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Evaluation of recycled glass and steel slag as partial replacement of filler in hot mix asphalt

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ABSTRACT

Recent studies have revealed the need to increase the volumetric properties of hot mixed asphalt (HMA) with various industrial solid waste materials. Hence, this study was carried out to investigate the use of crushed glass (CG) and steel slag dust (SSD) as fillers partially replaced in HMA. The optimum bitumen content (OBC) suitable for design mix was determined. The tested samples were prepared with CG and SSD separately, and the combination of the best results in each were mixed equally (CG+SSD) to replace filler partially with 5, 10, 15 and 20% respectively. Both conventional HMA, and modified samples were examined to determine their volumetric properties and stability. The OBC suitable for HMA mix design was 6%. The addition of CG, SSD, and CG+SSD had significant improvement on the properties of HMA, and the best results was observed at 15% replacement with 3.28%, 7.81%, and 55.49% increase in stability respectively compared with control HMA. The ANOVA results on the modified asphalt revealed that void in mix was not influenced by the modification of CG and SSD. In conclusion, 15% of CG+SSD as filler partial replaced in HMA can be considered reasonable alternative filler for concrete asphalt mixture production.

1. Introduction

Asphalt concrete is a complex material composed of asphalt binder, and mineral aggregates mostly used in pavement construction and airport runways among others [Oyedepo et al., 2021, Asphalt for Environment Liners, 2014] due to its high engineering performance capabilities among which are elasticity, adhesion, and water resistance. The aggregate acts as the structural frame work glued by the asphalt binder in asphalt pavement while the mineral filler generally referred to fine particle which passes a 0.063 mm sieve, used in asphalt mixture to improve the adhesion and cohesion thereby enhancing the properties of the mixture. It acts as a part of the mineral aggregate by filling the voids between the coarser particles in the mixtures and thereby strengthen the asphalt mixture, and also form matrix that cements larger binder particles together. The properties of the mixes are greatly influenced by the particle size, shape, surface area, surface texture, and other physio-chemical properties [Bahia, et al., 2011]

However, due to an Increasing rate of road construction, it has led to increase in consumption of aggregates which invariably resulted to depletion of natural aggregate. To provide possible alternatives to natural aggregates, researchers and practitioners have been studying several potential materials, suitable for producing synthetic aggregates [Tayabji et al., 2010]. According to [Aziz et al., 2014], the use of steel slag can reduce pollutants, save occupied land and prolong the service life of the pavement.

Currently, several waste materials, such as steel slag [Ji et al., 2021; Hansen and Copeland, 2016], crushed glass [Zaydoun et al., 2017], and construction and demolition wastes [Zhang et al., 2020, Hansen and Copeland, 2016; Aljassar et al., 2005 and Herrador et al., 2012] are used as aggregates in road construction. Utilization of by-products or waste materials in road construction activities can reduce the burden on natural sources, thereby saves construction costs and provide solution to the negative environmental effects of inappropriate solid waste disposal [Jony et al., 2011 and Aziz et al., 2014] facing some major solid waste management challenges [Ike et al., 2018]. Among the various waste materials, utilization of crushed glass and steel slag as aggregates in road construction have gained the most popularity worldwide. [Dalloul, 2013] examined the effect of samples containing different percentages of glass on Marshall Stability and established that the optimum percentage of glass that can be used in the binder course was 7.5% of the weight of the aggregates. However, [Wu et al., 2004] stressed that increase of glass replacement reduces stability and indirect tensile strength of asphalt concrete but improved by introducing hydrated lime or liquid anti stripping agent. According to [Arabani, 2011], glass particles with greater angularity can increase the fatigue life of an asphalt pavement due to higher internal friction angle it formed, and improved the interlocking between different constituent particles.

Steel slag is one of the industrial wastes, non-metallic product, consisting essentially of calcium silicates and ferrites combined with fused oxides of iron, aluminium, manganese, calcium and magnesium containing fused oxides [Rezaul et al., 2018] that are developed simultaneously with steel". It is a byproduct of steel manufacturing process obtained during parathion of molten steel from impurities in steel-making furnaces,

and the utilization rate of steel slag for road construction is 32.4~49.7%, with a perfect quality control system and production process [Das, et al., 2021]. The global iron slag output in 2015 was estimated to be in the range of 300 to 360 million metric tons, while that of steel slag was about 170 to 250 million tons (Oss, 2016), and disposed-off in an environment-unfriendly manner. However, the amount of steel slag by-products produced from steel-making increased significantly with the rapid development of the steel industry in the last century, thereby resulting in growing needs for effective recycling, and its usage in civil engineering constructions [Arribas et al., 2015; Faleschini et al., 2016 and Pramukh et al., 2018].

