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Research Article

Replacement of conventional aggregates and fillers with steel slag and palm kernel shell ash in dense-graded asphalt mixtures

Collins A. NKETIAH*[1], Kenneth A. TUTU[1], Ebenezer D. A. BARNOR[2], David A. AZONG-BIL[2]

[1]Regional Transport Research and Education Centre Kumasi, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana
[2]Department of Civil Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana

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ABSTRACT

Large quantities of steel slag and palm kernel shell ash (PKSA) – waste products from steel production and palm oil milling, respectively – are generated annually in several countries, and their disposal is challenging. Meanwhile, the over-reliance on conventional rock aggregates for asphalt mixture production poses increasing sustainability challenges. This study investigated the potential of entirely replacing granite aggregates with steel slag and PKSA in a dense-graded asphalt mixture. Two sets of asphalt mixtures were prepared; the control mixture contained crushed granite aggregate and hydrated lime, while the other set incorporated steel slag as coarse aggregate and PKSA as fine aggregate and filler. Both mixture types utilized AC-30 viscosity-graded asphalt binder. The properties of the waste materials met the quality standards required for aggregates in asphalt mixture production. Both mixture types were designed according to the Marshall design procedure and were evaluated for durability (Cantabro abrasion loss), fatigue cracking Resistance, rutting Resistance, and moisture damage susceptibility. The Cantabro abrasion loss test indicated that the waste-based mixture was 3% less durable than the control. However, the cracking Resistance of the waste-based mixture was approximately twice that of the control. Even though the rapid rutting test indicated that the control mixture was slightly superior in rutting Resistance, the Marshall quotient suggested otherwise. Both mixture types exhibited similar moisture damage resistance. Overall, the steel slag and PKSA samples have shown high potential to replace virgin granite aggregates and lime in asphalt mixtures fully and are, thus, recommended for field performance evaluation and possible adoption.

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1. INTRODUCTION

Aggregates must satisfy strict quality standards for asphalt mixture production, which often prevents using available marginal-quality aggregates. Apart from the challenge of obtaining high-quality aggregates, adverse environmental impacts associated with aggregate mining could be significant, including landscape alteration, land-use conversion, noise and air pollution, habitat loss, erosion, and sedimentation of water bodies. Dwindling high-quality aggregate reserves and sustainability concerns have warranted

***Corresponding author.**
*E-mail address: nacollins4u@gmail.com

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the exploration of alternative aggregate sources to meet the growing demand for durable pavements. Waste material recycling can enhance sustainable pavement engineering by minimizing virgin material use, reducing landfill space demand, conserving energy, and reducing greenhouse gas emissions associated with extracting and transporting virgin aggregates [1]. Steel slag and palm kernel shell ash are industrial waste materials from steel manufacturing and palm oil milling, respectively.

Steel slag has high strength and abrasive properties and has been found to improve the stability and moisture damage resistance of asphalt mixtures [2, 3]. Sorlini et al. [4] observed that slag-containing asphalt mixtures exhibited mechanical characteristics similar to or better than an asphalt mixture produced with natural aggregates. Kim et al. [5] observed significant improvements in rutting Resistance, tensile strength, and toughness in an asphalt mixture containing slag compared to a mixture with granite aggregate. The slag-containing mixture exhibited 121%, 110%, and 114% in rutting Resistance, tensile strength, and toughness, respectively, compared with the granite aggregate mixture. The relatively high dynamic modulus of the slag-containing mixture was attributed to the strong aggregate interlock and the rough surface texture of the steel slag aggregates. Kehagia [6] and Asi [7] observed that the high strength and irregular shape of steel slag aggregate contribute to improving the skid resistance of asphalt mixtures. Oluwasola et al. [8] found that replacing granite with steel slag (as fine and coarse aggregates) as well as copper mine tailings (as fine aggregate) in hot-mix asphalt improved rutting resistance, resilient modulus, moisture damage susceptibility, Marshall stability, and flow. Díaz-Piloneta et al. [9] noted that carbon emission savings associated with adding steel slag to asphalt mixtures could exceed 14%, compared with asphalt mixtures containing virgin aggregates.

Palm kernel shell ash (PKSA), also referred to as palm oil clinker (POC) or palm oil fuel ash (POFA), results from the incineration of palm kernel shells and other parts of the palm tree when used as fuel for steam generation at oil mills. The pyrolysis residue is typically described as palm kernel shell ash if the biomass fuel comprises predominantly palm kernel shells. PKSA accumulation in the furnace reduces its efficiency, lifespan, and maintenance cost [10]. Several researchers, including [11–14], have explored various engineering applications of PKSA. For instance, Usman [15] investigated the performance of refined dense-graded cold mix asphalt that incorporated PKSA as a filler and observed improved mechanical properties over conventional cold mix asphalt. POFA-modified binder improved Marshall stability and rutting resistance [16, 17], and when POFA was utilized as a filler, volumetric and Marshall properties improved [18, 19] - according to Maleka et al. [20], utilizing POFA as a filler improved durability, Marshall stability, flow, and indirect tensile strength compared with the control mixture which contained 1% Ordinary Portland Cement and 5% mineral filler. Incorporating POFA as a filler at 3% by aggregate weight yielded a mixture with optimum resilient modulus and Marshall stability [21]. Borhan et al. [22] noticed an improvement in the rutting Resistance of PKSA-containing asphalt mixtures when PKSA was used as a filler. Babalghaith et al. [23] concluded that PKSA could fully serve as a fine aggregate in stone matrix asphalt (SMA) mixture for improved rutting and fatigue resistance.

