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EVALUATION OF MARSHALL AND VOLUMETRIC PROPERTIES OF HOT-MIX ASPHALT WITH HIGH RECLAIMED ASPHALT PAVEMENT CONTENT, EXPANDED POLYSTYRENE-MODIFIED BITUMEN, AND WASTE ENGINE OIL

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Abstract: *The increasing use of virgin materials in asphalt production contributes to resource depletion, while the accumulation of non-biodegradable polymer waste poses significant environmental challenges. This study investigated the volumetric and Marshall properties of hot-mix asphalt (HMA) containing high proportions of reclaimed asphalt pavement (RAP), polystyrene-modified bitumen, and waste engine oil (WEO) as a rejuvenating agent. The constituent bitumen and mineral aggregates were initially characterized in accordance with relevant standards. A Marshall mix design was subsequently conducted to determine the optimum binder content (OBC) of a control mixture using virgin materials at bitumen contents ranging from 5.0 to 7.0% at 0.5% increments. RAP was then incorporated at replacement levels of 25, 50, 75, and 100% of the virgin coarse aggregate, while the bitumen was modified with 4, 6, and 8% polystyrene. WEO, corresponding to 15% of the OBC, was incorporated as a rejuvenating agent. The results showed that the constituent materials satisfied the relevant specification requirements, while an OBC of 7.0% was obtained for the control mixture. The Marshall stability values of the investigated mixtures exceeded the minimum specified value of 3.5 kN, and flow values generally remained within the specified range of 2–4 mm, although some mixtures containing 100% RAP exceeded the flow limits. However, most of the evaluated volumetric properties did not satisfy the specified requirements, despite VMA generally exceeding the minimum allowable value. These results indicate that the use of high RAP contents in combination with polystyrene-modified bitumen and WEO has potential for producing HMA with acceptable Marshall stability, but optimization of binder content, WEO dosage, polystyrene concentration, and compaction conditions is required to achieve satisfactory volumetric characteristics and full compliance with specifications. Further performance-based evaluation is recommended to establish the suitability of the modified mixtures for practical pavement applications.*

Key words: Marshall properties, reclaimed asphalt, expanded polystyrene, hot mix asphalt and waste engine oil.

1 Introduction

Reclaimed asphalt pavement (RAP) refers to asphalt concrete materials obtained from the milling or removal of existing or aged pavement. RAP is a highly recyclable construction material because it contains valuable non-renewable resources, consisting primarily of aggregates and aged bituminous binder. Typically, RAP contains approximately 95% aggregates and 5% aged bituminous binder by weight, which can be recovered and reused in the production of new asphalt mixtures (Tarsi et al., 2020). The reuse of RAP therefore provides an opportunity to conserve natural resources and reduce the demand for virgin materials in pavement construction.

RAP is increasingly recognized as a viable alternative to virgin materials because its incorporation reduces the demand for virgin aggregates, which are becoming increasingly scarce in some regions, and decreases the quantity of new bitumen binder required for the production of bituminous mixtures (Copeland, 2011; Magar et al., 2022). The use of RAP also aligns with global efforts to address environmental challenges by promoting resource efficiency, reducing the consumption of virgin materials, and potentially lowering the energy consumption and carbon emissions associated with asphalt production (Tarsi et al., 2020). These benefits are particularly important because road construction and maintenance require substantial quantities of energy and raw materials and generate significant greenhouse-gas emissions. Moreover, the increasing generation of pavement waste at the end of its service life further highlights the need for sustainable pavement materials and effective recycling strategies (Choi, 2019; Magar et al., 2022; Purchase et al., 2021; Tsakoumaki and Plati, 2024).

In addition to its environmental and economic benefits, the incorporation of RAP can influence the engineering properties of asphalt mixtures. Previous studies have shown that RAP can improve certain mechanical properties, particularly mixture stiffness and resistance to permanent deformation, thereby potentially enhancing resistance to rutting (Ozer et al., 2009). Thus, RAP provides a dual benefit to the pavement industry by contributing to the conservation of natural resources and reduction of construction waste while potentially improving selected mechanical characteristics of asphalt mixtures. However, the benefits of RAP may become increasingly complex as its content increases. The aged binder present in RAP is generally stiffer and more brittle than virgin bitumen, and its increasing contribution to the mixture can result in excessive stiffness and reduced flexibility, potentially compromising pavement performance. Consequently, although high RAP contents offer considerable environmental and economic advantages, appropriate binder modification and/or rejuvenation strategies may be required to mitigate the adverse effects associated with aged RAP binder and achieve an appropriate balance between stiffness, strength, flexibility, and workability.

