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Performance of Steel Slag as Constituent Material in Asphalt Concrete

C. S. Ezemenike[1], O. J. Oyedepo[2], O. O. Aderinlewo[3], I. O. Oladele[4]

[1,2,3]Department of Civil Engineering, Federal University of Technology, Akure, Nigeria.
[4]Department of Metallurgical Material Engineering, Federal University of Technology, Akure, Nigeria.
[1]ezestan2013@gmail.com

Research Article

Abstract

Increase in urbanization necessitate infrastructural facilities among which is road development. However, the use of limited and non-renewable constituents' materials such as bitumen, aggregate and filler lead to increasing cost of road construction, maintenance and rehabilitations. Thus, exploitation of alternative material (waste or by-products) that can improve the properties of pavement is important. The physical properties of steel slag (SS), aggregate and bitumen was analysed, while the chemical composition of SS was determined with the aid of X-ray diffraction and X-ray fluorescence. A cylindrical sample of the composite mixture of asphalt concrete was produced using varying proportion of steel slag (SS) at 2%, 4%, 6% and 8% to partially replace the conventional aggregates. Marshall Stability and flow test was performed on the sample produced, while the microstructural analysis of the sample was done using Scanning Electron Microscope (SEM). The marshal stability values obtained were 7.45 KN, 7.75 KN, 8.63 KN, 9.82KN and 11.0 KN for 2%, 4%, 6% and 8% replacement with SS. Comparing with criteria for the Marshal mix design method provided by Asphalt Institute (1997); 4%, 6%, and 8% of SS can be used as coarse and fine aggregate in heavy traffic roads while 2% is appropriate for medium traffic road. Hence SS can be used as partial replacement of aggregate (coarse and fine) in asphaltic concrete to improve the performance of the mix and reduces the cost of road construction.

Keywords

Asphalt concrete; Conventional aggregates; Marshal Stability; Pollution control; Steel slag.

Article History

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1. Introduction

Rapid depletion of natural resources used in the construction industry, particularly in road construction, as wellas improper disposition of industrial waste which causes CO_2 emission has become a global issue (Sukan *et al.*, 2014; Anastasiou *et al.*, 2015). Since the generation of non-biodegradable waste disposal from industry like granite dust, ceramic dust, polymers, stone dust, blast furnace slag, tire and others are ever increasing, the need for effective waste management is of paramount importance. The most dominant method of disposal industrial wastes is landfilling and incineration, which contaminate groundwater sources and contribute to greenhouse emissions (Poulikakos *et al.*, 2017; Brook and Cetin, 2012; Bennert*et al.*, 2000; Kalantar*et al.*, 2012; Lou*et al.*, 2013; Yang *et al.*, 2013; Sofilić*et al.*, 2010). Right now, proper waste management is one of the environmental challenges that Nigeria is facing. Traditionally, large amounts of natural materials are utilized in pavement, uncontrolled consumption of natural material; non-sustainable resource prompts destruction of the climate and twisting of the natural balance (Poulikakos *et al.*, 2017).

Asphaltic road pavement defects are mainly caused by moisture damage from harsh climatic conditions and excessive traffic loading. Defects include longitudinal cracking, transverse cracking, block cracking, alligator cracking, potholes and rutting (Asi and Khalayleh, 2011). Cementitious road pavements are an alternative to the asphaltic counterpart. When compared to asphaltic road pavements, concrete road pavements are more durable, have lower maintenance costs and vehicles consume less power as the pavement deflects significantly less under the vehicle wheels, especially with excessive loads. However, these are more expensive and can have less traction in wet conditions compared to asphaltic roads. Studies have shown that incorporating industrial waste, including steel slag aggregate (SSA), fly ash, and crumb rubber from recycled tires improved the properties and performance of asphaltic pavements. Numerous researchers have found that, the rough textured surface, angular shape and high specific gravity of SSA provides high skid resistance, mechanical interlocking, better stability and rut resistance. (Hainin *et al.*, 2012; Qian *et al.*, 2013; Skaf *et al.*, 2017; Ziari and Khabiri, 2007). SSA was found to also have properties to assist in deicing of the pavements (Gao *et al*., 2017).