With increasing urbanization and population growth, coupled with the growing demand for steel and palm oil products, slag and PKSA generation is expected to rise, with their accompanying disposal difficulties [10, 24–26], while dwindling quality-aggregate sources for asphalt mixture production and the sustainability issues surrounding their acquisition pose challenges to road agencies.

1.1. Aim and Scope

This study aimed to investigate the feasibility of completely substituting granite aggregate and hydrated lime, traditionally used in the production of dense-graded asphalt (DGA) mixtures, with steel slag and palm kernel shell ash to enhance the sustainability of asphalt mixtures. While prior research has individually examined the benefits of either steel slag or PKSA in asphalt mixtures, this study took a unique approach by concurrently incorporating both waste materials. To achieve the stated aim, lumps of steel slag and PKSA were collected from industry dump sites, crushed into desirable-size fractions using a laboratory device, and characterized to ascertain their suitability as asphalt mixture aggregates. Following the Marshall mixture design procedure, they were then utilized to produce DGA. The control DGA mixture utilized granite aggregate and hydrated lime. Both mixtures used the same grade of asphalt binder. Mixture characterization tests included Marshall stability and flow, moisture susceptibility, Cantabro abrasion loss (durability), indirect tensile cracking, and rutting. Presented in Figure 1 is a flow chart of the experimental program.

2. MATERIALS AND METHODS

2.1. Materials

Granite aggregates obtained from a local quarry in the Ashanti region of Ghana were used to produce a conventional dense-grade asphalt (DGA) mixture designated in this study as the control mixture. Steel slag and PKSA lumps were obtained from dump sites of a steel manufacturer and an oil mill, respectively, in their raw lumps. These lumps were crushed into desirable sizes using a laboratory crusher. The slags had undergone natural aging in a humid environment for several years, experiencing an average annual rainfall of approximately 750mm and daily ambient temperatures ranging between 25°C and 30°C. Subsequently, the crushed aggregates were washed to eliminate dust particles and then oven-dried at a temperature of 105°C. The steel slag served as coarse aggregate in the waste-based mixture, while the PKSA functioned as fine aggregate and filler. Several physical tests were performed on the aggregates to ascertain their suitability for asphalt mixture production. Also, an X-ray fluorescence (XRF) analysis was conducted to determine the chemical composition of the materials. AC-30 viscosity-graded asphalt binder was used in both mixtures; its

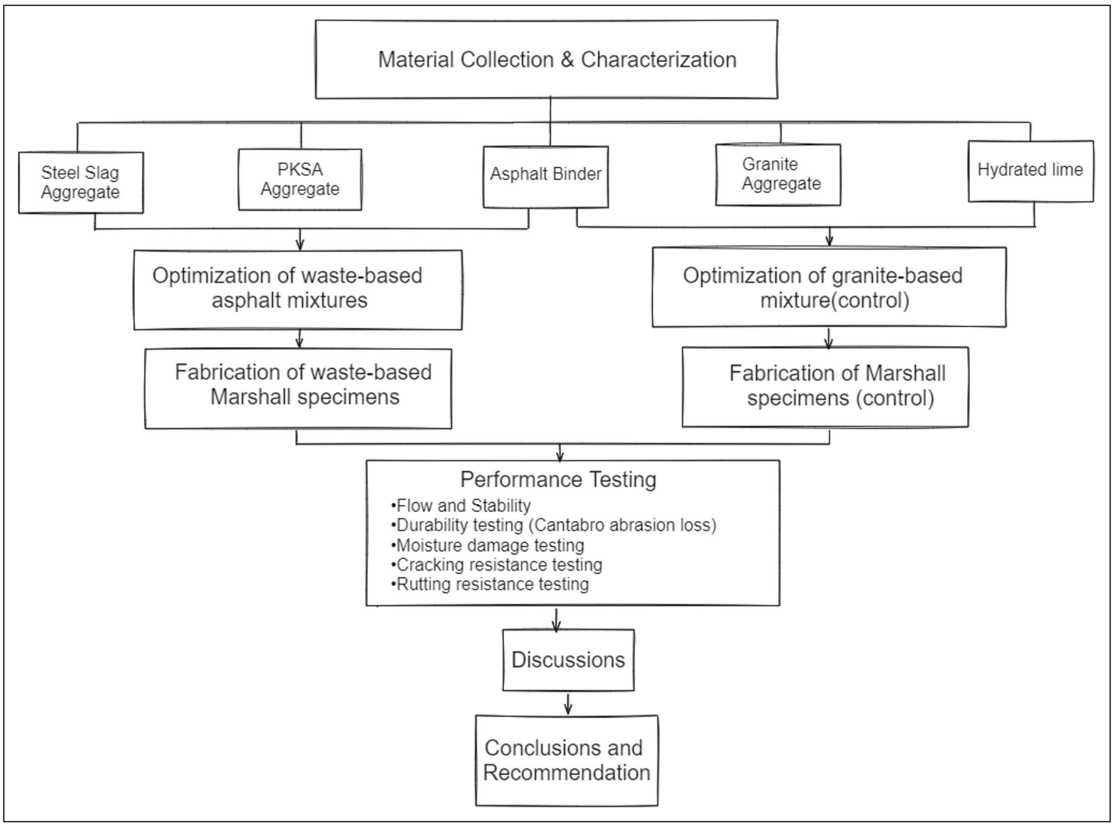

Figure 1. Flow chart of an experimental program.

