

Experimental Study of Steel Slag Used as Aggregate in Asphalt Mixture

Magdi M. E. Zumrawi, Faiza O. A. Khalill

Abstract—Steel slag is a by-product of the steel industry and can be used potentially as aggregate in the asphalt mixture. This study evaluates the use of Steel Slag Aggregates (SSA) as a substitute for natural aggregates in the production of hot mix asphalt (HMA) for road construction. Based on intensive laboratory testing program, the characteristic properties of SSA were assessed to determine its suitability to be used in HMA. Four different percentages (0, 50, 75, and 100%) of SSA were used, and the proposed mix designs for HMA were conducted in accordance with Marshall mix design. The experiment results revealed that the addition of SSA has a significant improvement on the properties of HMA. An increase in density and stability and a reduction in flow and air voids values were clearly observed in specimens prepared with 100% SSA. It is concluded that the steel slag can be considered reasonable alternative source of aggregate for concrete asphalt mixture production.

Keywords—Aggregate, asphalt mixture, stability, steel slag.

I. INTRODUCTION

STEELslag has been used to construct pavements for nearly one hundred years. Since it was discovered that the residue from the manufacture of steel could be crushed and processed into a product that looked like a crushed rock, research were started to investigate the usefulness of this “waste” product. In Sudan, Giad factory in Khartoum produces significant quantities of steelmaking slag as the major waste during the manufacture of iron and steel. The estimated daily production of steel slag is 15–20 tons. The disposal of steel slag in landfills may cause environmental hazards. The material produced by crushing and screening is the Steel Slag Aggregate (SSA).

In hot asphalt mixes (AHM), the physical and mechanical properties of the used aggregates play the major role in determining the overall properties of the mixtures. It is found that these required properties for AHM are found in the SSA, [1], [2]. The use of steel slag as an aggregate substitute to natural aggregates is considered a standard practice in many countries. The incorporation of steel slag as an AHM aggregate has been evaluated extensively in many parts of the world, but not yet in Sudan. To consider the use of SSA in Sudan, local materials, climate, and specifications must be taken into account. Therefore, it is imperative to carry out a comprehensive study, based on local materials and conditions, of the feasibility of utilizing the steel slag produced by

steelmaking factory in Khartoum as a replacement for natural aggregate in production of asphalt concrete mixture.

II. LITERATURE REVIEW

A. Steel Slag Production

Metallurgical slag is a waste or by-product formed in metallurgical processes from impurities in the metals or ores being treated. The metallurgical slags are classified in two types; ferrous and nonferrous slag. The ferrous slag includes iron slag generated in blast furnace process and steel slag produced from various processes (open hearth, basic oxygen and electric arc furnace). The nonferrous slag such as copper and nickel slag [3]. The Steel slag is defined by Kalyoncu [4] 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”.

Processing of steel slag for steel recovery is very important as it results in an angular, generally well-graded, material that is relatively free of metallic, and the recovered steel (2 to 4% of raw steel production) is a valuable scrap, [5]. There are several different types of steel slag produced during the manufacturing process, including furnace slag, raker slag, ladle slag, and cleanout or pit slag [6]. Fig. 1 shows a diagram of the general flow and production of different slag in a modern steel plant.

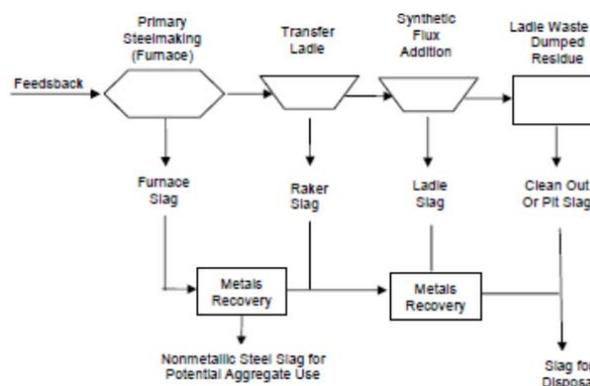


Fig. 1 Steel slag production in a modern integrated steel plant [6]

In the past, the application of steel slag was not attractive because vast volumes of blast furnace slag were available. Steel slag has been used commercially since the mid-19th century. Recently, due to availability of electric furnace steel throughout the world, also the growth of available amounts of this type of waste, steel slag is becoming increasingly

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important, while the application of steel slag is also rapidly growing in the developed countries, particularly in areas with high concentration of iron and steel production such as the United States, England, Japan, and Canada.

