PERFORMANCE EVALUATION OF STEEL SLAG AS NATURAL AGGREGATES REPLACEMENT IN ASPHALTIC CONCRETE

by

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PENILAIAN PRESTASI SLAG BESI SEBAGAI PENGGANTI AGREGAT SEMULA JADI DALAM KONKRIT ASFALT

Disediakan oleh

TEOH CHERH YI

Tesis yang diserahkan untuk
Memenuhi keperluan bagi
Ijazah Sarjana Sains

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Appendix A

Appendix B

Appendix C

PERFORMANCE EVALUATION OF STEEL SLAG AS NATURAL AGGREGATES REPLACEMENT IN ASPHALTIC CONCRETE

TEOH CHERH YI

UNIVERSITI SAINS MALAYSIA

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List of Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ACV	Aggregate Crushing Value
ACW	Asphaltic Concrete Wearing Course
AIV	Aggregate Impact Value
ASTM	American Society of Testing and Material
BOF	Basic Oxygen Furnace
$CaCO_3$	Calcium Carbonate
Ca (OH_2)	Calcium Hydroxide
$CaCO_3$	Carbon Dioxide, Calcite
DAMA	Darin Asphalt Modified Additive
DBC	Design Binder Content
EAF	Electric Arc Furnace
FEhS	Forschungsgemeinschaft Eisenhüttenschlacken e.V. (Research Association for iron and Steel Slags)
FHWA	Federal Highway Administration
GDA	Granite Dense Asphalt
GPA	Granite Porous Asphalt
HMA	Hot Mix Asphalt
JIS	Japan Industrial Standards
LAAV	Los Angeles Abrasion Value
LTOA	Long Term Oven Aging
NSA	Nippon Slag Association

OBC	Optimum Binder Content
PG	Penetration Grade
SG_{App}	Apparent Specific Gravity
SG_{Dry}	Dry Specific Gravity
SG_{SSD}	Surface Saturated Specific Gravity
SSDA	Steel Slag Dense Asphalt
SSGDA	Steel Slag/ Granite Dense Asphalt
SSPA	Steel Slag Porous Asphalt
STOA	Short Term Oven Aging
USA	United States of America
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VFB	Voids Filled with Bitumen
VMA	Voids in Mineral Aggregate
VTM	Voids in Total Mix

Penilaian Prestasi Slag Besi Sebagai Pengganti Agregat Semula Jadi dalam Konkrit Asfalt

Abstrak

Slag besi ialah salah satu bahan buangan industri yang dijadikan agregat pembinaan jalan raya. Penyelidikan ini dijalankan untuk mengkaji prestasi agregat slag besi sebagai bahan pembinaan jalan raya serta membandingkan prestasinya dengan agregat granit. Slag besi yang digunakan diuji untuk mendapatkan sifat fizikal dan mekanikalnya. Dua reka bentuk campuran tumpat dengan bitumen gred penusukan 80/100 dan satu reka bentuk campuran berliang dengan bitumen gred penusukan 60/70 juga digunakan dalam penghasilan spesimen ujian. Spesimen campuran tumpat dirujuk sebagai Asfalt Padat Slag Besi 100% (SSDA) dan Asfalt Padat 50% Slag Besi 50% Granit (SSGDA) manakala campuran berliang dirujuk sebagai Asfalt Berliang Slag Besi (SSPA). Dalam fasa pertama penyelidikan, SSDA dan SSGDA diuji untuk menilai prestasinya melalui ciri modulus kebingkasan, rayapan dinamik, kestabilan Marshall dan kekuatan tegangan tak langsung. Selain ujikaji yang dinyatakan (kecuali kekuatan tegangan tak langsung), SSPA juga dinilai melalui ujikaji Cantabro dan ujikaji kebolehtelapan air. Untuk fasa kedua penyelidikan, ujikaji dalam fasa pertama dijalankan ke atas spesimen yang melalui proses penuaan. Rintangan campuran tumpat dan campuran berliang terhadap rayapan dan retakan pada suhu rendah diperbaik selepas proses penuaan. Keputusan ujikaji menunjukkan bahawa slag besi berpotensi besar untuk dijadikan bahan pembinaan jalan raya.

Performance Evaluation of Steel Slag as Natural Aggregates Replacement in Asphaltic Concrete

Abstract

Steel slag is one of the industry wastes engineered into road construction material. This study was carried out to evaluate the performance of steel slag aggregates as road construction material and its performance compared to granite aggregates. The steel slag aggregates were tested for its physical and mechanical properties. Two dense mix designs incorporating penetration grade 80/100 bitumen and one porous mix design incorporating penetration grade 60/70 bitumen were used to produce the specimens for testing. The dense mix specimens are referred to as 100% Steel Slag Dense Asphalt (SSDA) and 50% Steel Slag 50% Granite Dense Asphalt (SSGDA) while the porous mix specimens are referred to as Steel Slag Porous Asphalt (SSPA). During the first phase of the study, SSDA and SSGDA were tested for performance evaluation through resilient modulus, dynamic creep, Marshall stability and indirect tensile strength. Apart from the tests stated (except for indirect tensile strength), SSPA were also tested for abrasion loss and water permeability. In the second phase of the study, the same tests as those carried out in the first phase were carried out on aged specimens. Resistant against permanent deformation and low temperature cracking improved after aging for both dense mixes and porous mixes. Test results revealed that steel slag inhibits great potential as road construction material.