Table 1. Asphalt binder properties

Property	Procedure (ASTM)	Value	Specification (ASTM D3381)
Penetration at 25°C, 100g, 5s	D5 [27]	65	30 (min)
Flash Point (Cleveland Open Cup)	D92 [28]	332°C	230°C (min)
Kinematic Viscosity at 135°C	D3381 [29]	370 mm²/s	250 mm²/s (min)
Viscosity at 60°C	D4402 [30]	322 Pa.s	240–360 Pa.s
Specific Gravity at 25°C	D70 [31]	1.04	–

Table 2. Aggregate blend composition

Aggregate fraction	Waste-based mixture		Control mixture	
	Material	Composition (%)	Material	Composition (%)
Coarse	Slag	45.5	Granite	46.3
Fine	PKSA	47.6	Granite	46.6
Filler	PKSA	6.9	Granite + Lime	6.1+1.0

properties are provided in Table 1. The aggregate test results are presented under the results and discussion section.

2.2. Mixture Design

The aggregate fractions were blended to conform to the Wearing Course Type I gradation envelope (Fig. 2) specified by the Ministry of Roads and Highways' Standard Specification for Road and Bridge Works [32]. As shown in Table 2, the waste-based aggregate blend comprised 45.5% steel slag aggregates (coarse aggregate) and 54.5% of PKSA (including 6.9% PKSA as filler). The control mixture com-

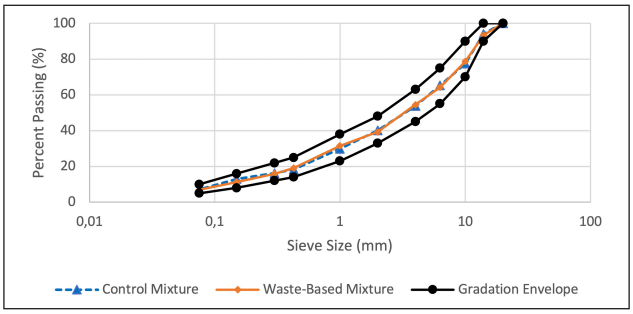

Figure 2. Aggregate gradations of the mixtures.