According to Brand and Fanijo, 2020, steel slag has the power to be a valuable commodity in civil infrastructure applications, especially road paving. [Asi et al., 2007], investigated skid resistances of asphalt concrete mixtures containing steel slag as an aggregate and emphasized that asphalt concrete containing 30% steel slag gave the best performance. Furthermore, it was reported that asphalt mix containing up to 75% steel slag as a coarse aggregate had better mechanical properties compared with conventional mix when examined indirect tensile strength test, fatigue life, resilient modulus, creep modulus and rutting resistance tests. This was established by [Ahmedzade and Sengoz, 2009 and Pasetto and Baldo, 2010] who examined its effect on fatigue resistance, and indirect tensile strength and modulus respectively. This research is carried out to investigate the effect of recycled glass with steel slag dust partially replaced filler in hot mix asphalt to match societal needs for safe, economic disposal of industrial waste materials in a friendly manner, and cost- effective construction materials in highway industries.

2. Materials and Methodology

2.1. Materials

The materials used in this study were coarse and fine aggregates, filler materials (crushed stone dust, waste glass and steel slag), and bitumen. These materials were sourced from different locations and processed as described in Table 1 below.

Table 1: Raw Materials for the study

Raw Materials		Source	Processing
Coarse Aggreg ate	(Granite)	Odeda Quarry along Ibadan – Abeokuta Road, Ogun State, Nigeria	Washed and freed from deleterious materials
Fine Aggreg ate	River sand	Federal University of Agriculture, Abeokuta (FUNAAB), Ogun State, Nigeria	Washed and freed from deleterious materials
Fillers	Crushed Stone	Odeda Quarry along Ibadan – Abeokuta Road, Ogun State, Nigeria	Crushed stone passing through sieve 75 μm
	Waste Glass	Abeokuta	Milling and Sieving through sieve 75 μm to give Crushed Glass (CG)
	Steel Slag	Steel Company (Pukit-Alloy steel company in Ikorodu, Lagos)	Milling and Sieving through sieve 75 μm to give Steel Slag Dust (SSD)
Bitumen	60/70 Penetrati on Grade	Federal Road Maintenance Agency (FERMA), Abeokuta, Ogun state	

2.2. Methods

Physical and engineering properties of bitumen, coarse aggregate, fine aggregate, crushed stone dust, waste glass and steel slag were determined. The components of the asphalt were subjected to laboratory tests based on the standard specifications recommended by the American Society for Testing and Materials (ASTM), namely: Penetration test of bitumen [ASTM, 2013], Flash and fire point test of bitumen [ASTM, 2016], Specific gravity of bitumen [ASTM D70], Specific gravity of the aggregates [ASTM D854-00], Marshall Test [ASTM D 1559-89] and X-Ray Fluorescence (XRF) [ASTM, 2019].

2.3. Marshall Mix Design

Determination of optimum bitumen content (OBC) suitable for the mix design was carried out for various sets of specimens at 5.0, 5.5, 6.0, 6.5 and 7.0% bitumen contents. Specimen prepared were tested in accordance with [ASTM D 1559-89] (Marshall Mix Design Method). Marshall Stability and flow tests were conducted on each specimen by placing cylindrical specimen in water bath at 600C for a period of 30 to 40 minutes. Compression on the lateral surface at constant rate of 50 mm/min was done until the maximum load was reached. The maximum load resistance, and the corresponding flow value observed were recorded. Three specimens for each combination were tested (Plate 1) and the average results were reported.

Thereafter, the asphalt specimen were treated with 0, 5, 10, 15, and 20% of Crushed Glass (CG) and Steel Slag Dust (SSD) separately, and the combination of two materials by equal percentage to replace filler partially. And One-way Analysis of Variance (ANOVA) was performed on the modified samples to examine the similarity of the results obtained.