Chapter 1

Introduction

1.1 Introduction to Steel Slag

Enormous quantities of waste materials are generated every year in Malaysia. As the country's population and industries grow, so do the amount and type of waste materials generated. Schroeder (1994) reported that many of these waste materials were non-decaying elements and will remain in the environment for hundreds and perhaps thousands of years. This situation combined with the ever increasing consumer population and demand, has resulted in a waste disposal crisis. The facts about reduced cost on extracting and processing new raw material and consumption of virgin materials through reusing these materials are stated in various studies since the past decades. Engineering waste materials innovatively and effectively into road construction materials can address concerns about the vast quantities of useful materials being discarded and wasted. One of these waste materials which could be made into good use for road construction is steel slag.

See and Hamzah (2002) also reported that steel slag amounts to approximately 10% of liquid steel output in a typical steel producing plant and represents the major waste item generated from the steel making industry. The cost for committing to an environmental friendly disposal plan can add tremendous burden to the industry. The solutions to this crisis lie in recycling and engineering these waste materials into useful products and reuse them for constructions and developments of the nation.

Steel slag is a by-product of the steel producing process, containing fused mixtures of oxides and silicates. Its highly compressed structure resulted in a very dense and hard material. It is the coarse portion of the residues produced during the separation of the molten steel from impurities in steel making furnaces (See and Hamzah, 2002). Steel slag occurs to be in liquid melt of complex solution containing silicates and oxides, primarily calcium, iron, unslaked lime and magnesium and solidified upon cooling (TFHRC, 2002)

Ali et al (1992) pointed out that steel slag asphalt concrete mixes have been used in countries such as the United States, England, Japan and Canada, particularly in areas with high concentration of iron and steel production. The use of steel slag as an aggregate substitute to natural aggregates is considered a standard practice in many jurisdictions, with applications that include its use in granular base, embankments, engineered fill, highway shoulders, and hot mix asphalt pavement. Experience gained in southern Ontario since early 1970’s has shown that the use of steel slag in asphalt concrete provides the advantageous features of the steel slag which results in high quality mix.

1.2 Objectives

The aim of this research is to study the performance of steel slag as road pavement aggregates compared to the conventional use of granites for the same purpose. The detailed objectives are outlined below:

(1) To assess the performance of dense bituminous mix prepared using 100% steel slag (SSDA) and dense bituminous mix incorporating a combination of 50% granite and 50% steel slag (SSGDA).

(2) To appriase the performance of porous asphalt incorporating steel slag (SSPA) as road pavement aggregates compared to the performance of conventional porous asphalt incorporating granite aggregates (GPA).

(3) To evaluate the effect of moisture, temperature and aging on the performance of mixes incorporating steel slag.

(4) To compare the performance of SSDA and SSGDA with dense bituminous mix incorporating 100% granite aggregates (GDA) and to compare the performance of SSPA with porous bituminous mix incorporating 100% granite (GPA) .

1.3 Justification of Research

Steel slag aggregate is a 100% recycled and engineered product with great potential as replacement to naturally occurring aggregates in road construction projects due to its physical and chemical properties. Most projects involving steel slag aggregate were incorporating this aggregate type in lower quality applications such as road base rather than wearing course. However, steel slag aggregate was reported to exhibit higher porosity, superior adhesion with binder due to its surface structure and chemical content, and favorable shapes. Pores continuity in steel slag aggregate may improve the water permeability in asphalt mixes and improve the skid resistance and aquaplaning, while the superior adhesion with bitumen may address the problem of stripping and moisture related damage on pavement. These characteristics may improve the performance of asphalt mixes and road safety level. Previous studies also suggested that asphalt mixtures incorporating steel slag aggregate may also improve the resistance against rutting and cracking.

From the economic point of view, utilization of steel slag as road construction aggregate may reduce the cost of extracting and processing naturally occurring aggregates. The steel producing industry may also reduce their cost for treating and disposing the vast number of steel slag stockpiles. Since the early days of Malaysian roads development, economic factor had played a major role in deciding the routes and qualities of paved roads. Malaysian road authorities activated a huge amount of funding to preserve the road structures in this country. Hundreds of millions Ringgit Malaysia had been allocated for road constructions and maintenances in every Malaysian Plan. While the lifespan of a pavement may be increased, the maintenance cost for pavements may also reduce, thus providing more funds for other development projects.