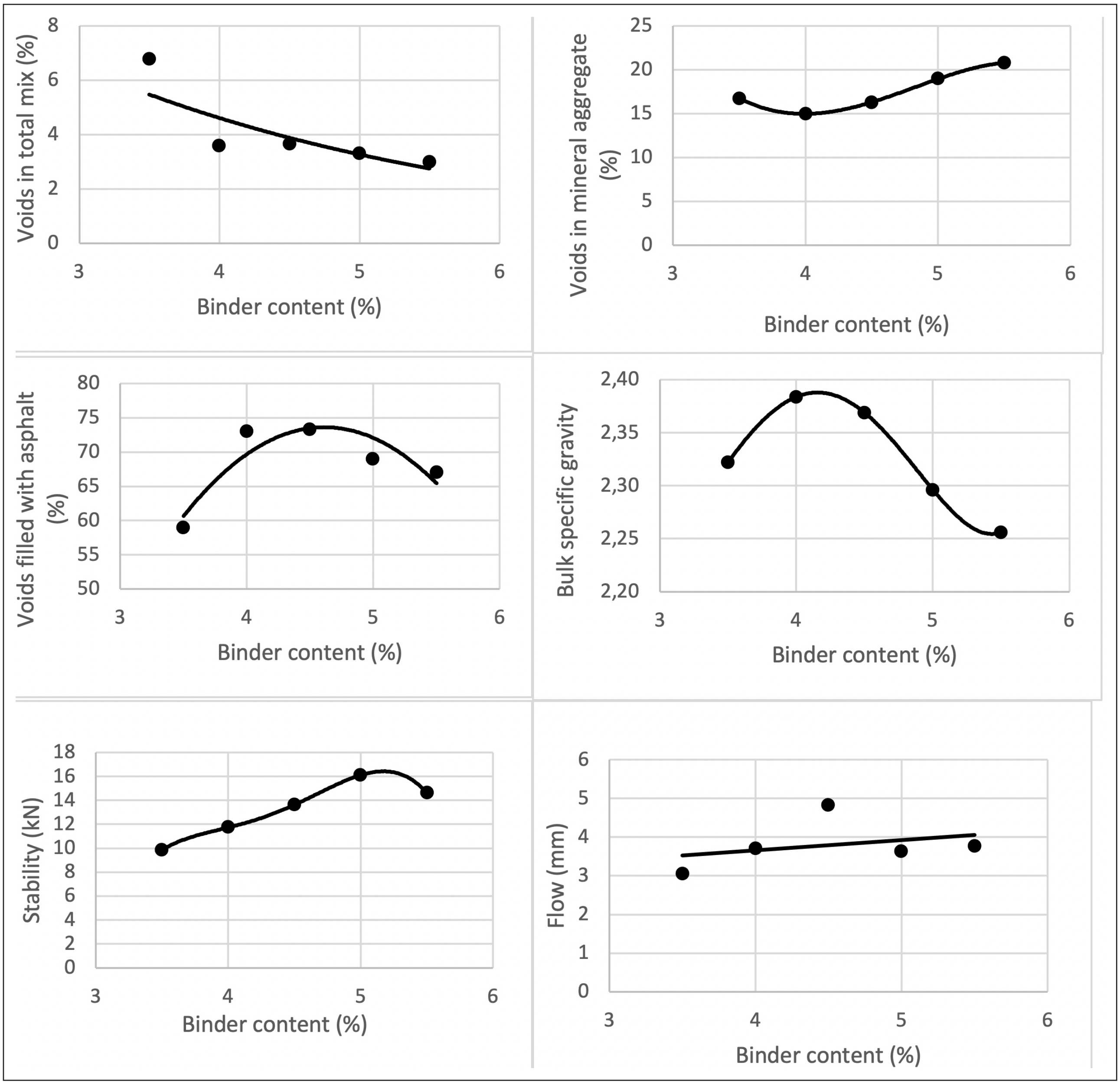

Figure 3. Marshall test results for the control mixture.

prised 99% granite aggregate (including 6.1% mineral filler) and 1% hydrated lime.

The asphalt mixtures were designed per the Marshall procedure [33] to conform to the Standard Specification for Road and Bridge Works [32]. Trial asphalt mixtures were prepared at 3.5% to 5.5% binder contents. The mixtures were produced at 160°C, aged for two hours per [34], and compacted at 130°C, with 75 blows per face. Figures 3 and 4 show asphalt binder content versus the properties of the control and waste-based mixtures, respectively. Following the Asphalt Institute method [35], the optimum binder content corresponding to 4% air voids was determined as 4.5% and 5% for the control and waste-based mixtures, respectively. The effective binder content, which refers to the amount of asphalt binder in an asphalt mixture that is available to coat and bind the aggregate particles together effectively, was, however, found to be 4.3% and 4.2%, respectively, for the control and waste-based mixtures. Table 3 shows the mixture properties at the respective optimum binder contents.

To cast samples at 7% air voids, trial mixtures were fabricated at different numbers of Marshall blows (i.e., 30, 45, and 60). Forty-eight (48) Marshall blows corresponded to 7±1% air voids for both mixtures.

2.3. Mixture Performance Testing

2.3.1. Durability

The Cantabro abrasion loss test [36] was employed to assess the durability of the mixtures. Traditionally utilized for characterizing Open Graded Friction Course (OGFC) mixtures, this test has undergone validation for its applicability to dense graded mixtures [37]. It has proven effective in distinguishing

Table 3. Mixture properties and specification requirements at optimum binder contents [32]

Mixture property	Mixture type		Specification
	Control (P_b=4.5%)	Waste-based (P^b=5.0%)	
Marshal Stability (2×75 blows) (kN)	13.8	11.0	9–18
Marshal Flow (mm)	3.7	2.8	2–4
VTM (%)	3.8	4.2	3–5
VFA (%)	73	69	65–75