Figure 1a. Asphalt samples

3. Results and Discussion

3.1. Tests on Bitumen

Results on preliminary tests carried out on the bitumen showed that the bitumen used fell within the specified standard and was found to be grade 60/70 (Table 2)

Table 2: Summary of Bitumen Properties Test

Properties	Specifications	Range Value	Results Obtained
Penetration (0.1 mm)	ASTM D5	60 -70	67
Flash point (^{0}C)	ASTM D92	250^{o}C (min)	256.7
Fire point (^{0}C)	ASTM D92	-	325
Specific gravity	ASTM D70	0.9 -1.01	1.01

3.2. Aggregates Properties

Test results on specific gravity of the natural constituent materials for control asphalt concrete, CG, and SSD revealed that SSD has the highest value among the others (Table 3). It implied that SSD is the heaviest, and this could be as a result of large percentage of iron oxide in SSD[Oluwasola et al., 2015] (Table 4), and all the values obtained for the natural constituent asphalt concrete, CG, and SSD were within the specifications, hence, suitable for Hot Mix Asphalt (HMA) design

Table 3: Specific Gravity test of Aggregates

Materials	Specification (ASTM)	Specific Gravity
Granite	2.5 -2.9	2.68
Sharp Sand	2.5 -2.9	2.64
Stone Dust	2.5 -2.9	2.57
Crushed Glass	2.4 -2.8	2.51
Steel Slag Dust	3.2 – 3.6	3.31

3.3. Chemical composition of Glass and Steel Slag

The chemical composition of the CG and SSD (Table 4) were analysed through X-Ray florescence, and these results agreed with [Euroslag, 2023]. Results revealed that silica is the most dominant constituent in CG, while calcium, iron oxides and Silicon dioxide dominated in SSD, this could be one of the contributory factors to its hardness and increase density compared with CG, and this agreed with [Hassan et al., 2021].

Table 4: Summary of X-Ray Florescence Test on Glass and Steel Slag

Major Chemical Element	Percentage Composition (%)	
	Crushed Glass (CG)	Steel Slag Dust (SSD)
Silicon dioxide, SiO_2	64.15	11.57
Aluminium Oxide, Al_2O_3	3.70	4.09
Iron (III) Oxide, Fe_2O_3	0.35	19.79
Titanium dioxide, TiO_2	0.14	0.24
Calcium oxide, CaO	10.10	40.11
Phosphorus Pentoxide, P_2O_5	0.95	2.43
Potassium Oxide K_2O	0.70	0.43
Manganese Oxide, MnO	0.20	5.70
Magnesium Oxide, MgO	2.20	5.21
Sodium Oxide, Na_2O	13.50	0.31
Loss of Ignition, LOI	4.01	9.54
Sulphur, S	-	0.18
Chromium, Cr	-	0.4

3.4. Asphalt Concrete Mix Design

Mix Design curve (Figure 1a) showed that the total aggregate proportion used for this research conformed to the [FMW&H, 1997] and the engineering implication of the result is that the selected material is quite suitable for asphalt concrete trial mix.

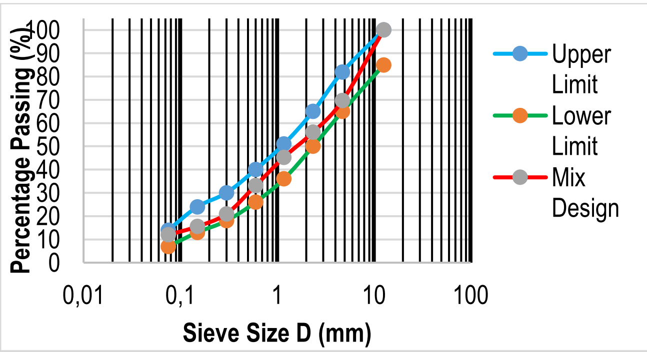

Figure 1b. Asphalt Mix Design Curve Envelope

3.5 Control Asphalt Mix

Results of the control sample showed that 6% OBC was suitable for control asphalt mix design. The stability value increases incrementally from 5.0% bitumen content to 6.0% (8.83 kN) before a reduction in value to 7.0% (Figure 2). The values obtained for Marshall Mix method were within the ASTM specification limits. The flow followed the same pattern as observed in stability but maintained a consistence value of 4 mm from 6.0% to 7.0% bitumen content (Figure 3).