Extensive research, nowadays, play a vital role to remove steel slag from industrial waste into modern industrial product which is effectively used for many industrial purposes, especially as raw material in road construction, [7], [8]. Particular attention has been directed at investigating the possibilities of using it as a substitute for natural mineral aggregates when producing asphalt mixtures. Even the old Romans used slag from furnaces in the construction of Roman roads in the Sussex District in England [5]. Recently, the use of steel slag as an aggregate substitute to natural aggregates is considered a standard practice in many countries. In the USA slag is used from the first half of the 19th century as road construction material, from the second half of the 19th century as railway ballast and in cement industry, and from the beginning of the 20th century as aggregate for asphalt mixtures [9].

B. Steel Slag Properties

Different properties of various aggregates influenced their level of performance and suitability for an application. The physical and mechanical characteristic of an aggregate played a significant role in providing the ideal durability, permeability, stability and resistance to 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. The National Slag Association (NSA) [10] along with the Federal Highway Administration (FHWA) [11] has documented some of the characteristics properties of steel slag.

1. Physical Properties

Steel slag aggregates (SSA) are highly angular, roughly cubical pieces having flat or elongated shapes. They have rough vesicular nature with many non-interconnected cells which gives a greater surface area than natural aggregates of equal volume; this feature provides an excellent bond with bitumen, [10]. The rough textured surface of SSA provides the particle interlock, and if properly compacted, the high stability required for good serviceable pavements can be attained. Moreover, SSA particle exhibits higher porosity, superior adhesion with binder due to its surface structure and chemical content, and favorable shapes. Pores continuity in SSA may improve the water permeability in asphalt mixes and improve the skid resistance while the superior adhesion with bitumen may address the problem of stripping and moisture related damage to pavement. SSA has high bulk specific gravity and less than 3% water absorption. Also, SSA exhibits high density, but apart from this feature most of the physical properties of steel slag are better than hard traditional rock aggregates.

GeoPave [12] pointed out that steel slag aggregates are strong and durable materials. They have an excellent angular

shape that helps to develop very strong interlocking properties. They have high resistance to abrasion and impact.

2. Chemical Properties

The chemical composition of steel slag is a complex matrix structure consisting primarily of simple oxides determined from elementary analysis of x-ray fluorescence. According to Emery [13], steel slag usually contains four major oxides, namely lime, magnesia, silica, and alumina. Minor elements include sulfur, iron, manganese, alkalis and trace amount of several others. Table I shows the list of various ranges of compounds presents in steel slag as reported by Emery [13].

TABLE I
CHEMICAL COMPOSITION OF STEEL SLAG [13]

Constituent	Open Hearth Steel Slag	Basic Oxygen Steel Slag
Calcium oxide (CaO)	25.8	41.3
Silicon dioxide (SiO ₂)	16.4	15.6
Iron (FeO or Fe ₂ O ₃)	26.0	20.0
Magnesium oxide (MgO)	10.0	6.9
Manganese oxide (MnO)	11.2	8.9
Aluminum oxide (Al ₂ O ₃)	2.4	2.2
Titanium dioxide (TiO ₂)	0.8	0.5
Free lime (free CaO)	2.1	3.3

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 [11], 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 [6].