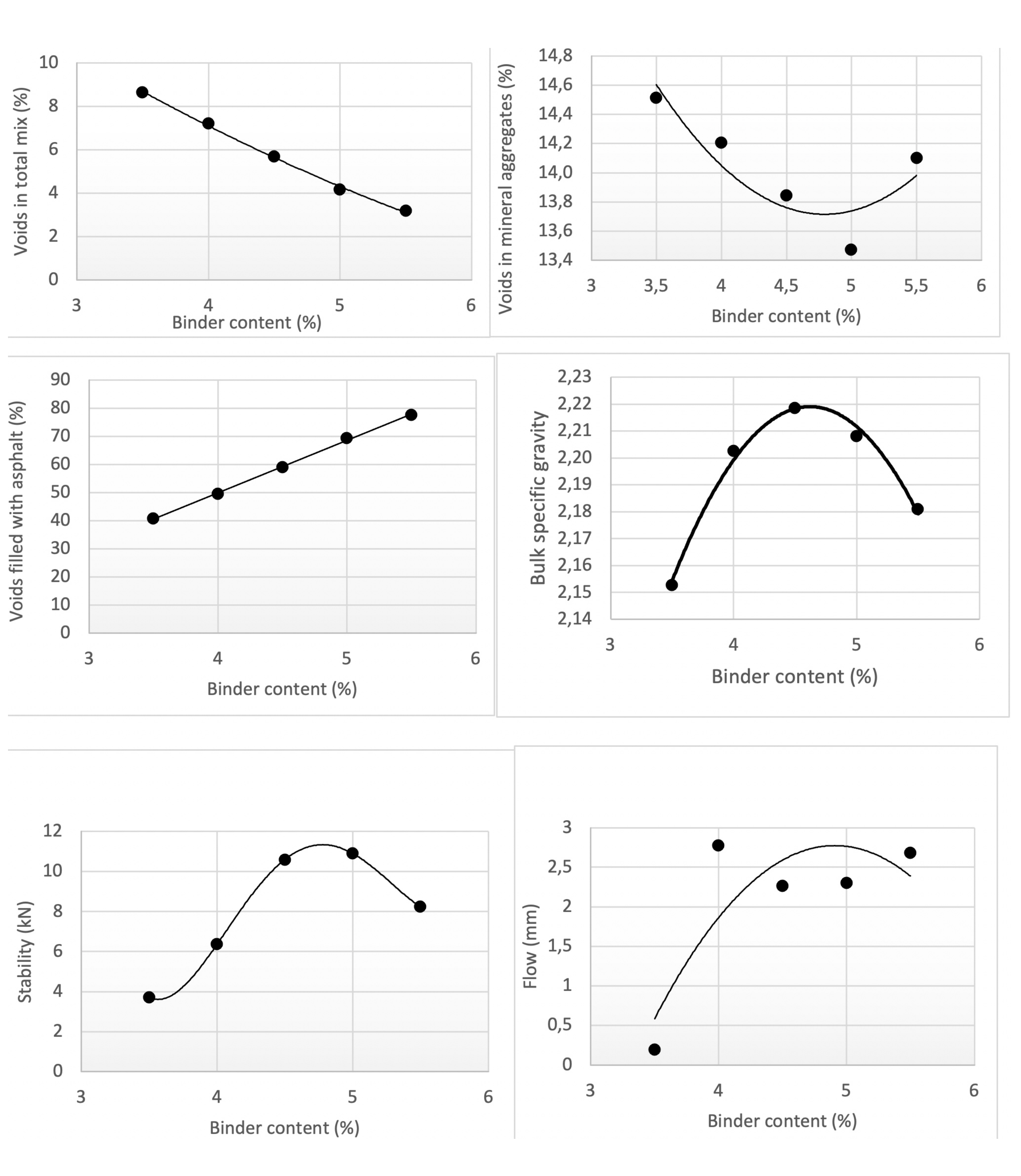

Figure 4. Marshall test results for the waste-based mixture.

Table 4. Aggregate test results

Property	Procedure	Value			MRH (2007) Specification
		Granite	Steel Slag	PKSA	
Los Angeles Abrasion (%)	ASTM C131 [52]	25	37	–	40 (max)
Ten Percent Fines (kN)	BS 812 [53]	211	234	–	160 (min)
Flakiness Index (%)	ASTM D4791 [54]	9	25	–	25 (max)
Coarse aggregate angularity (%)	ASTM D5821 [55]	100	100	–	[2]90–100
Fine aggregate angularity (%)	ASTM C1252 [56]	47	51	29	[3]45 min.
Plasticity index (%)	AASHTO T90 [57]	NP	NP	NP	NP
Moisture Absorption (%)	ASTM C127 [58]	0.11	0.60	7.2	1.0 (max)*
Aggregate Crushing Value (%)	BS 812 [53]	18	20	–	30 (max)[1]
Aggregate Impact Value (%)	BS 812 [53]	12	15	–	30 (max)[1]
Elongation Index (%)	ASTM D4791 [54]	14	10	–	15 (max)[1]
Specific Gravity	ASTM C127 [58]	2.692	2.835	1.903	–
Sodium Sulphate Soundness (%)	ASTM C88 [59]	0.9	1.2	1.8	15 (max)[2]

Source: [1][60], [2][61]; [3][62]; NP – Nonplastic; *: Not applicable to PKSA.

various mixture characteristics that play a role in durability, encompassing factors such as binder type and content, aggregate type, air void content, binder absorption, and aging [38, 39].

Three Marshall specimens for each mixture type were prepared at the 4.5% and 5.0% optimum binder content for the control and waste-based mixtures, respectively. The loose mixtures were short-term aged [34] and then compacted to 7% air voids. Having measured the initial mass of the Marshall-compacted specimens, each was subjected to abrasion in the Los Angeles abrasion machine for 300 revolutions (without steel balls). The final specimen mass was measured, and the Cantabro abrasion loss index (CALindex) was computed using Equation 1.

$$\mathrm{CAL_{index}} = \left(\frac{\text{Initial Specimen Mass} - \text{Final Specimen Mass}}{\text{Initial Specimen Mass}}\right) \times 100 \quad (1)$$

2.3.2. Moisture Damage Resistance

The modified Lottman test [40] was performed to evaluate the moisture damage susceptibility of the mixtures. Six Marshall specimens for each mixture type were fabricated at 7% air voids using the optimum binder contents of 4.5% and 5.0% for the control and waste-based mixtures, respectively. A subset (three of the specimens) of each mixture type was conditioned per [40] (except for the freeze-thaw cycle), while the other subgroup was unconditioned. Both sets of specimens were subjected to monotonic loading at a rate of 50 mm/min, and the failure load was used to calculate the tensile strength using Equation 2. The tensile strength ratio (TSR) was calculated as the ratio of the average tensile strength of the conditioned specimens to that of the unconditioned specimens.

$$S_t = \frac{2000P}{\pi t D} \quad (2)$$

where,
S_t=tensile strength (kPa)
P=maximum load (N)
t=specimen thickness (mm)
D=specimen diameter (mm)

