications.

The feasibility of expanding the use of steel slag as an aggregate in concrete will depend on its volume stability. It is recommended that the steel producers and slag processers conduct further research on the treatment methods previously discussed in Section 5.4. The four treatment options that would be recommended for further investigation are the addition of silica sand and oxygen, the 3 day steam treatment, three day hot water aging, and chemically treating the steel slag with an acid. The weathering of steel slag in stockpiles is somewhat effective at stabilizing the slag, but it was shown in this research that it does not completely remove the expansion characteristics of the slag.

Some treatment methods discussed were more effective at reducing the expansion of the slag. The treatment of the steel slag by the addition of silica and oxygen process was introduced into a converter line of Thyssen Krupp Stahl in Duisburg has been operating successfully, and produces slag that was reported to have a free lime content of less than 1% by weight. The three day steam aging of the steel slag at a temperature of 212 °F (100°C) and the three day hot water aging, which immersed the slag in water of 176 °F (80°C), were effective at reducing the expansion of the slag aggregate (Moon et al., 2002). The expansion ratio for the 3 day steam treatment and the three day hot water aging had expansion ratios of 0.06% at 10 days for the EAF slag. Both of these methods were more effective then air aging and reduced the expansion of the slag by 62.5%. Using these methods would reduce the amount of time needed for the treatment of the slag from three months to three days. These methods would also reduce the large amounts of space required to weather the slag. It is for these reasons that these methods have been recommended for further study. The possibility of treating the slag chemically with an acetic acid is also a promising treatment method. This method might be able to stabilize the slag, which would allow it to be used in concrete and as a structural backfill. This method would also produce a second product that could be sold which might offset the cost of this treatment process.

The expansion of steel slag as an aggregate can result in the failure of a concrete pavement and for this reason it is not recommended that it be used in the construction of a highway at this point. The results from laboratory studies have demonstrated that properly treated steel slag can be below the expansion limits set by ASTM, but there still exists some expansion. It is recommended that a test pavement application be constructed to further study its use in PCC. A suitable test pavement application would be a parking lot or other small field test. This would minimize the cost for construction and would minimize the deleterious impact, if the steel slag expands and causes failure of the pavement.

The following recommendations are suggested to further study the steel slag as an aggregate in a low use PCC pavement application. Minimum use pavement applications would include a parking lot, sidewalk, or small test sections of a rural road. All sections of the pavement should be designed with the same compressive strength and an air entraining admixture should be used to help with freezing / thawing.

It is recommended that separate pavement sections using arc furnace and basic oxygen furnace slags be used for the following reasons. It was shown in this research, that the BOF slags had a median percentage of CaO that was 10% higher than the EAF slags. However, the EAF slags had almost twice the percentage of MgO. The expansion of the BOF slag was also 10% greater than the EAF slag in the study conducted by Moon et al. (2002). Chemical analysis of the slags should also be conducted on the slags prior to their use, and should include the testing for free lime and free periclase by the methods previously discussed in this paper. The testing for the expansion of the slag aggregate should also be conducted prior to using it in the pavement.

It is recommended that the pavement be divided into four sections with the following compositions. The first test section should contain all natural aggregates and serve as the control for the study. The second section should be constructed with 100% natural fine aggregate and replacement of 25% of the coarse aggregate with steel slag. The third test section should be constructed with 100% natural fine aggregate and replacement of 50% of the coarse aggregate with steel slag. The final section would contain 50% replacement of all the natural aggregate with steel slag. It is not recommended to replace 100% of the fine aggregate with steel slag due to gradation concerns that were previously discussed in this research.

9.3 Recommendations for Further Study

1) Study different aging processes on the slag from the same plant. Determine effect, if any, of the different aging processes on the mechanical and physical properties. There were several studies that investigated the effects of the aging processes on expansion (Yunxia et al., 2008) & (Moon et al., 2002), but no studies researched the effects on the physical and mechanical properties.
2) Study the effect of the aging processes on the chemical composition using the slag from one plant. Complete for both an EAF slag, BOF slag and a LF slag. There

are many studies that report the chemical compositions of slags, but there was no study examined, that researched the effects of the aging processes from one slag processor.

3) Study the effect of the different aging processes on the expansion of the slag aggregate for EAF slag, BOF slag and Ladle Furnace slag. There is limited research that compares the effects of the aging processes, which use the same slag. Both Yunxia et al. (2008) and Moon et al. (2002), studied the effects of aging processes on EAF slags. No studies were examined that used a BOF slag or an LFS.
4) Examination of the interactions between the chemical and mineral components of the slag to see if there is any effect on the stability of the slag. The studies examined focuses on the free lime and free periclase in the slag. There are many chemical and mineral components in the slag that could potentially interact with each other, or the fluxing agents, and no studies were found that examined this.
5) Study the effects of the type and amount of fluxing agent used in the production of the steel on the chemical and mineralogical composition. This study should also investigate its effect on the expansion of the slag.
6) More laboratory analysis on the chemical components, such as content of free lime and periclase, needs to be completed on the slag before, during, and after the various treatment processes. This should be done to determine how effective the treatment processes are on the hydration of free lime and periclase.
7) Further examination and testing using the boiling test, accelerated aging test and delayed autoclave test to develop standards in the United States for possibly using

these methods of testing. These methods may be able to be developed, and serve as additional testing methods, that could then be used to test the slag for expansion just as the PennDot test is used.