On its impact at preserving the environment, utilization of steel slag aggregate in various ways may directly reduce both the dependent on naturally occurring aggregate and the number of raw material-extracting projects. On the other hand, incorporating steel slag in road construction projects may reduce the area used as landfill.

1.4 Scope of Work

The scope of work for this research is to develop bituminous mixes compatible or out performing existing conventional bituminous mixes, using steel slag and a combination of 50% steel slag and 50% granite as aggregates.

The mix type investigated was a dense mix confirming to the JKR ACW14 gradation using 100% steel slag (SSDA), 100% granite (GDA) and combination of 50% steel slag and 50% granite (SSGDA). Bitumen penetration grade 80/100 was incorporated as the binder for all dense mix design. The performance of GDA stated in this study was obtained from Mohamed (2007) and used as a comparison to the performance of SSDA and SSGDA. Besides, porous mixes confirming to the gradation developed by Samat (2006) using 100% steel slag (SSPA) and 100% granite (GPA) were also studied. For porous mixes, the binder type used was penetration grade 60/70. Darin Asphalt Modified Additive (DAMA) was also incorporated in both mixes in the form of a dry process. DAMA was developed by Darin Tech Corporation Ltd., Korea. A detailed description of DAMA is available elsewhere (Samat, 2006).

Steel slag aggregates were obtained from the Natsteel plant at the Prai Industrial Area. These aggregates were selected from two different stockpiles of coarse aggregates (> 10mm) and fine aggregates (< 10mm). These aggregates were then crushed and sieved into their designated bins.

A range of tests was carried out to evaluate the mix properties and performance, including obtaining volumetric properties, the optimum binder content, stability, potential of cracking and permanent deformation, susceptibility to moisture, water permeability and abrasion loss. These testing procedures were repeated for specimens subjected to accelerated ageing process in a force draft oven to evaluate their performance under service. The test results of mixes incorporating steel slag aggregates were then compared with those of conventional mixes.

1.5 Organization of the Thesis

An introduction to this research is presented in chapter one. This chapter briefly outlined the objectives and scope of work to fulfill the necessary evaluation of steel slag aggregates as road construction material.

The studies on steel slag as road construction material had been continuously carried out in an advancing manner. An overview of previous studies on the feasibility, performance and suitability of steel slag aggregates as road construction material is summarized in the next chapter. Various topics regarding aggregates properties, mix designs, testing methods and test results compiled in laboratory and field tests from these studies and researches are related in this chapter.

A description of the materials used in this research is narrated in chapter three. Included in the discussions are the naturally occurring granite aggregate, the engineered steel slag aggregate, fillers and additive used to produce the test specimens. The different properties inhibited by steel slag aggregate and their relationship to the acceptability of steel slag as road construction material is also detailed in this section. On the other hand, the handling of the materials and methods used for mixture design and testing of the test specimens are crucial to obtain consistent outcome. The procedures for preparing SSPA, SSDA and SSGDA specimens are outlined in the fourth chapter of this thesis. Once the specimens are designed, their engineering properties and performances need to be determined. These testing methods and analysis techniques are also related in this chapter.

The mix design parameters including the volumetric properties of mixes incorporating steel slag are evaluated, and analysis of the results is discussed in chapter four. The patterns of these results, including the advantages and shortcomings are then studied and compared between steel slag bituminous mixes and granite bituminous mixes. Through the compilation of results in the form of figures and tables, the analysis provides the optimum binder content for the steel slag mixes and a better view of the best possible way to cooperate these mixes into practical usage.

Apart from the tests mentioned in chapter four, there are several other tests conducted to thoroughly evaluate the mechanical properties of mixes incorporatng steel slag aggregates. These test results in chapter five provides a prediction on the performance of these mixes including the tensile strength and creep behaviour under simulation of the service conditions. The effects of moisture susceptibility and temperature on the specimens tested are also available. Moisture is one crucial factor which influences the performance and lifespan of a pavement. In places with very cold climate, the presence of moisture in the pavement structure could mean intensive damage due to ice and cracking. Besides, there are also discussion on the matter of possible loss of bonding between aggregate and asphalt due to moisture. Temperature changes affected the viscosity of asphalt hence playing a role in affecting the performance of the mixes.

The durability of steel slag mixes are put to the test through the accelerated aging process and the results obtained are discussed in chapter six. The simulated performance of steel slag mixes after seven to ten years in service is evaluated and detailed in this part of the thesis.

The conclusions provided a clear view of the achieved objectives and justifications of this research. Besides, a list of scope and possibility of improvements related to this study for further researches is also enclosed in chapter seven.