3. Mechanical Properties

According to The Federal Highway Administration (FHWA) [11] the processed steel slag has favorable mechanical properties for use as aggregates in construction; these include good abrasion resistance, good soundness characteristics, and high bearing strength. These properties greatly improve the performance of asphalt mixes and road safety level. SSA exhibits less susceptibility to abrasion due to its high particle density, allowing it to provide better skid resistance than the natural aggregate. Steel slag has a high degree of internal friction and high shear strength. FHWA [11] has documented the general mechanical properties of steel slag as given in Table II.

C. Previous Investigations

Many researchers have investigated the use of steel slag in asphalt concrete. The previous studies have been conducted on HMA with the varied percentage of SSA. Most of the studies were concerned with the utilization of steel slag in HMA as a coarse aggregate replacement [1], [5], [16]-[18]. The effects of steel slag on the performance of asphalt concrete are reviewed below.

TABLE II
MECHANICAL PROPERTIES OF STEEL SLAG [11]

Property	Value
Los Angeles abrasion (ASTM C131), %	20 - 25
Sodium sulfate soundness loss (ASTM C88), %	< 12
Angle of internal friction	40° - 50°
Hardness (measured by Moh's scale of mineral hardness) ¹	6 - 7
California bearing ratio (CBR), % top size 19 mm (3/4 inch) ²	Up to 300

¹ The hardness of dolomite measured on the same scale is 3 to 4.

² Typical CBR value for crushed limestone is 100%.

United States have extensive experience with the addition of steel slag to HMA. Their experiences indicate that the addition of steel slag may enhance the performance characteristics of the pavement. In asphalt mixtures, the steel slag is usually added as part of the coarse aggregate fraction of the mixture at a percentage of 20% to 100%, depending on the application of the mixture. Since the slag is rough, the material improves the skid resistance of the pavement. Also, because of the high specific gravity and angular, interlocking features of the crushed steel slag, the resulting HMA is more stable and resistant to rutting [1], [14], [15].

Ahmedzade and Sengoz [16] evaluated the effect of steel slag in HMA with 100% coarse aggregate (limestone) replaced by SSA. They observed improved fatigue resistance as the steel slag mix exhibited higher indirect tensile strength and modulus values than the coarse aggregate mix. Pasetto and Baldo [17] conducted a study on steel slag in HMA by substituting the natural aggregate at 0%, 30%, 60%, and 90% SSA based on the total aggregate weight. The substitution included both coarse and fine aggregate particles. It was found that all the slag mixes exhibited better rutting resistance than the control mix under repeated axial loads. However, the 90% SSA mix performed better than all the other slag mixes.

Due to its high levels of hardness and angularity, steel slag is able to improve skid resistance. Kehagia [18] carried out a study on the skid resistance of a thin wearing surface using three different mixes: 100% slag mix, partial slag replacement mix, and a natural aggregate mix. Skid resistance was measured four months and one year after installation on a high traffic highway in Greece. After one year, all the slag mixes had outperformed the natural aggregate mix. The mix with 100% slag exhibited the best skid resistance. The minimum allowable skid number on this type of roadway was 35. After one year of service, the value for the 100% slag mix section ranged from 58 to 64, whereas the section with partial slag replacement varied from 48 to 60. The natural aggregate section without steel slag displayed acceptable numbers from 40 to 57. The study showed that steel slag can improve HMA roadway conditions.

Based on the results of the previous studies reviewed, adding steel slag in HMA has a significant improvement on the mechanical properties of the mix in terms of resistance to fatigue cracking, rutting and thermal cracking. Improvements in skid resistance also increase the safety of drivers on the roadway. The results indicated from the studies clearly show potential benefits of using SSA in HMA. However, due to

climate and material variations, the use of steel slag in HMA must be investigated using local materials, based on local specifications. Therefore, the aim of this study is to investigate the effects of steel slag in HMA specifically for Sudan local materials and climate.

III. LABORATORY TESTING

As the objective and purpose of this paper are to test the suitability of SSA for its application in the manufacture of asphalt mixtures, an intensive laboratory testing program was conducted. The tests were carried out to determine the characteristic properties of SSA and evaluate them in accordance with the standard specifications. It also presents the details regarding the proposed mix design for HMA that contains SSA. Then it describes in detail the tests of HMA that contains SSA and presents and analyzes the physical and mechanical property tests results.