Previous studies have demonstrated that the incorporation of relatively low RAP contents, typically up to approximately 30%, can produce satisfactory or promising asphalt mixture performance. However, the increasing generation of RAP, coupled with the declining availability and rising cost of natural aggregates and petroleum-derived materials such as bitumen, has strengthened the need to explore the incorporation of higher RAP contents in asphalt mixtures. The use of high RAP contents can substantially reduce the consumption of virgin aggregates and bitumen and provide greater opportunities for recycling pavement materials. Nevertheless, increasing the RAP content also introduces performance-related challenges that require appropriate material and mix-design strategies.

One of the major concerns associated with high RAP contents is the increased stiffness of the resulting asphalt mixture due to the presence of aged and relatively stiff binder. Excessive stiffness may reduce mixture flexibility and increase susceptibility to cracking, particularly under low-temperature conditions (Li et al., 2008; West et al., 2013). Similarly, the increased stiffness and brittleness associated with high RAP contents have been reported to adversely affect fatigue performance under repeated traffic loading (Li et al., 2018; Shen et al., 2007). High RAP contents have also been associated with increased susceptibility to moisture-related damage and reduced workability during mixing and compaction (Copeland, 2011; Hidalgo et al., 2020; Majidifard et al., 2019). Although these performance concerns are well documented in the literature, they also highlight the importance of developing appropriate modification and rejuvenation approaches for high-RAP asphalt mixtures.

The use of rejuvenating agents is one approach for mitigating the adverse effects associated with aged RAP binder. Asphalt binders consist primarily of asphaltene and maltene fractions, with asphaltenes generally regarded as the dispersed phase and maltenes as the dispersion medium. During asphalt ageing, changes in the relative proportions and interactions of these components contribute to increased binder stiffness and reduced flexibility. Consequently, an important function of a rejuvenating agent is to reduce the stiffness of aged RAP binder and restore desirable binder characteristics, partly through modification of the balance and interaction between its maltene and asphaltene fractions (Rafiq et al., 2021). Rejuvenating agents can therefore restore some of the desirable properties of aged asphalt binders, including flexibility and workability (Al-Saffar et al., 2021).

However, restoration of rheological properties of bitumen does not necessarily imply complete restoration of the original chemical characteristics of virgin bitumen. Mazzoni et al. (2018) reported that aged binders blended with rejuvenating agents can exhibit rheological properties comparable to those of virgin binders, while their chemical compositions, including the asphaltene-to-maltene ratio, may remain substantially different. Such differences may influence the long-term behaviour and performance of asphalt mixtures containing rejuvenated RAP binder. Therefore, the selection and dosage of rejuvenating agents are important considerations in the development of high-RAP asphalt mixtures.

Among the materials investigated as rejuvenating agents, waste engine oil (WEO) has attracted considerable attention because of its availability, relatively low cost, and compatibility with asphalt binder. The molecular constituents of WEO share certain similarities with those of petroleum-derived bitumen materials, allowing WEO to interact with and soften aged bitumen (Al-Saffar et al., 2021). The use of WEO as a rejuvenating agent also provides an opportunity to convert an environmentally problematic waste material into a useful construction resource, thereby generating potential environmental and economic benefits. Nevertheless, the dosage of WEO must be carefully controlled. Excessive WEO can excessively soften the binder and adversely affect properties such as adhesion, rutting resistance, and cracking resistance, whereas insufficient WEO may not adequately restore the properties of the aged binder. Several studies have reported approximately 15% WEO, relative to the binder content, as an effective dosage for rejuvenating aged asphalt materials (Khan et al., 2021; Mamun et al., 2018).