Chapter 2

Literature Review

2.1 Introduction

Asphalt mixture designs around the world were developed on the basis of producing the most suitable combination of aggregate and binder which provides the best performing roads with the longest possible lifespan. The designated mixture must suits the respective geological and climate conditions, traffic and economy demands, and interpolations of future developments. A good design of bituminous mix was expected to result in a mix which is adequately strong, durable, and resistive to damages due to either traffic loads or climate changes, environmental friendly, economical and any other related criteria.

Mix designs were achieved by putting test mix specimens with varied proportions through numerous tests and finalized the best one which complied with the set requirements. This process often resulted in a balance mixture incorporating mutually conflicting parameters. One of the most crucial aspects of mix design is to obtain the most qualified materials and engineered it into an ideal aggregate for road construction. For centuries, the aggregates used for road constructions were naturally occurring rocks and the most frequently used were granites. Nevertheless, contemporary studies have unearthed more synthetic and artificial materials fit to qualify as aggregates for road construction.

2.2 Efforts in Utilizing Waste Materials as Construction Materials

The United States of America had been one of the earliest nations utilizing waste and recycled materials in the construction field. These efforts were continuously documented since decades ago. A recent report entitled 'Transportation: Leading in Recycling' (AASHTO, 2003) reported the following efforts by various road authorities in the United States on the matter of utilizing recycled materials in road constructions:

(a) The Texas Department of Transportation (TxDOT) had spent more than USD 506 million on 'green products' and diverted more than 13 million tons of materials from the landfill since launching its recycling program in 1994.

(b) Pennsylvania Department of Transportation (PennDOT) started the Strategic Recycling Program as a comprehensive effort to systematically identify, evaluate, and implement recycling opportunities throughout Pennsylvania. They also worked in hand with the state Department of Environmental Protection to reduce waste materials from transportation operations and to encourage use of recycled materials throughout transportation applications in the state.

(c) The Massachusetts State Transportation Agency (MassHighway) reported an impressive statistics, including recycling more than 15,000 tons of waste and more than 111,000 tons of recycled materials were used in construction projects. Overall, nearly USD 27 million was spent on recycled-content and environmentally preferable materials and products.

(d) The California Department of Transportation (Caltrans) recycled asphalt and concrete pavement by converting it into base and sub-base under the new road surface, and at the same time the agency is looking for new ways to use recycled materials in road surfaces.

In an effort to study the utilization of recycled materials in road constructions, the University of Texas in Austin, United States of America (USA) undertook three substantial and creative research initiated by their Center of Transportation Research (CTR) from the Cockrell School of Engineering on behalf of the Texas Department of Transportation (TxDOT) involve old tires, used copier and printer toner, and fly ash (CTR, 2002).

Combs (2001) quoted in a fiscal note that recycled materials commonly used by TxDOT included recycled asphalt pavement (RAP), which was made by taking the top layer of existing asphalt during road expansion or replacement and separated it, dried it and mixed it with new asphalt pavement and according to the United States Environmental Protection Agency, more than 80 million tons of RAP were placed back into new roads, shoulders and embankments in the USA each year.

Efforts in minimizing the wastage of reusable materials in construction projects were evenly comparable across the Atlantic Ocean. The Europeans had started using recycled materials especially in road constructions since the 1970s. A number of countries in Europe had been routinely using recycled materials with a high degree of success. The most remarkable thing about the European experience was that the recycling rate of materials in the highway environment frequently reaches 100 percent. The utilization of recycled materials in Europe had even matured beyond the standard set by the Americans. Remarkable efforts in utilizing recycled materials were reported in Germany, Sweden, Denmark and Netherland due to respective social, economy and geological requirements. These efforts were mentioned by Holtz and Eighmy (2000) in a report for Federal Highway Administration (FHWA).

2.2.1 Utilization of Waste Materials in Road Constructions

Noureldin and McDaniel (1989) mentioned that the demand for good quality highway materials continued to increase whereas economical sources were becoming more limited. This demand became more critical, especially with the policy (adopted by some USA state highway departments) of banning some aggregate types that had been frequently used in the past for producing paving mixtures.

Davio (2000) stated that according to the United States Geological Survey (USGS), more than 330 million tons (300 million metric tons) of crushed stone were used in road base during 1996. The mining of such stone, however, was being constrained by urbanization, zoning regulations, increased costs, and environmental concerns. In some parts of the United States, the supply of local stone was exhausted, requiring long hauls and higher prices

Davio (2000) also reported that several alternative materials were incorporated into the mix design of road construction projects besides naturally occurring aggregates since decades ago and among them were blast furnace slag, steel slag, plastic, glass, ashes, reclaimed concrete, reclaimed asphalt concrete or reclaimed asphalt pavement and scrap tires.

Schroeder (1994) reported that in 1992, 6.9 million metric tons (7.6 million tons) of steel slag was sold in the United States at a total value of USD21.9 millions. The average selling price for steel slag at the plant was USD3.02 per metric ton. Besides, Schroeder (1994) also quoted a statement from the Bureau of Mines reporting that some 14 million metric tons of blast furnace slag were sold in the United States in 1992 and out of this value, 90% were air-cooled slag primarily used in road constructions. In other cases, plastics were recycled and used as polyethene additive in asphalt mix designs.