Steel slag, among other industrial wastes is generated during the separation of molten steel from impurities in steel-making furnaces as a by-product of the various processes of smelting metallic ores. It has different type such as stainless slag, carbon slag, pre-treatment slag, electrical arc furnace slag, basic oxygen furnace, casting residue and ladle refining slag in according to steel making process (Huang Yi *et al.*, 2012). SS contain chemical composition which is similar to that of cement properties like Si, Al, Ca, Mg, Fe, S and Mn with their oxide content. The oxides present in SS are hazardous and dangerous to the environment. Sadly, SS is non-renewable material, however it recent regard for construction is an advantage (Awoyera *et al.,* 2016). SS has the potential to be a valuable commodity in civil infrastructure applications, especially road paving (Brand and Fanijo, 2020). Steel is primarily manufactured in Nigeria from the refining of salvaged material (scrap material) and many huge tons of steel slags are generated each year and about 0.35-0.45 million metric tons were manufactured in Nigeria and discarded into the surrounding careless with the majority of steel slag disposed near steel-producing centres, posing environmental risks (Akinwumi,2014).

In recent years, several studies have centred on the potential use of steel slag as a road building material (Falchetto and Moon, 2015; Poulikakos*et al.,* 2017; Dunster, 2002; Rockliff *et al.,* 2017). Its mechanical properties of steel slag and other desirable characteristics have unfolded its uniqueness to many researchers as a possible material in road paving. Among the number of studies carried out on the steel slag includes Zumrawi and Khalill, 2017 which studied the SS utilization in asphalt concrete and the investigation showed that replacement of SS as aggregate substitution have essential enhancement on the hot mix asphalt concrete properties and Aziz *et al.,* 2020 investigated the performance of SS in highway industry, they also concluded that the steel slag aggregate in asphalt mixture was able to bring so many benefit that outperformed conventional aggregate in terms of stiffness resistance, rutting and fatigue life of the pavement. Moreover Muralidhara *et al.,* 2020 analysed the flexible pavement with SS as coarse aggregate, the results showed that addition of natural aggregate with SS provides better result at any percentage for asphalt concrete. Solomon *et al.,* 2021 investigated the significance of steel slag in replacement of natural aggregate at varying proportions of 0%, 40% and 60% in rigid pavement and the outcome of the result indicated that the compressive and flexural strength of the concrete increased with increased in steel slag proportions. Yuechoa *et al.,* 2021 studied the evaluation of volume stability and resource benefit of steel slag and its asphalt mixture based on field application and concluded that the economic evaluation of steel slag instead of natural aggregate for surface course construction could reduce the investment by 16.87%. A study on the utilization of activated steel slag as partial replacement of cement in rigid pavement was done by Anjali and Sajitha, 2022 and they found out that steel slag fines resulted reduction in normal consistency water requirement, this may be because of the fineness of cement maybe more when compared to steel slag fines. Giulio *et al.,* 2021 used steel slag as an alternative to aggregate and filler in road pavement, the mechanical characterization such as Marshall Stability and indirect tensile resilient modulus tests were used to evaluate the laboratory performance of the mixture and the result showed that the use of steel slag has a favoured an increase in stiffness of the mixtures. Nugraha *et al.,* 2021 also used steel as replacement of coarse aggregate on indirect tensile strength and Marshall properties of AC-WC and concluded that the replacement of steel slag for coarse aggregate were able to increase Marshal stability, Marshall Quotient and indirect strength of the mixture. Hitesh and Sudhir, 2020 reviewed the utilization of steel slag in hot mix asphalt and concluded that the properties of steel slag obtained can significantly influence the performance of roads positively. The findings of these studies indicate that slag-based asphalt mixtures are ideal for flexible pavement structures and especially outperform traditional asphalt mixtures made with natural aggregates. However, the addition of SS as aggregate has been studied, analysed and accepted in many parts of the world, but not yet in Nigeria. so, in order to regard the use of SS as alternative replacement to aggregate in Nigeria, the climate, standard specification, local material (scrap metals) and availability has to take into consideration. First, there must be a sound understanding of the overall compositional and physical properties of the specific Steel slag from scrap metals being investigated. However, it is necessary to carry out a comprehensive research base on local material and conditions of the feasibility of using SS generated by steel making factory in Ile-ife, Osun state Nigeria as partial replacement for conventional aggregate in asphalt concrete mixture production. This research evaluated the performance of asphalt concrete on the utilization of steel slag as fine and coarse aggregate.