A. Materials Used

The materials used in testing include asphalt, natural aggregate, and steel slag aggregate. The asphalt used in preparing all specimens of penetration grade 60-70. This asphalt was obtained from asphalt plants belong to road contractors at Toria hill in Omdurman town.

The natural aggregate used in this study is crushed stones of different sizes. This aggregate was collected from the crushing plants at Toria hill.

Steel slag was delivered from the by-product of steel manufacturing at Giad factory in Khartoum. After the steel slag has been crushed and graded to the desired sizes, it was stockpiled for delivery (Fig. 2). The surface texture of the slag was observed to be quite variable, from very dense and solid like basalt, to vesicular like volcanic cinders. SSA samples were selected from three different stockpiles of coarse aggregates, fine aggregates, and mineral filler. The samples of SSA were delivered to the road laboratory at the University of Khartoum.



Fig. 2 Stockpiling of steel slag aggregates at crushing plant

B. Sampling and Testing

The steel slag sample was subjected to crushing and screening into the desired sizes. Samples of steel slag and natural aggregates were prepared to three different sizes; the coarse sizes are 19 to 5 mm, the fine sizes passing sieve no. 4 (4.75mm) and retained on sieve no. 200 (0.075mm) and a filler material of size finer than 0.075 mm.

A series of tests were carried out to determine the quality of asphalt used and the characteristics properties of SSA and

natural aggregates. Laboratory tests conducted on aggregates include gradation, specific gravity and absorption, crushing value, Los Angeles abrasion test. Consistency tests performed on asphalt include penetration, ductility, softening point, kinematic viscosity and specific gravity test. Safety tests of flash and fired points were also conducted on asphalt. The tests were carried out in accordance with ASTM [14].

C. Mix Design

For the evaluation of using SSA in asphalt mixes, Marshall specimens using natural aggregate were prepared at asphalt content 4, 4.5, 5, 5.5, 6% by weight of aggregate to be compared with those prepared with 50, 75 and 100% of SSA. Marshall Specimens were prepared and tested in accordance with ASTM D1559.

For all specimens, aggregate and asphalt were heated at temperatures of 140 and 180 °C, respectively. Specimens were compacted with 75 blows of Marshall's hammer on each side to count for heavy traffic category. Specimens were extracted from the molds and kept at ambient temperature for one day. Necessary data for obtaining the specific gravity, percentage of air voids (VA), voids filled with bitumen (VFB) and voids in Mineral Aggregates (VMA) and to count for stability correction were measured and recorded. These data are mainly the weight in air and water and the height of the specimens. To conduct the Marshall stability and flow tests, the specimens were kept in a water bath at 60°C for 30 minutes. The Optimum Asphalt Content (OAC) values for the specimens prepared with different aggregate combinations were determined according to Marshall Stability, the percentage of air voids and voids filled with bitumen.

D. Results and Discussion

The results of the experiments conducted by measuring the physical properties of asphalt cement are listed in Table III.

TABLE III
PHYSICAL PROPERTIES OF ASPHALT CEMENT USED

Test	Method	Result
Penetration, 0.1mm	ASTM D5	62
Ductility, cm	ASTM D113	100
Softening Point, °C	ASTM D36	58
Kinematics viscosity, cst	ASTM D2170	340
Flash point, °C	ASTM D92	250
Fire point, °C	ASTM D92	320
Specific gravity	ASTM D70	1.03

The steel slag and natural aggregate samples were used to determine the physical and mechanical properties such as abrasion resistance, specific gravity, water absorption, flakiness and elongation, and stripping and coating. The tests results are shown in Table IV.

The abrasion test provides an indication of the relative quality of competence of various sources of aggregate with similar mineral compositions. The abrasion test is used as an indication of aggregate wear resistance. In this case, comparing the steel slag aggregate results to the natural aggregate results illustrate that slag particles show high

resistance to abrasion as given in Table IV. Also, the specific gravity values of the slag are always more than the natural aggregate.