8) The delayed autoclave test was designed to test the expansion and strengths of concrete containing MgO (Gao et al., 2007). It may be possible to use this testing method on slag as an aggregate, since the slag may contain MgO. There was no study examined that used the delayed autoclave test on slag. Testing of steel slag using the delayed autoclave method to determine if the expansion results of this test are comparable to the results from other testing methods.
9) Further examination of the delayed autoclave test to see if it could be used in the testing for expansion of concretes containing steel slag aggregates. The study examined did not use concrete that contained steel slag (Gao et al., 2007). This testing method may be developed as another to examine the expansion of concrete that uses steel slag as an aggregate.
10) Further testing and studying of the forces generated by the expansion of a slag particle. If enough testing could be performed and a safety factor could be derived from the internal stress created by the expansion of the steel slag and related to the tensile stress of the concrete. Then it would be possible to predict if the slag could be used as an aggregate based on the testing of one or two samples from a slag pile using the safety factor.
11) There is very limit research on the expansion of BOF slag and it is suggested that more research and testing on this subject. This is probably because the BOF slag usually has higher CaO percentages that an EAF slag. If the different treatment

processes are effective in the reduction of the free lime and free periclase, then more investigation is warranted

12) Recommend more research on the boiling test and possible development of limits for loss in mass of the slag pieces for use in PCC. This testing method could prove to be a valuable method, since the cost of conducting this test on the slag would be minimal. It may be possible to establish guidelines and limits from the results of testing on EAF, BOF, and LF slags.
13) Expansion testing from slag produced from the addition of silica sand and the injection of oxygen treatment process was not found during the course of this research. A comparison of the expansion of the slag from this treatment process to the expansion of the same slag treated by another method, like outdoor aging to determine the effectiveness of the different treatment processes.
14) Small scale field testing of test sample pavements with varying percentages of steel slag versus control pavements. This was discussed in detail and can be found in section 9.2.
15) Exposure blocks containing varying percentages of an EAF slag aggregate could be tested. This study could examine the possible effects of using the steel slag as an aggregate and would reduce the financial risk associated with performing a small scale field test.
16) The cost associated with the treatment processes is not mentioned in any of the literature. A cost analysis on the possible treatment processes is recommended to determine if the treatment processed are economically viable.

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APPENDIX A

ASTM SPECIFICATIONS

The American Society for Testing and Materials (ASTM) defines steel slag as "A non-metallic product, consisting essentially of calcium silicates and ferrites combined with fused oxides of iron, aluminum, manganese, calcium and magnesium that are developed simultaneously with steel in basic oxygen, electric arc, or open hearth furnaces," (National Slag Association (d), No Date). The following specifications listed below are summarized and are not the complete standards. The ASTM standards listed below have been obtained from the ASTM International Web Site and are listed to give a general definition of the standard. These testing methods maybe used for the testing of the steel slag to determine its physical, mechanical, and chemical properties when it is used as an aggregate. For the complete standard see http://www.astm.org/index.shtml.

<u>ASTM C 33/ C33M – 11a: Standard Specification for Concrete Aggregates -</u> This specification gives the requirements for the quality and grading of fine and coarse aggregates for concrete. It states that fine aggregates will consist of natural and or manufactures sands and coarse aggregates will consist of gravel, crushed gravel or stone, air-cooled blast furnace slag, or crushed hydraulic-cement concrete. It also states, "Fine

aggregate for use in concrete that will be subject to wetting, extended exposure to humid atmosphere, or contact with moist ground shall not contain any materials that are deleteriously reactive with the alkalis in the cement in amount sufficient to cause excessive expansion of mortar or concrete.”

ASTM C 88 – 05: Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate - This specification is for estimating the soundness of the aggregates for concrete and other uses. It is intended as a guide to determine if an aggregate is acceptable for use and this specification is to be used in conjunction with other specifications in order to determine if the aggregate is suitable for use.

ASTM C 127 - 07: Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate – This specification provides the procedures to find the average density of coarse aggregate particles, the relative density, and the amount of absorption of the coarse aggregate. This method should not be used with lightweight aggregates.

ASTM C 131-06: Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine - This method is used to indicate the quality of an aggregate that possesses similar mineral composition. It outlines the testing procedures for coarse aggregates which are smaller than 37.5 mm (11/2 in.) for resistance to degradation using the Los Angeles testing machine.