2. Methodology

2.1 Materials Used

Aggregate, Steel Slag (SS), and Bitumen are materials utilized for this study. Aggregate was procured from RCC and JCC quarry, Oba-Ile, Ondo state, Nigeria. Ife Steel and Iron Company located in Ile-Ife, Osun State, Nigeria was where we sourced steel slag (SS) (Figures 1-2). The 60/70 penetration grade Bitumen was obtained from K.K. Hassan Construction Company in Akure, Nigeria.

Figure 1: Indiscriminately dumping Steel Slag at Ile-ife, Osun State, Nigeria

Figure 2: the completed prepared steel slag at Ife steel and iron company

2.2 Processing and Characterization of Steel Slag, Aggregate and Bitumen

The pulverised SS as shown in Figure 2 was sieved to obtain this size range of 150 µmm to 10 mm. This was performed to guarantee steel slag utilized as aggregate in fine and coarse form to substitute conventional aggregate at proportion of 2%, 4%, 6% and 8%. Determination of the physical properties of the aggregates and the SS used were conducted in accordance with standard methods of measurement: Moisture content test was conducted using BS 812-109:1990. Other necessary tests such as the Aggregate Impact Value test (AIV) and Aggregate Crushing Value (ACV) were determined as specified in British Standard (BS 812-112:1990) and America Standards for Testing and Materials ASTM C131/C131 respectively. Specific Gravity Test, Flakiness and elongation index test were carried out in accordance with ASTM CI27-12 and BS 812: Part 105: 1: 1985 respectively while chemical analysis of SS were performed by x-ray diffraction and x-ray fluorescence test in accordance with ASTM D 113-17 and ASTM D3906-19 respectively. Also, for the bitumen, the following test were conducted: Penetration Test, Softening Point Test, Flash and Fire Point Test, Viscosity test and Ductility Test as specified in America Standards for Testing and Materials ASTM D5/D5M-13; ASTM D36/D36M-14el; ASTM D92-16b; ASTM D2170/D2170M-10; ASTM D113-17.

2.3 Production of Asphalt Concrete

Aggregates of about 1200 g comprising distinct aggregate fraction with sizes of 8.00, 5.00 and 2.36 mm and, filler (stone dust) of 4.76 µm were pre-heated within the range of 160-178 ^{0}C. The selected bitumen content of 5% was melted to 150^{0}C. The aggregates and bitumen were mixed together inside the steel bowl. The mix was completely blended at mixing temperature of about 185 ^{0}C. The mixture was compacted in fore-heat marshal mould by applying 50 blows on each face of the sample. Ten (10) samples were set up by replacing aggregates (coarse and fine) with steel slag at different proportion of 2, 4, 6 and 8% were produced. The marshal stability and flow were carried out on the samples while Void in mineral aggregate (VMA), Air void (AV), bulk density (BD) and Void filled with bitumen (VFB) was determined.

2.4 Microstructural Image of Steel Slag Modified Asphalt

The SEM of the Steel slag modified asphalt fracture surface was carried out using EVO MA 15, Carl zeiss SMT to analyse the microstructure of asphalt mixture. The samples were gold sputtered to improve electrical conductivity

3. Result And Discussion

The result, as shown in Table 1, revealed the physical properties of the aggregates and the steel slag used. Based on the FGN, (1997) the values obtained for each parameter property falls within the specified range for road surfacing. It can also be observed that the steel slag had lower moisture content, AIV and ACV values as compared to that of the aggregates.