TABLE IV
PHYSICAL AND MECHANICAL PROPERTIES OF AGGREGATES

Test	Percent of SSA			
	0	50	75	100
Bulk specific gravity	2.92	2.93	2.95	3.10
Absorption,%	2.3	2.6	2.7	3.2
Los Angles abrasion, %	14.0	12.0	11.5	10.0
Flakiness, %	22.1	14.0	11.2	8.4
Elongation, %	21.0	12.2	10.0	7.5
Stripping & coating	Above 95			

The results of the mix design for both the SSA mix and the conventional natural aggregate mix are presented in Table V. Comparing the results, it can be observed that steel slag aggregate provide better properties and high values of density and stability, which resist permanent deformation. The Marshall tests results on the prepared specimens showed that the Optimum Asphalt Content (OAC) was increased from a value of 5.1% in the case of specimens prepared with natural aggregate to a value of 6.1% for specimens prepared with 75% SSA. The reason is due to the high absorption value of the (SSA) used.

TABLE V
ASPHALT HOT MIX DESIGN RESULTS

Property	Percent of SSA			
	0	50	75	100
Optimum Asphalt Content, %	5.1	5.6	6.1	5.3
Max. Unit Weight, KN/m ³	24.0	23.9	24.0	24.0
Marshall Stability, KN/m ²	1390	1530	1700	1560
Flow, %	3.5	3.4	3.5	3.2
Air Voids, %	4.6	4.1	4.3	3.3
VMA, %	15.8	16.7	17.4	17.4
VFB, %	71	74	74	80

When stability and density values are considered, specimens prepared with SSA had the highest stability compared with the specimens prepared with natural aggregates, as shown in Fig. 3. It is believed that the reason for this is due to the low crushing and Los Angeles abrasion values of the (SSA) when compared to natural aggregates.

A slight decrease in the flow value was noticed in the case of specimens prepared with SSA when compared to the natural aggregate (NAG) specimens. The curves shown in Fig. 4 show that all specimens prepared at their optimum Asphalt Content (OAC) are in the range recommended by the Asphalt Institute between 3-5 mm for the surfacing and heavy traffic category [15]. The Percentage of air voids (AV) decreased while VMA increased for specimens prepared with SSA when compared to the values of the NAG specimens as shown in Figs. 5 and 6, respectively. It seems that the particle shape, grading and maximum nominal size for the aggregate used play the major role in the determination of these values. It is important to mention that the AV and VMA values obtained

for specimens prepared with SSA and NAG specimens comply with the values recommended by the Asphalt Institute [15].