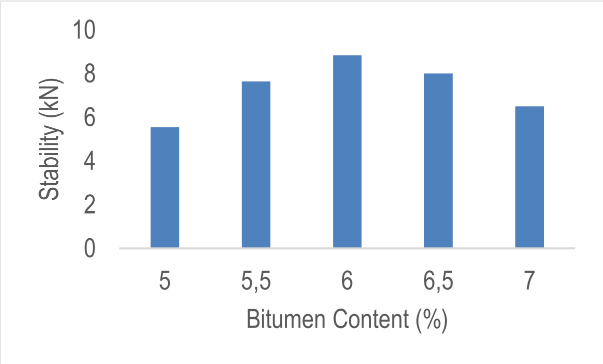

Figure 2. Stability against Bitumen Content

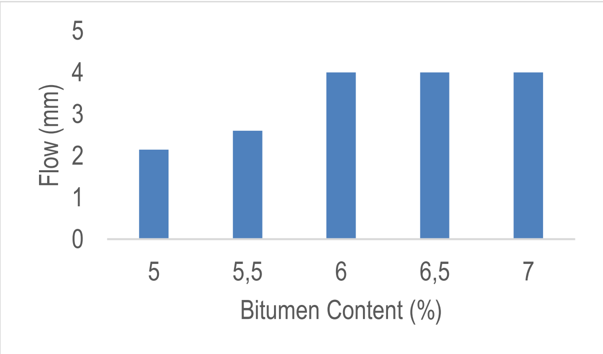

Figure 3. Flow against Bitumen Content

The void in mix (VIM), void filled with bitumen (VFB) and void filled with mineral aggregate (VMA) followed a similar trend of increasing from 5.0% to 5.5% bitumen content as shown in Figures 4 to 6 respectively, and a consistence increase in bulk density was observed with an incremental in bitumen content up to 6.5% (Figure 7).