Table 2 showed the summary of the tests results conducted on the bitumen such as penetration, softening point, flash point, fire point, ductility, viscosity and water-in-bitumen as; 62 mm, 46℃ , 207 ℃, 252 ℃, 148 cm, 129.4 sec and 3.4%, respectively, all these values conformed to the range specified Government of the Federal Republic of Nigeria, General Specifications For Roads and Bridges (FGN, 1997)

Table 1: Test Results on the Aggregates and Steel Slag

S/N	MATERIALS	MOIST. CONTENT	AIV %	ACV%	Gs	Flakiness and Elongation Index Test
1	AGGREGATES	0.65%	22.20%	30.18%	3.0g	20.64%
2	STEEL SLAG	0.46%	20.50%	28.73%	3.32g	25.31%
FMWHM, 2013		*Max 5%*	*20-30%*	*27-35%*	-	*Max 30%*

Table 2: Physical Characterization of Bitumen

FMWHM, 2013	Properties	Obtained Value
Min. 75	Ductility, cm	148
Min.200	Flash point, ℃	207
Min.240	Fire Point, ℃	252
Min 100	Viscosity, sec	129.4
Min 3	Water-in-Bitumen	3.4
60-70	Penetration, mm	62
Min. 45	Softening Point, ℃	46

3.1 Chemical Characterization of the Steel Slag

The Steel slag result on X-ray diffraction (XRD) and X-ray Fluorescence (XRF) test are indicated in Figure 3 and Table 3 respectively. The diffractogram XRD comply with that of a crystalline structure with identity of major phases which was in conformity with Yildirim and Prezzi (2013). Limestone, silica, and iron oxide are crystalline mineral made out of steel slag. Henceforth, the XRD acclimates to that of crystalline material with its credits especially portrayed by Bragg top

(Banerjee, 2020). XRF analysis report as shown in Table 3 revealed the steel slag to basically contain larger quantity of Silicon Oxide (SiO_2), Iron Oxide (Fe_2O_3), Calcium Oxide (CaO_2) and Magnesium Oxide (MgO) composition with little hint of Aluminium oxide Al_2O_3, Lead Oxide Pb_2O_5, Manganese Oxide MnO, Sulfide SO_3, Sodium Oxide Na_2O, Potassium Oxide K_2O etc, the lower composition of free lime and magnesia is most essential part for the use of steel slag in civil engineering aims with respect to their volume stability (Motz and Geiseler, 2001)

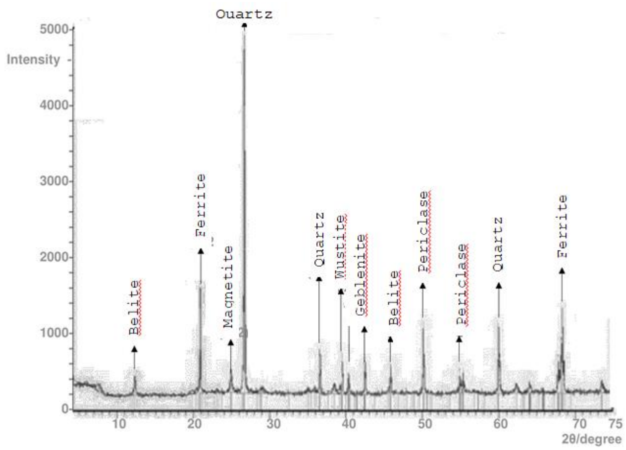


Figure 3: Steel slag Diffractogram

Table 3: The XRF Analysis of Elemental Composition

S/N	Parameter	%Composition
1	TiO_2	0.76
2	MgO	5.21
3	Fe_2O_3	24.86
4	CaO	50.93
5	Al_2O_3	1.21
6	Pb_2O_5	1.36
7	SiO_2	12.45
8	Na_2O	0.27
9	SO_3	0.04
10	MnO	0.06
11	K_2O	1.03
12	Loss of Ignition	1.82

3.2 Marshal Mix Design

Table 4 provides Marshal Characteristics result of Steel slag while Table 5 give present specification of Marshal Mix design method utilised.