ASTM *C 136 - 06*: Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates: Provides testing methods to find the grading of materials proposed for use as aggregates. It determines the particles distribution for fine and coarse aggregates. The findings from this test can be used to see if the results are in compliance of the particle size distribution and can be used in deriving relationships pertaining to porosity and packing.

ASTM C – 227 – 03: Potential Alkali Reactivity of Cement – Aggregate combinations (Motor-Bar Method) – Aggregate Combinations - expansion of greater than 0.05% at 3 months or 0.10% at 6 months when high alkali cement is used. Combinations of aggregate and cementitious materials have produced excessive expansion should be considered potentially reactive.

ASTM C 469 / C469M – 10: Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression - This test method outlines the stress to strain ratio value and the ratio of lateral to longitudinal strain for hardened concrete for different age and curing conditions. The modulus of elasticity and Poisson's ratio values are applicable within the working stress range of 0 to 40 % of ultimate concrete strength. They can be used in the sizing of concrete structural members that may or may not contain reinforcement. The modulus of elasticity and Poisson's ratio values can also be used to establish the amount of reinforcement and for computing the stress for observed strains.

ASTM C496 / C496M – 11: Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens – This specification provides the procedures and methods for finding the splitting tensile strength for molded and core cylinders of concrete. It is used to evaluate the shear resistance in structural concrete.

ASTM C666 / C666M - 03(2008): Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing- This testing method is used to determine the resistance of a concrete specimen to repeated cycles of freezing and thawing. There are two different procedures used: procedure A, which is rapid freezing and thawing in water and procedure B which has rapid freezing in air and thawing in water. These two procedures are for finding the effects of freezing and thawing and not for determining the expected life of a concrete.

ASTM C – 1260 - 07: Potential Alkali Reactivity of Aggregates (Mortar bar Method) – This method is an accelerated method for detections of reactions that develop deleterious expansion slowly over a long period of time. An expansion of less than 0.10% at 16 days means the specimen's reaction is harmless and an expansion of greater than 0.20% shows the specimen is revealing potentially deleterious expansion.

ASTM C 1556 – 11a: Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion - This testing method is used for cementitious mixtures not previously subjected to external chloride ions other than the negligible quantities of chloride ion exposure from the preparation of the sample using potable water before the test. The calculation procedures prescribed in this testing method is only applicable to laboratory test specimens exposed to a sodium chloride solution. This calculation technique is not applicable to samples exposed to chloride ions during the cycle of wetting and drying. The diffusion of ionic species in concrete occurs within the fluid-filled pores and void spaces. The rate of change of the apparent diffusion coefficient for cementitious mixtures containing pozzolans or blast-furnace slag is usually different than that for mixtures containing only portland cement. The resistance of chloride penetration can be affected by the following factors: the environment, mixture composition, curing, age of the concrete, finishing, and workmanship.

ASTM D559 – 03: Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures- This specification outlines the procedures used for determining a compacted soils resistance to cycles of wetting and drying. It is to be used with Test Method D 560 to find the minimum amount of cement to achieve the degree of hardness, which will be able to resist the weathering in the field. The test method used for the preparation of the specimen depends on the soils gradation. Method A is for soils that 100% passes sieve No. 4 (4.75-mm) and method B is when a portion of the material is retained in the No. 4 sieve.

ASTM D 2940 / D2940M – 09: Standard Specification for Graded Aggregate Material for Bases or Sub-bases for Highways or Airports - This specification covers aggregates that are expected to provide adequate stability for use as highway or airport bases or sub-bases. The coarse aggregate will consist of durable particles of crushed stone, gravel, or slag that are able to withstanding the effects of handling, spreading, and compacting. Fine aggregate will consist of fines from the operation of crushing the coarse aggregate. The following tests are needed to be completed: grain-size test (dry and wet sieving), liquid limit test, plastic limit test, plasticity index test, sand equivalent value test, and expansion test. The expansion limit is less than 0.5% tested at 7 days according to the procedures of ASTM 4792 - 00.

ASTM D4792- 00(2006): Standard Test Method for Potential Expansion of Aggregates from Hydration Reactions – This specification gives the procedure for determining if a steel slag is in compliance with specifications like ASTM D 2940 which limit the amount of expansion as an aggregate. It can be used to find the effectiveness of aging process or other treatments for reducing the expansion potential. The results have not been correlated with field performance and the results found do not necessarily indicate the expansion that may occur in the field. The expansion limit is less than 0.5% tested at 7 days.

ASTM D5106-08: Standard Specification for Steel Slag Aggregates for Bituminous Paving Mixtures- This specification covers the use of steel slag in bituminous pavements as a fine and coarse aggregate. It specifies the physical qualities that the slag should have, how the slag should be processed and what the slag should have and not have in it at the time of delivery.