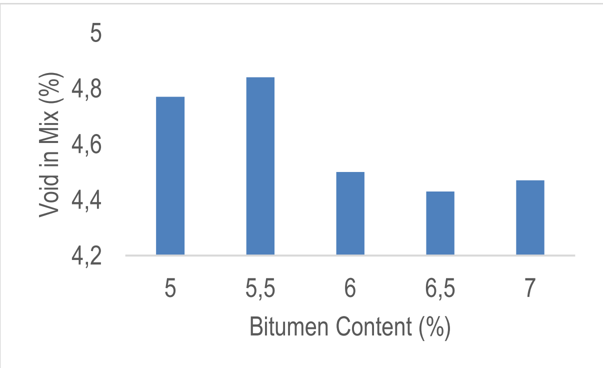

Figure 4. VIM against Bitumen Content

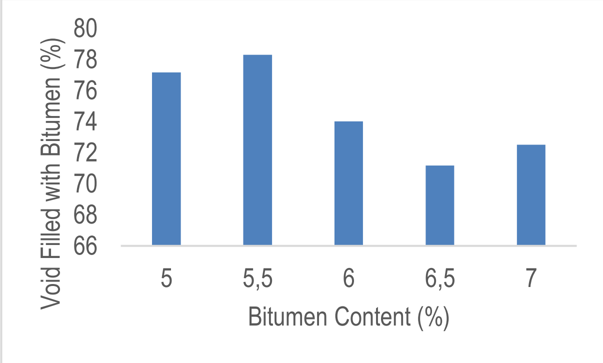

Figure 5. VFB against Bitumen Content

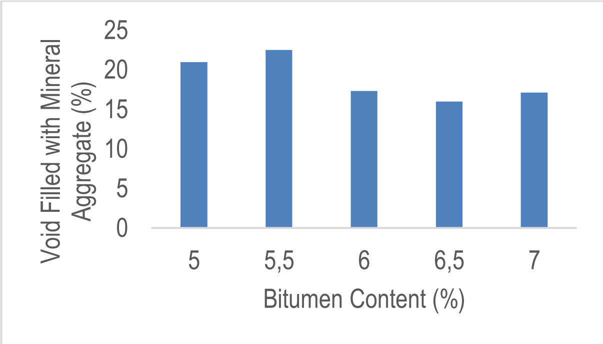

Figure 6. VMA against Bitumen Content

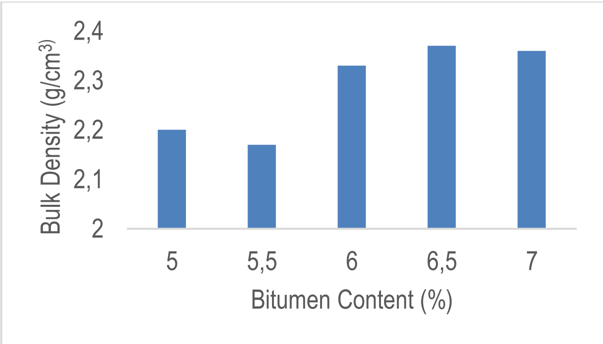

Figure 7. Bulk Density against Bitumen Content

3.6 Stability and flow for the modified Asphalt

Comparing the results of stability and flow of the modified asphalt with control sample (Figures 8 and 9), the stability of the asphalt concrete modified with CG is lower at 5% and 10% replacement than control sample. The decrease in stability at these percentage replacement could be as a result of lower specific gravity of the CG compared with the natural filler material which invariably increased the density of the asphalt composite. Also, the CG added as percentage of the total mix acted as a binding material, sliding over aggregates. However, this caused a reduction in stability, and hence, reduced the stiffness of asphalt mixture. In spite of these, a noticeable improvement was observed with further increment in percentage replacement of CG from 15% to 20%, and 5.54% and 13.36% increase in stability was observed at this percentage replacement respectively which could be considered to be significant.

This implied that CG is a good modifier for asphalt, and agreed with [Issa, 2016]. A reduction in flow was observed with an increment in CG replacement, and the maximum flow was observed at 20% increment with 2.75% reduction compared with control sample.

A consistence increase in stability was observed with an increment in SSD at 10% up to 20%. The highest value (11.28 kN) was noticed at 20% replacement with 27.75% increase in percentage compared with control sample while a reduction in flow was observed consistently.

The Marshall stability test for modified asphalt concrete with CG+SSD at different percentages (5%, 10%, 15%, and 20%) for filler replacement gave the best improvement in stability compared with control sample, modified asphalt concretes with CG, and SSD. The improvement was 16.65%, 38.84%, 55.49%, and 27.75% respectively compared with control sample (Figure 8) along with a decrease in flow from 9.5%, 8.5%, 6.5%, and 0.5% respectively (Figure 9). This could be as a result of the combined effect of the chemical composition of the constituent material in the mix. It can be established from these results that Marshall Stability values satisfied the specification given by [Asphalt Institute, 2003]. However, the high value of Marshall Stability implied increase in Marshall Stiffness, and high stiffness of asphalt mixture means good resistance to traffic loadings but inversely shows lower flexibility which may be required for long term performance

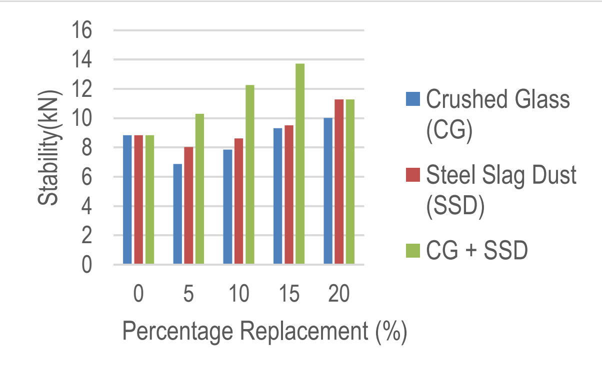

Figure 8. Stability with increment Percentage.