Table 5. XRF analysis results

Oxide	Percent composition by mass			
	Granite	Steel slag	PKSA	Hydrated lime
SiO_2	84.4	52.4	70.8	43.9
Al_2O_3	13.0	15.0	6.6	12.4
K^2O	0.8	0.0	7.3	2.0
Fe_2O_3	0.4	11.8	3.8	3.9
CaO	0.1	5.3	3.9	31.6
MnO	0.0	9.7	0.0	0.1
MgO	0.0	1.2	3.7	4.7
Traces	1.3	4.6	3.9	1.4
Total	**100.0**	**100.0**	**100.0**	**100.0**

2.3.3. Cracking Resistance

The indirect tensile cracking test [41] was employed to evaluate the cracking susceptibility of the mixtures. The efficacy of the test has been confirmed through the analysis of pavement performance data gathered from various experimental facilities. It has effectively predicted fatigue, reflective, top-down, and thermal cracking [42]. To add to its practicality, laboratory specimens, and field cores, prepared using Marshall or Gyratory compactors, can be readily utilized in this test, eliminating the need for additional procedures such as notching, drilling, instrumentation, or cutting [43–45].

The control and waste-based compacted specimens (three each) were produced at 4.5% and 5.0% optimum binder content, respectively. Similarly, the loose mixtures were short-term aged [34] and compacted to 7% air voids. The specimens were loaded in a universal testing machine at a constant rate of 50 mm/min at 25°C until failure. The cracking tolerance index (CT_{index}), a fracture mechanics-based parameter, was computed using Equation 3 [41] to evaluate the cracking Resistance of the mixtures. A higher C.T. index denotes higher cracking resistance.

$$\mathrm{CT_{index}} = \frac{t}{62} \times \frac{l_{75}}{D} \times \frac{G_f}{|M_{75}|} \times 10^6 \quad (3)$$

where:
CT_{index}=cracking tolerance index
Gf=failure energy (Joules/m^2)
$|M_{75}|$=absolute value of the post-peak slope (N/m)
l_{75}=displacement at 75% of the peak load after the peak (mm)
D=specimen diameter (mm)a
t=specimen thickness (mm)

2.3.4. Rutting Resistance

The rapid rutting test [46] was performed to assess the rutting Resistance of the mixtures, except that Marshall-compacted specimens were used instead of 150-mm diameter gyratory-compacted specimens. Additionally, a concave supporting cradle with a curvature radius equal to the nominal radius of the test specimen was not used. This omission proved inconsequential in the comparative assessment of rutting Resistance between the two mixture types, given the absence of a standard RT_{index} criterion for asphalt mixtures at the time of the study. This simple test – which is repeatable, reproducible, and sensitive to asphalt mixture components such as binder type and content, aggregate type and gradation, additives, and mixture aging – has shown good correlation with well-established simulative and fundamental rutting tests and field performance [47–49].

The mixtures were produced at 4.5% and 5.0% binder content for the control and waste-based mixtures, respectively. They were short-term aged [34] and compacted to 7% air voids. The specimens were then conditioned in a 60°C water bath for 45 minutes and loaded at 50 mm/min until failure. The failure loads were used to calculate the shear strengths of the mixtures (Equation 4), which were subsequently used to determine rutting tolerance indices (RT_{index}) using Equation 5. The rutting tolerance index is a performance indicator where higher values indicate higher rutting Resistance.

$$\tau_f = 0.356 \times \frac{P_{max}}{t \times w} \tag{4}$$

where:
τ_f=shear strength (Pa)
P_{max}=maximum load (N)
T=specimen thickness (m)
W=width of upper loading strip (=0.0191 m)

$$RT_{Index} = 6.618 \times 10^{-5} \times \frac{\tau_f}{1P_a} \tag{5}$$

where:
RT_{Index}=rutting tolerance index
τ_f=shear strength calculated from Equation 4.

2.3.5. Marshall Quotient

Marshall quotient, computed as the ratio of stability to flow, is a recognized indicator of asphalt mixture rutting resistance [2, 50]. The Marshall stability and flow were measured per [51]. Three Marshall-compacted specimens (4% air voids) for each mixture type produced at the optimum binder content (4.5% and 5.0% for the control and waste-based mixtures) were conditioned in a 60°C water bath for 30 minutes. The conditioned samples were loaded at a 50.8 mm/minute rate until failure. The failure load was recorded as the stability, and the total plastic deformation was recorded as the flow. A higher Marshall quotient indicates higher asphalt mixture rutting Resistance.

3. RESULTS AND DISCUSSION

3.1. Aggregate Characteristics

Tables 4 and 5 show the physical and chemical properties of the aggregates, respectively. Although higher for steel slag, the Los Angeles Abrasion (LAA) values met specification requirements [32]. The granite and steel slag passed water absorption specifications [32]. PKSA had the highest water absorption value, which may be explained by the presence of a significant proportion of the deliquescent compound K_2O, as the XRF analysis results in Table 5 show. While binder absorption and water absorption are not equal in value, higher water absorption of the steel slag and PKSA aggregates indicates higher porosity, which could result in increased binder absorption.