Holtz and Eighmy (2000) stated that in the United States, the process of recycling waste materials were estimated to be producing between 352 million tons (320 million metric tons) and 859 million tons (780 million metric tons) recycled materials per year. When compared to the use of new materials in highway construction which was estimated to be about 350 million tons (317.5 million metric tons) per year of which 320 million tons (290 million metric tons) were used as aggregate in the mid-1990s, Holtz and Eighmy (2000) mentioned it was obvious that there were potentially a number of recycled materials that could be considered as substitutes provided that they were economical, met engineering and environmental specifications, and performed as well as traditional materials in the field.

In Sweden, a large country with a relatively low population density and high aggregate availability, 45% blast furnace slag, 100% steel slag and 95% RAP were reused in road constructions. Germany, a larger country with much industry and high aggregate availability, incorporated 100% blast furnace slag, 92% steel slag, 97% coal bottom ash, 88% coal fly ash, 69% municipal solid waste combustion bottom ash, and 55% RAP into road constructions. While, Denmark, with a high population density and low natural aggregate availability, utilized 100% steel slag, 81% crushed concrete, 100% coal bottom ash, 100% coal fly ash, 100% RAP in road constructions and finally, the Netherlands, a populous country with more limited aggregate resources and a high degree of industrialization, had a 100% recycling rate in several categories. 100% of all recycled materials were engineered into construction materials due to their close loop recycling policy where recycled and waste materials were continually reused without wastage (Holtz and Eighmy, 2000).

The utilization of recycled materials in road construction started to gain attentions in country which previously considered these secondary materials as inferior products only fitted for marginal applications. New Zealanders, due to less availability of natural sources in recent times, initiated their first stretch of pavement incorporating 100% recycled materials through Fulton Hogan in 2003 (Slaughter, 2005).

In Japan, the Japan Iron and Steel Federation (JISF) and Nippon Slag Association (NSA) have promoted the institution and widespread adoption of Japan Industrial Standards (JIS). As a result, 99% of slag was useful material and employed by national agencies such as the Ministry of Land, Infrastructure and Transport and by local governments and other users, and it had gained both high acclaim and certification (NSA, 2006).

Using recycled materials in road construction offered opportunities to use huge quantities of recycled materials while extending the supply of traditional construction materials and ensuring good-quality roads. The United States Geological Survey (USGS) calculated that even though the use of recycled crushed concrete aggregates increased by 170 percent between 1994 and 1996, it still constituted only 0.4 percent of the total aggregates consumed in 1995 (Davio, 2000).

2.2.2 Advantages of Utilizing Waste Materials in Road Construction

Recycled materials can be a source of good quality, cost effective road materials that also benefit the environment. Using recycled materials can frequently improve materials performance and reduce the rate of natural resources depletion. Using recycled materials may also cut costs because materials costs may be less than new materials; transportation/delivery costs may be less; and disposal costs for job-site materials may be less. Utilization of recycled materials benefits the environment by extending the life of limited natural resources, reducing air and water pollution, and extending landfill life. The use of waste materials (recycling) in the construction of pavements has benefits in not only reducing the amount of waste materials requiring disposal but can provide construction materials with significant savings over new materials. The use of these materials can actually provide value to what was once a costly disposal problem (USACE, 1999 and, Wilburn and Goonan, 1998).

2.2.3 Problems Concerning Utilization of Recycled Materials in Road Constructions

Utilization of recycled materials might address the problems concerning the environment and exhaustion of naturally occurring aggregates, but there are still a few concerns raised by researchers regarding leaching, future reusable value, production cost and availability, properties, quality control and consistency as mentioned by Kandhal (1992).

The United States Environmental Protection Agency (USEPA) Office of Solid Waste mentioned their concern over the potential environmental damage caused by mishandling of recycled materials in a very recent report. The concerns included leaks, spills, dumps or other types of hazardous substances released into the environment, which were serious enough to require some type of cleanup actions (USEPA, 2007).

Wilburn and Goonan (1998) mentioned that comprehensive planning should be done before recycling operation began to avoid premature failure. They feared that without proper site layout, equipments, operator efficiency and creative marketing, the whole project may go into abrupt.

2.3 Material Description of Steel Slag

The German Research Association for Iron and Steel Slag described steel slag as a non-metallic by-products generated from the non-metallic constituents of the raw materials ore, coke and fluxes during the production of steel. After slow cooling in air they form an artificial crystalline rock. Their formation was comparable to that of natural magmatic rocks like basalt or granite. Molten slag fulfilled important metallurgical functions and must be distinguished from ashes which were residues of incineration processes. Steel slag was separated from the liquid metal at the end of the metallurgical treatment by means of their lower density. The separated slag underwent appropriate heat treatment processes followed by mechanical processing to provide the specific properties required by standards and regulations (FEhS, 2004).