Table 4: Marshal Characteristic result of Steel Slag (SS)

S/N	Proportion (%)	bulk density	AV	VMA	VFB	Stability	Flow
1	0	2.467	4.18	21.70	80.73	7.45	3.8
2	2	2.469	4.13	21.78	80.36	7.75	3.6
3	4	2.473	3.98	21.90	79.80	8.63	3.4
4	6	2.479	3.73	22.21	78.35	9.82	3.2
5	8	2.485	3.50	24.42	77.43	11.00	2.9

Table 5: Typical Bituminous Marshall Design Criteria

Mix Specification	Heavy traffic (greater than 10^6 ESALS)		Light traffic (less than 10^4 ESAL)		Medium Traffic (10^4-10^6 ESAL)	
	Min	Max	Min	Max	Min	Max
Stability (minimum)	6672N	-	2224N	-	3336	-
Flow (0.25mm)	8	16	8	20	18	-
Air voids (%)	3	5`	3	5	3	5
Compaction (50 blows each side of specimen)	35	-	50	-	75	-

Note: *ESAL is the Equivalent Single Axle Load; Source: Asphalt Institute (1997)*

3.3 The result of Marshal Stability and Steel slag

Stability is an important property of the asphalt mixture in the wearing course design. Marshall Stability gives the indication about the resistance of asphalt mixture to permanent deformation; a high value of Marshall Stability indicates increased Marshall Stiffness. The high stiffness of asphalt mixture means good resistance to traffic loadings but it also indicates lower flexibility which is required for long term performance, high stiffness values are not recommended due to thermal cracking which expected to occur in future. There was consistent rise from 2% to 8% in marshal stability result as shown in figure 4. The reason for rise might be as a result of low impact and crushing value of steel slag which have more resisting force than aggregate, hence provide more strength to asphalt concrete mixture. The result also showed that the percentage of 4% 6% and 8% falls within minimum specified value for heavy traffic and 2% which is value (7.45 KN) falls within minimum specified value for medium traffic as shown in Table 5. It can be deduced from result that marshal stability values satisfied the specification given by Asphalt institute (1997).

3.4 The result of Flow and Steel slag

Generally, high flow values indicate a plastic mix that is more prone to permanent deformation problem due to traffic loads, whereas low flow values may indicate a mix with higher-than-normal voids and insufficient asphalt for durability and could result premature cracking due to mixture brittleness during the life of the pavement. The flow properties on steel slag were indicated in Figure 5. From the result, a predictable reduction was noticed as the percentage of steel slag was added. This could be that asphalt concrete which lack ability to mix up with bitumen which brings down the functionality of the mixture. The flow values conformed to Nigeria general specification for road and bridge (1997) which stated that maximum of 4mm to minimum of 2mm is the acceptable range for wearing course in production of asphalt concrete.