Both steel slag aggregates and granite demonstrated similar characteristics in coarse aggregate angularity. However, steel slag aggregates showed a higher fine aggregate angularity (FAA) than granite. The angularity of aggregates plays a crucial role in determining mixture stability, with higher angularity values contributing to increased strength. The high FAA of steel slag has the potential to counterbalance the low FAA associated with PKSA to improve overall mixture stability. The steel slag aggregates generally exhibited comparable or better mechanical strength characteristics to the granite. The steel slag aggregates were denser and less elongated but flakier than the granite aggregates. Considering their Resistance to sodium sulfate deterioration, all three aggregates could withstand weathering.

The X-ray Fluorescence (XRF) analysis revealed the presence of CaO, Al_2O_3, Fe_2O_3, and MgO in significant proportions in the steel slag and PKSA, indicating their inherent pozzolanic properties. Pozzolanic property has the potential to improve the strength and durability of asphalt mixtures [63]. However, volume instability failures have been found to be typical of slag due to the presence of free lime (f-CaO) and MgO [64, 65]. The f-CaO, or free calcium oxide, refers explicitly to an unhydrated form of CaO in a material. High levels of f-CaO in materials like slag can lead to delayed ettringite formation in asphalt concrete, causing expansion and potential durability issues. One recommended approach, as suggested by Juckes [66], involves subjecting CaO-containing aggregates to an aging process. This method has proven effective in promoting the complete hydration of f-CaO. Wu et al. [67] noted that after three years of aging, the f-CaO content of steel slag aggregates fell below 6%, which posed an insignificant threat to deleterious expansion. According to the XRF results in Table 5, both steel slag and PKSA aggregates have CaO contents of 5.3% and 3.9%, respectively – suggesting low levels of f-CaO and adequate aging of both materials. The relatively low levels of f-CaO in these aggregates suggest a diminished threat of volume instability.

Furthermore, the dominant presence of silica (Si_2O) in all three aggregates (ranging from 52% to 84% by mass) indicates remarkable similarities, positioning them as viable alternatives to granite aggregate in asphalt mixtures. In essence, both the waste-based aggregates (steel slag and PKSA) and natural aggregates (granite) characterized in this study met the criteria for asphalt mixture production, emphasizing steel slag and PKSA aggregates' suitability and potential contribution to sustainable asphalt construction practices.

3.2. Mixture Performance

Figure 5 shows the average values for the mixture performance indicators: tensile strength ratio (TSR), rutting tolerance index (CT_{index}), Cantabro abrasion loss index, cracking tolerance index (CT_{index}), and Marshall quotient.

3.2.1. Moisture Damage Resistance

Although hydrated lime was absent in the waste-based mixture, it exhibited similar moisture damage resistance as the control, which contained 1% hydrated lime. Hydrated lime improves moisture damage resistance [68, 69]. Even without lime, the waste-based mixture's comparable performance may have been influenced by the low acidity and high porosity observed in steel slag and PKSA aggregates. Adequate adhesion within a bitumen-aggregate system enhances moisture damage resistance [70]. The mechanical interlocking theory [71] provides insights into the formation of a strong bond between bitumen and aggregate. This bond arises from the interlocking when hot bitumen permeates aggregate pores and air voids, coating irregularities on the aggregate surface. Subsequent cooling establishes and forms robust mechanical forces. A higher number of pores, a rough texture with angularity, and microstructures such as pores, voids, and microcracks contribute to mechanical interlocking [72]. In contrast, aggregates with high silica content (>65% by mass) tend to be geologically acidic, resulting in a weaker bond with asphalt binder. Conversely, a rough aggregate surface and fine microstructures increase the adsorptive surface available for binder adhesion [73]. It is worth noting that while the standard specification for Road and Bridge Works [32] currently does not incorporate the moisture damage test as a criterion for the mixture design of the wearing course, it is commonly recommended to adhere to a minimum tensile strength ratio of 0.8 as a best practice, which both mixtures exceeded.

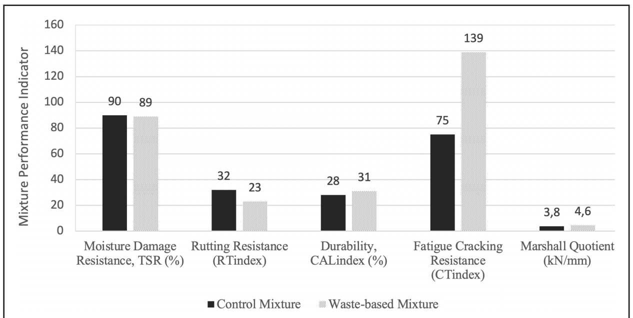

Figure 5. Performance testing results of the control and waste-based asphalt mixtures.

Analyzing the X-ray fluorescence (XRF) results from Table 5, it becomes evident that the waste-based mixture aggregate exhibited low acidity (weighted silica content of 62.43%) compared to the control mixture aggregate (weighted silica content of 84%). Looking closely at the steel slag and PKSA aggregates, conspicuous permeable pores were observed on their surfaces. Notably, the steel slag aggregate particles exhibited a more angular morphology than the granite aggregates. These physical characteristics may have influenced the moisture damage resistance of the waste-based mixture. Several studies have also reported improved asphalt moisture damage resistance when palm oil fuel ash (and its variants including PKSA) [19, 20, 74] and steel slag aggregates [2, 8] were utilized separately in asphalt mixtures, in some cases better than hydrated lime.