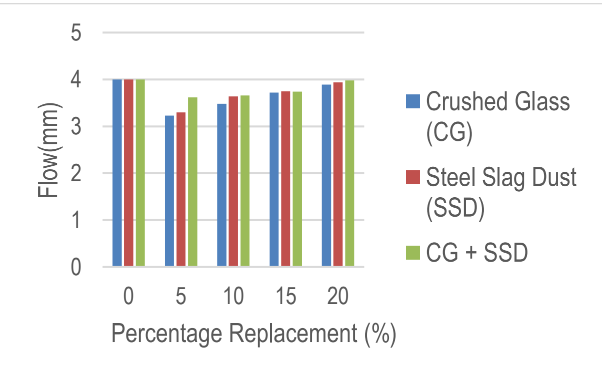

Figure 9. Flow with increment Percentage Replacement

3.7. Void in mix for the modified Asphalt.

Figure 10 displayed void in mix (VIM) results for different percentages of filler replacement. A consistence decrease in VIM value was observed in asphalt modified with an increment in CG replacement with the lowest value at 15% replacement, and 1.78% reduction compared with control sample. In the asphalt mix modified with SSD, a reduction in VIM was observed in all the percentage replacement compared with control sample. At 15% replacement, the VIM was 4.37% which gave 2.89% reduction compared with control sample. However, in the asphalt modified with CG+SSD, a consistence in reduction was observed through all the percentage replacement except at 15% with value 4.53% which was more than control sample by 0.67%.

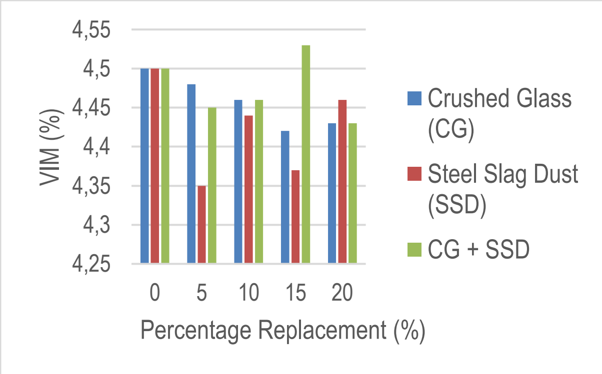

Figure 10. VIM with increment Percentage

3.8 Void Filled with Mineral Aggregate (VMA) and Void Filled with Bitumen (VFB) for the modified Asphalt

In Figures 11, the void filled with mineral aggregate (VMA) decreased with an increment both in CG and SSD percentage replacement in the modified asphalt respectively compared with control sample. The maximum values observed were at 5% and 20% percentage replacement with values lower than the control sample by 3.29% and 5.25% respectively. However, maximum VMA was observed in asphalt modified with CG+SSD at 15% replacement which gave 2.66% increase compared with control sample, and this implied that it gave a better result than asphalt modified CG, and SSD. Moreover, at 15% replacement, enough asphalt could be incorporated into the mix to obtain maximum durability without the mix flushing, and lower stiffness modulus at low temperatures could be achieved. Consequently, VMA is sufficient enough to accommodate space for the required asphalt cement, for its durability purpose, and air space. Reduction in VFB value was observed in all the modified asphalts compared with the control sample. The highest values in asphalts with CG, SSD, and CG +SSD were at 10%, 20%, and both at 10% and 15% percentage replacement respectively (Figure 12) with 0.41%, 0.27%, and 0.48% reduction in value respectively compared with control sample. The results indicate that both VMA and VFB were within the specifications