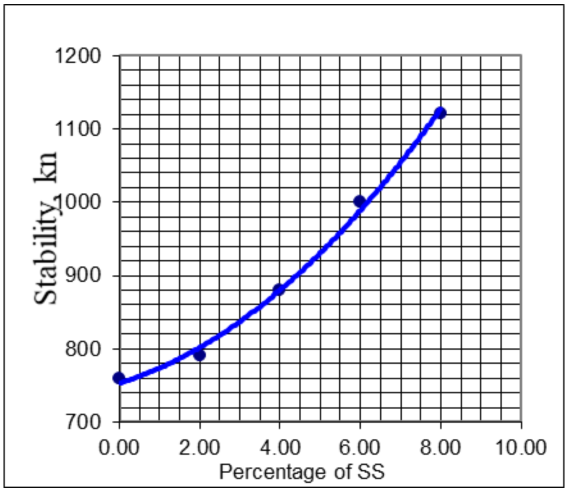


Figure 4: Stability properties of SS

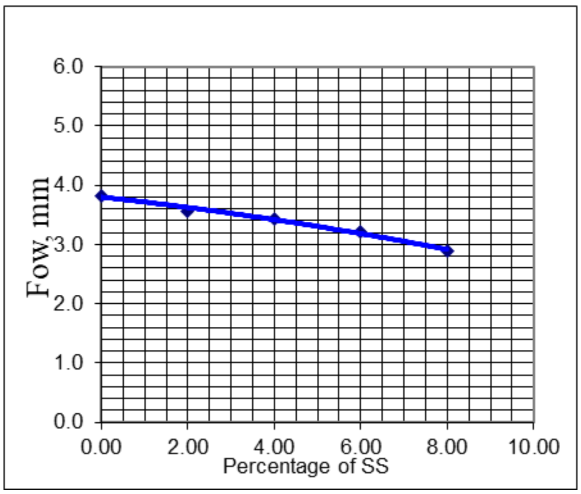


Figure 5: Flow properties of SS

3.5 The result of Bulk density and Steel slag

In the Marshall Mix design procedure, the density varies with asphalt content in such a way that it increases with increasing asphalt content in the mixture. The density reaches a peak and then begins to decrease because additional asphalt cement produces thicker films around the individual aggregates, and tend to push the aggregate particles further apart subsequently resulting lower density. Figure 6 indicated the bulky density properties of steel slag. Since the specific gravity of steel slag is higher than natural aggregate, there was increment from 2 to 8% when steel slag was added because of the great amount of oxides present in the steel slag. These values all lie within the permissible limit specified by Nigeria general specification for Road and Bridges (1997).

3.6 The result of air void (AV) and steel slag

Air void in the mixture is an important parameter because it permits the properties and performance of the mixture to be predicted for the service life of the pavement, and percentage of air voids is related to durability of asphalt mixture. Air void proportion around 4% is enough to prevent bleeding or flushing that would reduce the skid resistance of the pavement and increase fatigue resistance susceptibility. The properties of AV result are shown in Figure 7. From the result, a steady increment was observed as the percentage of steel slag increases. This could be as result of sufficient molecules arrangement of steel slag. The Air void values obtained are suitable for light, medium and heavy traffic when compared with the Marshall Design criteria in Table 5.

3.7 The result of void in mineral aggregate (VMA) and steel slag

The voids in the mineral aggregate is the total available volume of voids between the aggregate particles in the compacted paving mixture that includes the air voids and the voids filled with effective asphalt content expressed as a percent of the total volume. It is significantly important for the performance characteristics of a mixture for any given mixture; the VMA must be sufficiently high enough to ensure that there is space for the required asphalt cement, for its durability purpose, and air space. If the VMA is too small, there will be no space for the asphalt cement required to coat around the aggregates and this subsequently results in durability problems. On the other hand, if VMA is too large, the mixture may suffer stability problems. Figure 8 showed the properties of VMA result. It can be seen that there is a gradually and gently fall as percentage of steel slag increases. Steel slag which is made of iron and steel have higher density than natural aggregate and also have finer particle which could fill some void created in mix and this could be the reason for the increase. The void in mineral aggregates values all lie within the permissible limit specified by Nigeria general specification for Road and Bridges (1997).

3.8 The result of void filled with Bitumen (VFB) and steel slag

Voids filled with asphalt (VFA) are the void spaces that exist between the aggregate particles in the compacted paving asphalt mixture that are filled with binder. The purpose for the VFA is to avoid less durable asphalt mixtures resulting from thin films of binder on the aggregate particles in light traffic situations. The value of VFB properties of steel slag were indicated in Figure 9. A steady increase was observed as percentage of steel slag increases and the reason for this can be attributed to the effects on porosity and thick quality of steel slag in the asphalt blend. The values obtained falls within the allowable limit provided by Nigeria general specification for Road and Bridges (1997).