3.2.2. Cracking Resistance

The waste-based mixture exhibited a higher cracking resistance performance, with a CT_{index} 85% higher than the control. Several studies have also reported improved cracking resistance of mixtures by incorporating steel slag [75–78] and PKSA (and its variants) [22, 74] into asphalt mixtures. The frequently cited reasons have been the strong, angular, rough-textured steel slag aggregates, which provide better interlocking, contributing to improved cracking resistance [79], as well as the pozzolanic cementing nature of PKSA which improves aggregate-binder adhesion and overall durability. The better-cracking Resistance of the waste-based mixture, despite its lower effective binder content of 4.2% compared to 4.3% of the control, suggested that the PKSA-based mastic better tolerated cracking than the mastic of the control mixture, which contained mineral filler and hydrated lime. There is no established standard criterion for DGA mixtures based on the C.T. index. However, it is reported that poorly performing DGA mixtures typically exhibit CT_{index} values below 70, while well-performing ones usually yield values exceeding 100 [80].

3.2.3. Rutting Resistance

The rapid rutting test results showed that the waste-based mixture possessed slightly lower rutting Resistance. However, this finding was inconsistent with the Marshall quotient, which indicated that the waste-based mixture had higher rutting Resistance. This inconsistency between the two test results suggests that factors other than those captured by the Marshall quotient may influence the waste-based mixture's rutting behavior. The RT_{index} is a shear strength-based rutting performance indicator. Since rutting is considered a shear failure, it is reasonable to suggest that the RT_{index} better characterizes the rutting Resistance of asphalt mixtures. Thus, it is logical to infer that the rapid rutting test is sensitive to specific characteristics of the waste-based mix that are not fully reflected in the Marshall Stability and Flow test. Therefore, further analysis and investigation may be needed to understand better the factors contributing to the rutting behavior observed in the waste-based mixture. The Marshall testing protocol involves the application of a monotonic compressive loading along the circumference of a fully, laterally confined specimen, causing shear or deformation failure.

The rapid rutting test, on the other hand, applies monotonic compressive loading; however, as is done in the indirect tensile test, the specimen is placed in a supporting concave cradle before loading. Due to the three-point bending, this process creates two separate shear planes along the specimen's diametral surface. In this study, only one shear plane was developed since the supporting cradle was not used. It is worth noting that the RT_{index} in this study serves as indicative metrics to compare the rutting Resistance of the waste-based and control mixtures. They should not be interpreted outside the scope of this study.

3.2.4. Durability

The Cantabro abrasion loss test indicated that the control mixture was marginally better than the waste-based mixture. While there is no widely accepted criterion of Cantabro abrasion loss for dense graded asphalt mixtures, for open-graded friction course mixtures, [81] specifies an average Cantabro abrasion loss of 20% and 30% for unaged and aged compacted specimens, respectively. In comparison, the maximum loss for an individual specimen is 50%. The better abrasion resistance performance of the control mixture over the waste-based mixture may be attributed to the synergetic effect of the higher effective binder content and 1% active filler (hydrated lime) of the control mixture. Binder cohesion is crucial for abrasion loss resistance [82]. Hydrated lime has a high surface area and can absorb fines present in the asphalt mixture. This absorption can lead to a uniform distribution of fines within the binder, promoting better cohesion in the asphalt mortar. Higher Cantabro values indicate less Resistance to material loss due to abrasion, as the Los Angeles Abrasion Machine simulated.

4. CONCLUSIONS AND RECOMMENDATIONS

This study investigated the potential of entirely replacing granite aggregates with steel slag and palm kernel shell ash (PKSA) in a dense-graded asphalt mixture. The control mixture incorporated granite aggregate and 1% hydrated lime as an active filler, while the waste-based mixture utilized steel slag and palm kernel shell ash. The following conclusions and recommendations are provided based on the findings from this study:

- Steel slag and PKSA passed aggregate quality requirements for use in asphalt mixtures.
- XRF analysis identified silica (SiO_2) as the dominant compound in the steel slag and PKSA, which is also prevalent in granite aggregate. The steel slag and PKSA also contained the cementitious compounds CaO, MgO, and K_2O, which might have benefited the moisture damage resistance of the asphalt mixture.
- Despite the absence of hydrated lime in the waste-based mixture, it exhibited similar moisture damage resistance as the control mixture, which contained hydrated lime.
- The rapid rutting test and Marshall quotient predicted contradictory rutting performance of the mixtures. While the rapid rutting test suggested the control mixture had higher rutting Resistance, the Marshall quotient indicated otherwise. This inconsistency underscores the need to diversify asphalt mixture rutting performance characterization.
- The waste-based mixture exhibited cracking Resistance approximately twice as the control. The higher asphalt binder content of the waste-based mixture might have contributed to this observation.
- The Cantabro abrasion loss suggested that the control mixture was slightly durable; however, the difference is insignificant. Hence, both mixtures could have similar durability in service.
- Overall, steel slag and PKSA have shown high potential to replace conventional aggregates in asphalt mixtures thoroughly and are, thus, recommended for field performance evaluation to confirm the observed laboratory performance and possible implementation on real-life projects.

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ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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