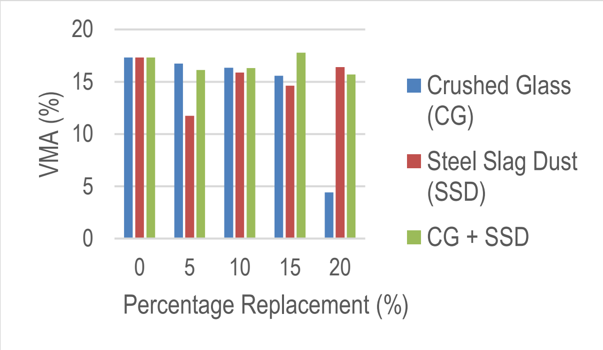

Figure 11. VMA with increment Percentage

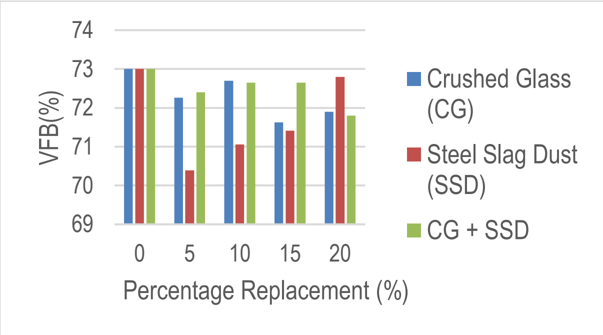

Figure 12. VFB with increment Percentage

3.9. Analysis of Variance

Statistical analysis was carried out to study the significance of the CG+SSD (filler with the best result) percentage replacement in changing the tested parameters values of the modified asphalt concrete to know if the difference in values obtained was as a result of the addition of the CG+SSD percentage replacement or experimental error. One-way ANOVA was used for this analysis with the aim to determine the significant difference between the variable. The results are significant statistically if the p-value is less than the selected significance level, and usually 5%, indicating 95% Significant Level, and the p-value should be < 0.05 for a significant effect of any factor.

Table 5a, showed that voids in total mix were not affected by the modification of CG+SSD, p-value 0.833 > 0.05 while voids in mineral aggregates, and voids filled with bitumen were significant statistically by the modification of CG+SSD, p-value < 0.05 (Tables 6a and 7a).

Table 5a. One-way ANOVA: VIM 0, VIM 1, VIM 2, VIM 3, and VIM 4

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	4	0.008067	0.002017	0.36	0.833
Error	10	0.056467	0.005647		
Total	14	0.064533			

Table 5b. Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0751443	12.50%	0.00%	0.00%

Table 6a:One-way ANOVA: VFB 0, VFB 1, VFB 2, VFB 3, and VFB 4

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	4	15.5000	3.87501	78.89	0.000
Error	10	0.4912	0.04912		
Total	14	15.9912			

Table 6b: Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.221630	96.93%	95.70%	93.09%

Table 7a: One-way ANOVA: VMA 0, VMA 1, VMA 2, VMA 3, and VMA 4

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	4	9.1514	2.28786	84.55	0.000
Error	10	0.2706	0.02706		
Total	14	9.4220			

Table 7b: Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.164499	97.13%	95.98%	93.54%

3.10. Marshall Quotient

Marshall Quotient, MQ (Tables 8a-8c) gave the material resistance to deformation during material's life span while in use. There was an improvement in MQ value of the modified asphalt concrete with an increment in CG, SSD, and CG+SSD. Modified asphalt concrete with CG+SSD had the highest value at 15% replacement while asphalt concrete with CG, and SSD were at 20% replacement. The improvement noticed at 15% replacement compared with control sample was 82.81%, 19.0%, and 18.1% increase for CG+SSD, SSD, and CG respectively. The values at this replacement suggest that the modified asphalt mixtures had stiffer combination, and more resistant mixtures.

Table 8a: Marshall Quotients for Crushed Glass

Percentage Replacement (%)	Stability (kN)	Flow (mm)	MQ (kN/mm)
0	8.83	4.00	2.21
5	6.88	3.23	2.13
10	7.85	3.48	2.26
15	9.32	3.72	2.51
20	10.01	3.89	2.57

Table 8b: Marshall Quotients for Steel Slag Dust

Percentage Replacement (%)	Stability (kN)	Flow (mm)	MQ (kN/mm)
0	8.83	4.00	2.21
5	8.04	3.3	2.44
10	8.63	3.64	2.37
15	9.52	3.75	2.54
20	11.28	3.94	2.86

Table 8c: Marshall Quotients for CG+SSD

Percentage Replacement (%)	Stability (kN)	Flow (mm)	MQ (kN/mm)
0	8.83	4.00	2.21
5	10.03	3.62	2.77
10	12.26	3.66	3.35
15	13.73	3.74	3.67
20	11.28	3.98	2.83

3.11. Water sensitivity

One of the parameters usually used to assess the durability of asphalt mixtures is their water sensitivity. The ratio between the average results of the wet group (ITSw) and the dry group (ITSd) is known as the indirect tensile strength ratio (ITSR) and is the primary indicator of the sensitivity of the mixture to the presence of water. This test helps to determine the effect of water in the loss of affinity between the bitumen and aggregates, and to evaluate its mechanical performance through indirect tensile strength (ITS) tests.