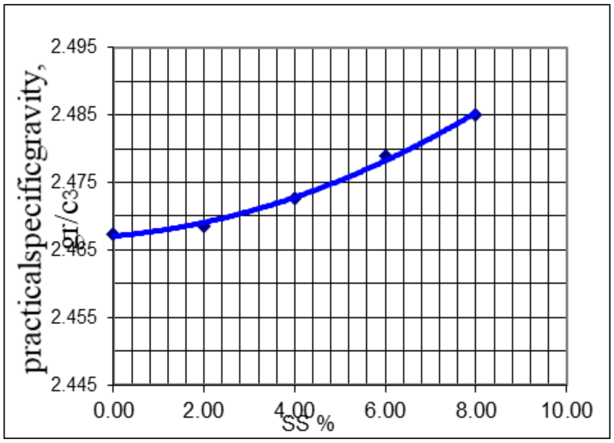


Figure 6: Bulk density properties of SS

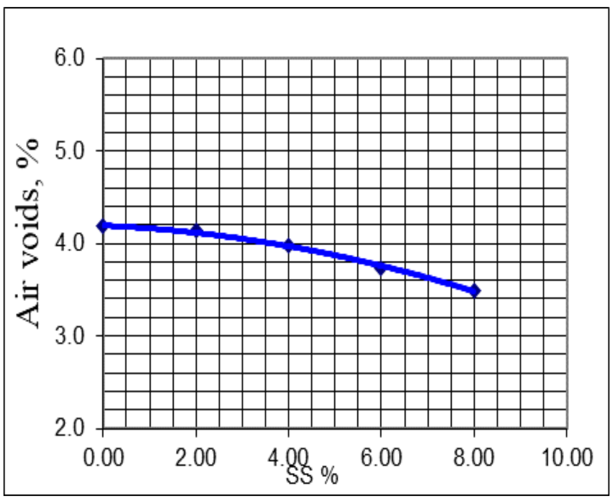


Figure 7: AV properties of SS

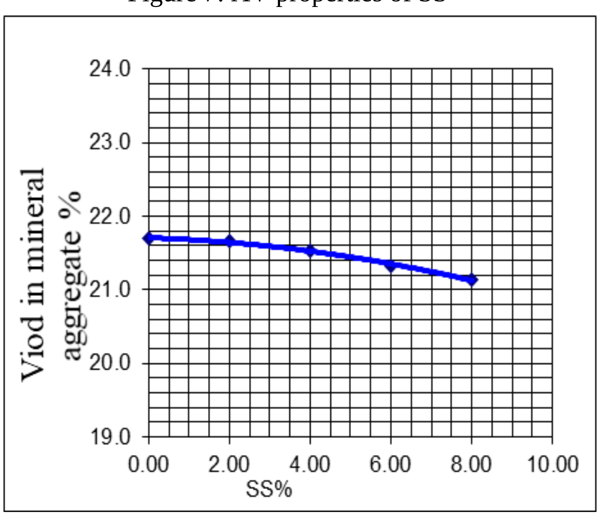


Figure 8: VMA properties of steel slag

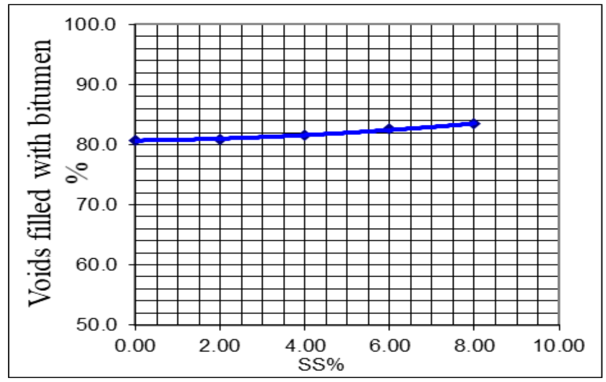
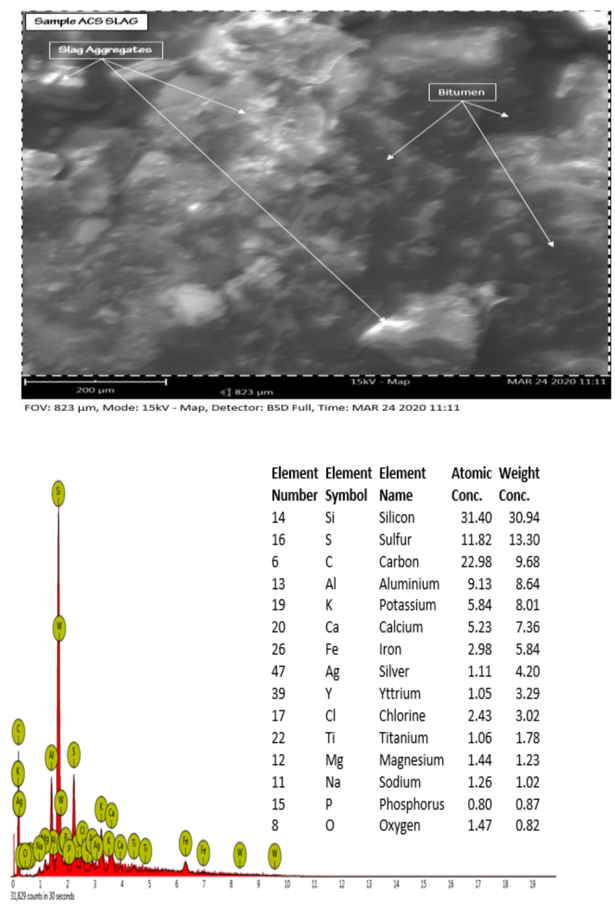


Figure 9: VFB properties of steel slag

3.9 Microstructural Image of Steel slag

The mixture of asphalt and steel slag showed a homogenous phase with proper distribution of steel slag in the asphalt. It can be observed from Figure 10, that the structure of steel slag is porous and this structure may affect the mechanical properties of asphalt mixtures due to its higher binder consumption. The main elements were Ca, Fe, Si, and Mg. the proportion of Si was more than 30.94%, this higher value may due to high fluxes dosages for minimizing the impurities during the conversion of molten iron to steel.



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
14	Si	Silicon	31.40	30.94
16	S	Sulfur	11.82	13.30
6	C	Carbon	22.98	9.68
13	Al	Aluminium	9.13	8.64
19	K	Potassium	5.84	8.01
20	Ca	Calcium	5.23	7.36
26	Fe	Iron	2.98	5.84
47	Ag	Silver	1.11	4.20
39	Y	Yttrium	1.05	3.29
17	Cl	Chlorine	2.43	3.02
22	Ti	Titanium	1.06	1.78
12	Mg	Magnesium	1.44	1.23
11	Na	Sodium	1.26	1.02
15	P	Phosphorus	0.80	0.87
8	O	Oxygen	1.47	0.82

Figure 10: SEM/EDX Image of Steel slag modified asphalt

4. Conclusion

The results of the study have revealed that steel slag can be favourably used as replacement for aggregates in asphalt concrete because it enhances the properties of asphalt concrete mixture. The stability value of (7.75kN) obtained at 2% replacement of SS can be utilized in medium traffic road. The stability value of (8.63kN, 9.82kN, 11.00kN) obtained at 4%, 6%, 8% replacement of SS can be utilized in heavy traffic roads in accordance with the criteria for the Marshall mixture design method provided by the Asphalt Institute. Hence also Utilization of steel slag in road construction works can significantly offset need of natural aggregates, thus, reducing burden on natural aggregate sources.

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