The Japan Iron and Steel Federation and Nippon Slag Association narrated that the steel-making process consists of refining pig iron, scrap and other material to produce steel, either in a basic oxygen furnace or an electric arc furnace. Steel slag (basic oxygen furnace slag and electric arc furnace slag) was the by-product generated from this steel-making process, in amounts of 110 to 120 kg per ton of crude steel (NSA, 2006).

See and Hamzah (2002) on the other hand described steel slag as a by-product generated during steel making due to addition of flux such as lime during the melting process. The flux reacted with the oxides or any inorganic non-metallic components present in the metallic scrap and formed complex minerals comprising of various forms of metal oxides silicates, ferrites and others.

2.4 Source of Steel Slag

Steel slag could normally be obtained from slag processors who collected the slag from steel-making facilities. Slag processors handled a variety of materials such as steel slag, ladle slag, pit slag, and used refractory material to recover steel metallic. These materials were source separated, and well-defined handling practices were in place to avoid contamination of the steel slag aggregate. The slag processors were also aware of the general aggregate requirements of the end user (Liz Hunt and Boyle, 2000).

FHWA mentioned that the processing of steel slag from metals recovery was not only important to remove excess steel at the source for reuse at the steel plant, but was also important to facilitate the use of the nonmetallic steel slag as construction aggregate. This nonmetallic slag could either be crushed, then screened for aggregate use (steel slag aggregates), or sintered and recycled as flux material in the iron and steel furnaces (TFHRC, 2002).

2.5 Production of Steel Slag

Steel Slag was generated as a melt at about 1650°C during steelmaking from hot metal, direct reduced iron or scrap. It consisted of oxidized co-elements of the hot metal and other metallic charges which reacted with the added limestone and dolomite. Depending on the process technology, one could distinguish Basic Oxygen Furnace (BOF), Open Hearth, and Electric Arc Furnace (EAF) slag (FEhS, 2004).

There were several different types of steel slag produced during the steel-making process. These different types were referred to as furnace or tap slag, raker slag, synthetic or ladle slag, and pit or cleanout slag. Figure 2.1 presented a diagram of the general flow and production of different slag in a modern steel plant. The steel slag produced during the primary stage of steel production was referred to as furnace slag or tap slag. This was the major source of steel slag aggregate. After being tapped from the furnace, the molten steel was transferred in a ladle for further refining to remove additional impurities still contained within the steel. This operation was called ladle refining because it was completed within the transfer ladle. During ladle refining, additional steel slags were generated by again adding fluxes to the ladle to melt. These slags were combined with any carryover of furnace slag and assist in absorbing deoxidation products (inclusions), heat insulation, and protection of ladle refractories. The steel slags produced at this stage of steel making were generally referred to as raker and ladle slags (TFHRC, 2002).