Figure 13 revealed that increase in CG, and SSD contents gave a decrease in ITSR compared with the control value which means an average loss in strength due to water damage was lower in the samples that included the CG and SSD separately than in the conventional asphalt mix sample. The reason could be attributed to the porosity of the CG and SSD fillers, which allowed the asphalt cement to penetrate more than in the crushed stone filler in the control, creating better bonding and resistance to stripping. But at every increment in CG-SSD content, an increase in ITSR up to 15% replacement was observed which is the highest value given an increase 4.06% compared with the conventional mix, and this implied that the samples that included CG+SSD is less susceptible to moisture damage and hence, improved resistance to moisture. This could also be attributed to the improvement in structure when CG and SSD were combined together for a filler in the sample. However, asphalt concrete with SSD, and CG+SSD have the potential to resist moisture damage while asphalt concrete with CG has the potential to resist moisture damage only at 10% replacement since the ITSR values obtained are greater than the 80% minimum value of ITSR recommended specification [AASHTO. 2003].

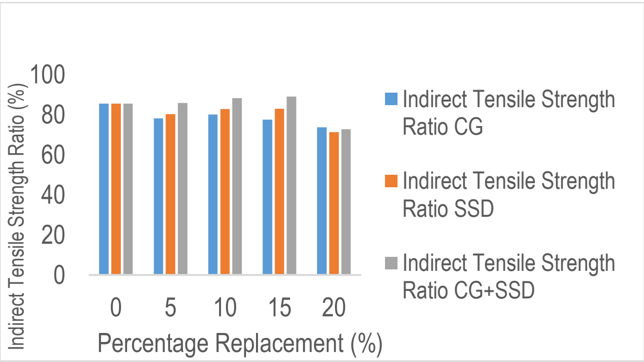

Figure 13. Indirect tensile strength of the different asphalt concrete mixes

4. Conclusion

In this study, the natural filler used in road paving was replaced by recycled glass and steel slag materials to determine if these materials could be a promising fillers alternative source for HMA. Their sustainability was examined separately and the combination of these two materials CG+SSD by equal weight. Changes in the physical and mechanical properties attributes of the various blends were evaluated. The overall study revealed that CG+SSD in place of natural filler in asphalt concrete showed excellent performance followed by SSD, and CG with a proper HMA mix design.

Based on the outcomes and discoveries, the following conclusions can be drawn:

- **i.** The physical properties of asphalt component materials used, including CG and SSD basically satisfied the requirements specified by ASTM.
- **ii.** The physical properties of CG and SSD basically satisfy the requirements of Marshall Specification for the design of HMA.
- **iii.** The Marshal Stability of asphalt concrete modified with CG+SSD was increased by an incremental of CG+SSD in the mixture up to 15% percentage replacement with 55.49% increase compared with control sample while the Marshall Stability of asphalt concrete modified with CG and SSD separately initially experienced reduction at 5% replacement before increased with addition of CG, and SSD contents compared with control sample.
- **iv.** Asphalt concrete modified with CG, and SSD showed a decrease in ITSR values with an increment in content compared with the control sample which means an average loss in strength due to water damage was lower in these modified asphalt concretes than in the control sample but at every increment in CG+SSD content, there was an increase in ITSR up to 15% replacement with 4.06% increase compared with control sample which is an indication that asphalt concrete modified with CG+SSD is less susceptible to moisture damage and hence, improved resistance to moisture.
- **v.** There was an improvement in MQ value with an increment in CG, SSD and CG+SSD compared with control sample and the implication was the modified asphalt concrete experienced more resistance to deformation during material's life span while in use. The order of improvement is 82.81%, 19.0%, and 18.1% increase at 15% replacement compared with control sample for the asphalt modified with CG+SSD, SSD, and CG respectively
- **vi.** Asphalt concrete modified with SSD, and CG+SSD have the potential to resist moisture damage while asphalt concrete modified with CG has the potential to resist moisture damage only at 10% replacement since the ITSR values obtained are greater than the 80% minimum value of ITSR recommended specification.
- **vii.** Use of crushed waste glass (10% replacement) and steel slag dust (15% replacement) and their combination, CG+SSD at equal weight (15% replacement) in asphalt concrete as fillers will improve adhesion and water resistance.

viii. The use of these materials in asphalt mix will reduce pollutants, and provide solution to negative environmental effects of inappropriate solid waste disposal.

ix. It will save occupied land, and prolong the service life of the pavement.

x. There will be decrease in cost of treating and disposing existing huge stockpiles of steel slag and waste glass.

xi. In all, it will ensure sustainability of natural materials use as fillers.

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