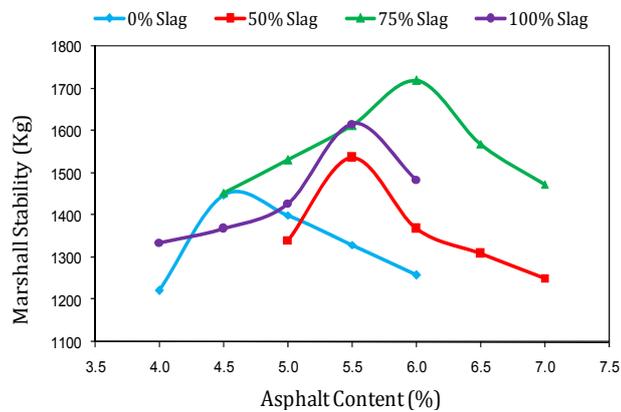


Fig. 3 Corrected stability curves for different asphalt mixtures

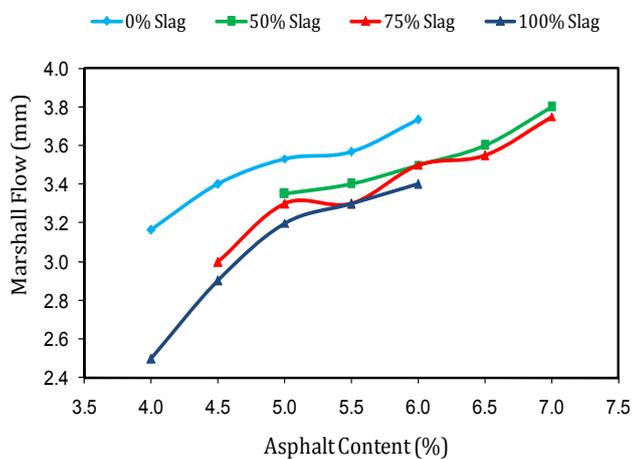


Fig. 4 Flow curves for different asphalt content and mixtures

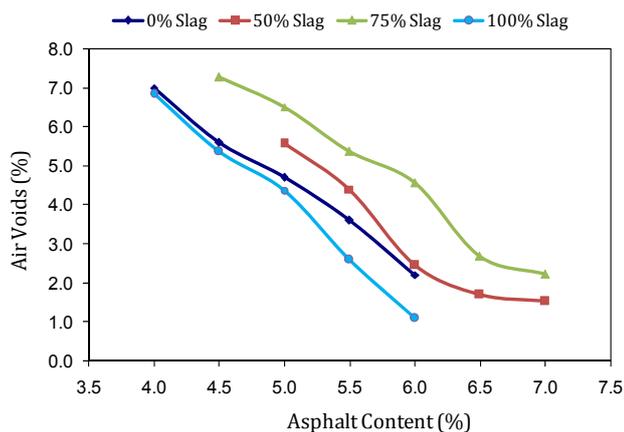


Fig. 5 Air voids versus asphalt content relationship for different asphalt mixtures

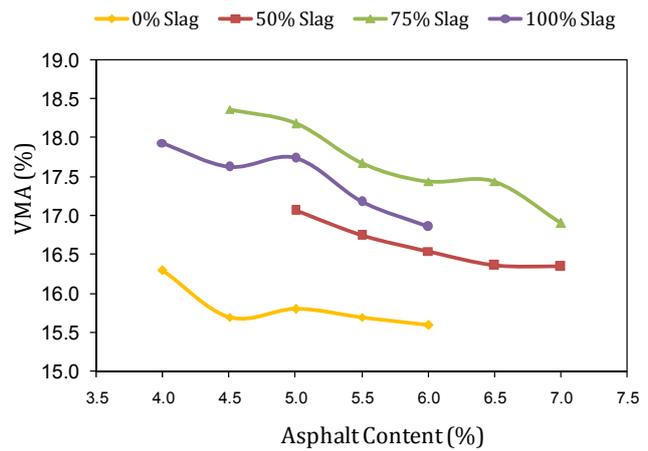


Fig. 6 Voids in mineral aggregate for different asphalt mixtures

IV. CONCLUSION

In this research, the natural aggregate was replaced by SSA, which is waste material derived from the steel industry, in different asphalt concrete mixes. The effectiveness of replacing natural aggregate by SSA was judged by the improvement in the physical and mechanical properties of the tested samples. The following conclusions can be drawn:

- The physical properties of SSA basically satisfy the requirements of Marshall Specification for the design of HMA. Based on laboratory test results, SSA appears to be especially beneficial for the use in Sudan to reduce the dependent on naturally occurring aggregate. Thus, it is recommended that the producers and the users of AHM in Sudan consider the use of SSA.
- 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 of treating and disposing the huge number of steel slag stockpiles.
- The use of natural aggregate in the HMA layer of road pavement is seen as a wasteful use of a finite natural resource. Therefore, the use of waste (secondary) materials is recognized as being of benefit to both environment and society. Of the various waste materials, the steel slag can be considered reasonable alternative sources of aggregate for concrete asphalt mixture productions.
- Further research is still required to obtain new specifications for the use of SSA in different fields of application to conserve Sudan natural resources and preserve the environment.

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