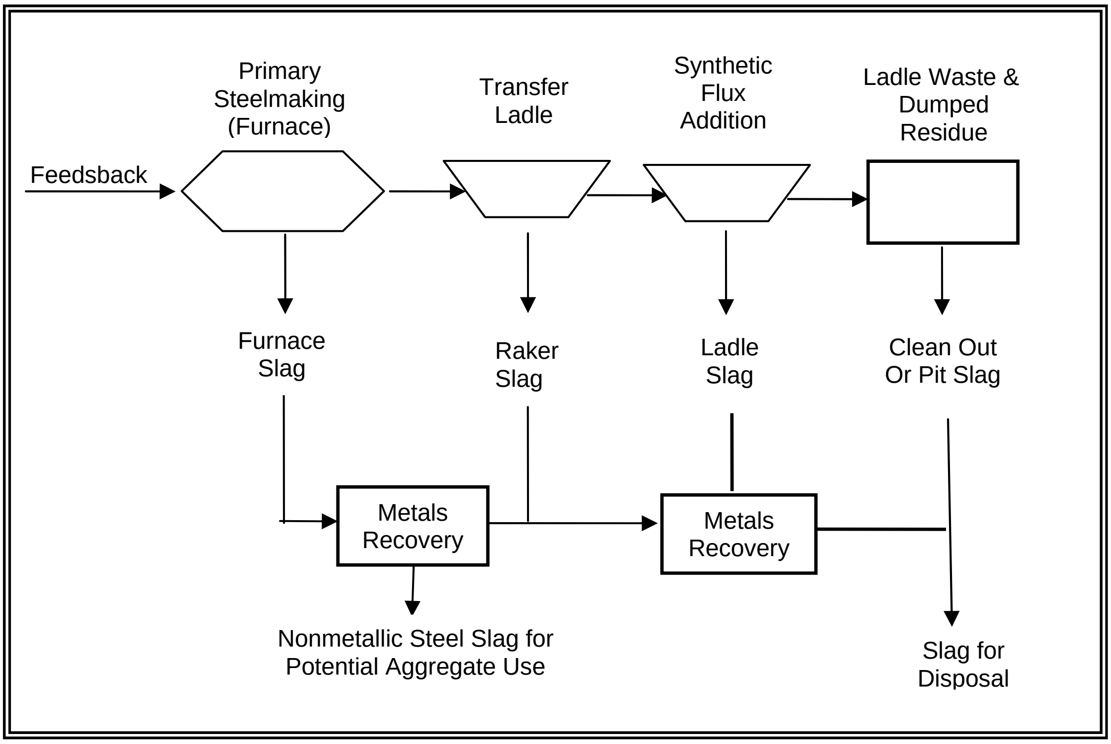

Figure 2.1: Overview of Steel Slag Production in A Modern Intergrated Steel Plant. (TFHRC, 2002)

According to See and Hamzah (2002), the most commonly found steel slag in Malaysia is EAF slag. This slag was formed from re-melting of steel and iron scrap. EAF method utilized high voltage current to melt the scrap. This method involved the removal of excess carbon, silicon and other elements from the molten iron. This process was aided by the addition of lime as part of the flux which serves to combine the unnecessary constituents contained in the iron source and separated them (i.e. the resulting slag) from the molten steel.

In the basic oxygen process, hot liquid blast furnace metal, scrap, and fluxes, which consist of lime (CaO) and dolomitic lime ($CaO.MgO$ or “dolime”), were charged to a converter (furnace). A lance was lowered into the converter and high-pressure oxygen is injected. The oxygen combined with and removed the impurities in the charge. These impurities consisted of carbon as gaseous carbon monoxide, and silicon, manganese, phosphorus and some iron as liquid oxides, which combined with lime and dolime to form the steel slag. At the end of the refining operation, the liquid steel is tapped (poured) into a ladle while the steel slag was retained in the vessel and subsequently tapped into a separate slag pot (TFHRC, 2002). Both EAF and BOF processes of producing steel slag are presented in Figure 2.2.

Both BOF and EAF steel slag inhibited similar physical and chemical properties. The chemical composition of steel slag varied with the steel making practice and the quality of steel being produced. However, in accordance with the description from FHWA, there were many grades of steel that can be produced, and the properties of the steel slag can change significantly with each grade. Grades of steel can be classified as high, medium, and low, depending on the carbon content of the steel. High-grade steels had high carbon content. To reduce the amount of carbon in the steel, greater oxygen levels were required in the steel-making process. This also required the addition of increased levels of lime and dolime (flux) for the removal of impurities from the steel and increased slag formation (TFHRC, 2002).

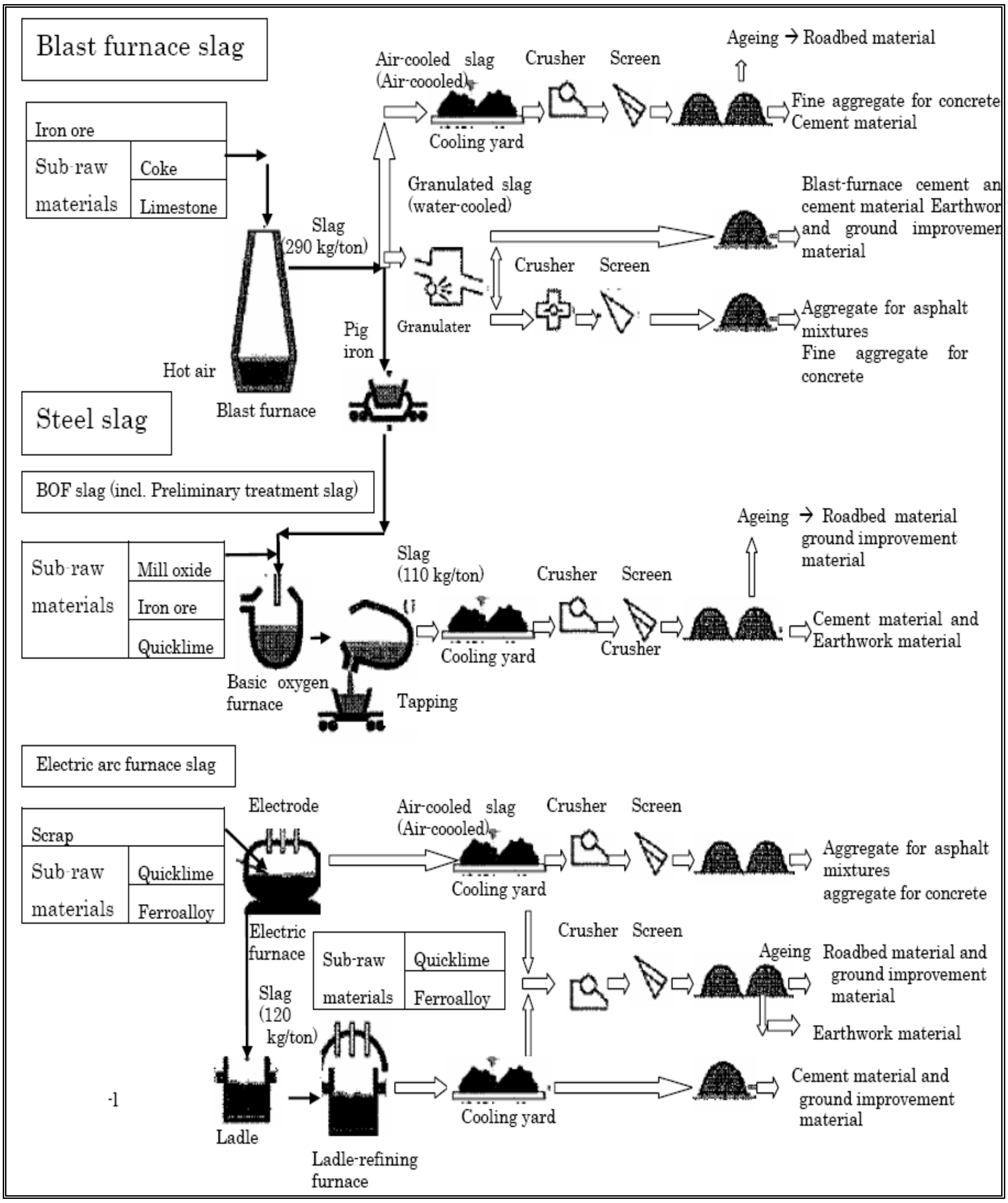

Figure 2.2: Flow Diagram of Steel Slag Production Through BOF and EAF (NSA, 2006).

2.6 Properties of Steel Slag

Different properties of various aggregates influenced their level of performance and suitability for an application. The physical and mechanical characteristic of an aggregate played an important role in providing the ideal durability, permeability, stability and resistance against abrasion, cracking, and permanent deformation. Besides, the chemical composition of an aggregate was continuously studied and found to be a factor affecting its adhesion with other construction material to form an ideal combination.

2.6.1 Physical and Mechanical Properties

Earlier tests by See and Hamzah (2002) on the 20 mm and 10 mm steel slag stockpiles revealed the physical and mechanical properties presented in Tables 2.1 and 2.2 respectively. These properties were measured at the Highway Engineering Laboratory of the School of Civil Engineering, Universiti Sains Malaysia following test procedures in the appropriate British Standards (BS) and ASTM standards. The results were then compared to the Jabatan Kerja Raya (JKR) or Public Works Department specifications.

Table 2.1: Steel Slag and Granite Physical Properties and JKR Specifications (See and Hamzah, 2002)

Parameter	Steel Slag Property	Granite Property	JKR Specifications	Reference Document
Water absorption (20 mm)	1.2%	0.51%	Not exceeding 2%	SPJ88 (JKR, 1988) Arahan Teknik 8/85 (JKR, 1985)
Water absorption (10 mm)	2.8%	0.75%	Not exceeding 2%	SPJ88 (JKR, 1988) Arahan Teknik 8/85 (JKR, 1985)
Flakiness Index	4	19	Not exceeding 30	SPJ88 (JKR, 1988) Arahan Teknik 8/85 (JKR, 1985)

Table 2.2: Steel Slag and Granite Mechanical Properties and JKR Specifications (See and Hamzah, 2002)

Parameter	Steel Slag Property	Granite Property	JKR Specifications	Reference Document
ACV	26.05	26.10	Not exceeding 30	SPJ88 (JKR, 1988)
AIV	17.20	20.54	-	-
LAAV	9.80	9.80	Not exceeding 60	Arahan Teknik 8/85 (JKR, 1985)
Soundness	No disintegration	5.2	Not exceeding 12	SPJ88 (JKR, 1988)
PSV	56.6	52.7	Not less than 40	SPJ88 (JKR, 1988)
Resistance to Stripping	> 95% coated area	-	Not less than 95% coated area	SPJ88 (JKR, 1988)

See and Hamzah (2002) commented on each property as the following stated:

(a) The flakiness index at 4% for steel slag aggregates was considered very low. This indicated that steel slag aggregates were largely consisted of rounded shape aggregates. Such character together with the high surface roughness of steel slag provided much improved interlocking properties when the bitumen mixture of steel slag aggregates is compacted compared to granite aggregates.

(b) The Aggregate Crushing Value (ACV) and Los Angeles Abrasion Value (LAAV) of the steel slag aggregates were all within the JKR specifications. These indicated that the material possess sufficient strength for utilization as road construction aggregates.