Although rejuvenation can restore some desirable properties of aged RAP binder, excessive softening and increased flow have also been reported following the addition of rejuvenating agents (Khan et al., 2021). This limitation has encouraged the use of binder modification techniques to improve the rheological and mechanical properties of asphalt mixtures containing RAP (Al-Ghurabi and Al-Humeidawi, 2023; Khan et al., 2021; Li et al., 2024; Rafiq et al., 2021; Stimilli et al., 2017). In particular, polymer modification has received considerable attention because polymers can improve selected binder and mixture properties while, when waste polymers are used, simultaneously contributing to waste reduction and environmental sustainability. Various waste and polymer-based materials have been investigated for asphalt modification, including waste tyre rubber (Wang et al., 2018), waste plastic bottles (Modarres and Hamedi, 2014), lignin (Xin et al., 2016), polyvinyl chloride (Murana et al., 2024), and expanded polystyrene (EPS) (Anwar et al., 2021; Murana et al., 2021; Nciri et al., 2020).

Expanded polystyrene (EPS) is a lightweight, cellular thermoplastic material derived from polystyrene and is commonly produced by expanding polystyrene beads using steam. Its physical and adhesive characteristics make it potentially suitable for incorporation into bituminous binders and asphalt mixtures (Anwar et al., 2020; Zhu et al., 2014). The use of EPS in asphalt materials is also attractive from a sustainability perspective because waste EPS from packaging and other applications can be diverted from disposal and converted into a value-added construction material.

Several studies have demonstrated the potential of EPS for modifying asphalt binders and mixtures. Nassar et al. (2012) reported that the incorporation of

EPS increased viscosity at 60°C and 135°C, increased the softening point, reduced penetration, and improved Marshall stability, while also increasing air voids and reducing flow. Al-Haydari and Masued (2017), however, reported that EPS modification reduced penetration and ductility and increased viscosity and softening point, but its effects on stability and volumetric properties differed from those reported by Nassar et al. (2012). Murana et al. (2020) investigated EPS obtained from disposable food packaging and reported reductions in penetration, ductility, flow, and specific gravity with increasing EPS content, accompanied by increases in softening point and stability. Similar beneficial effects of polymer-based modification of asphalt materials have also been reported by Baker et al. (2016), Oriaje et al. (2022), Kumar et al. (2019), and Abinaya et al. (2016). These findings suggest that EPS has potential for modifying asphalt binder and improving selected properties of asphalt mixtures.

Despite the growing interest in high-RAP asphalt mixtures and the separate application of polymer modifiers and waste-derived rejuvenating agents, limited research has investigated the combined use of EPS-modified bitumen and WEO as a rejuvenating agent in high-RAP hot mix asphalt, particularly at very high RAP replacement levels. Furthermore, the interaction between RAP content, EPS modification level, and WEO dosage and their combined effects on the Marshall and volumetric properties of HMA remain insufficiently understood. This knowledge gap is particularly important because increasing RAP content can increase mixture stiffness, whereas rejuvenation with WEO can excessively soften the binder. The simultaneous use of EPS and WEO may therefore provide a means of achieving a more appropriate balance between stiffness and flexibility in high-RAP asphalt mixtures.

Accordingly, this study evaluates the volumetric and Marshall properties of hot mix asphalt incorporating high RAP contents, EPS-modified bitumen, and WEO as a rejuvenating agent. The study examines the effects of varying RAP and EPS contents on Marshall stability, flow, Marshall Quotient, and volumetric properties and assesses the extent to which WEO can be used to rejuvenate the aged RAP binder while maintaining acceptable mixture characteristics.

The findings provide insight into the potential of combining EPS modification and WEO rejuvenation for the production of high-RAP asphalt mixtures and provide a basis for further performance-based investigations of their moisture susceptibility, fatigue, rutting, and long-term durability.

2 METHODOLOGY

2.1 Materials

The materials used for this and their sources is presented as follows.

2.1.1 Bitumen

The bitumen used for this study is of penetration grade obtained from Julius Berger Nigeria limited.

2.1.2 Waste Expanded Polystyrene (EPS)

EPS obtained from disposable food pack was sourced from open dumps in Zaria metropolis and was used to modify bitumen.

2.1.3 Waste Engine Oil (WEO)

WEO, which served as a rejuvenator to restore the aged binder's properties in Reclaimed Asphalt Pavement (RAP) was obtained from a filling station in Zaria, Kaduna state.

2.1.4 Coarse Aggregate

Coarse aggregates used are aggregates with particle sizes retained on a 4.75 mm sieve and sourced from a local quarry in Zango, Zaria, Kaduna state, Nigeria.

2.1.5 Fine Aggregate

Fine aggregates used are aggregates with particles sizes between 4.75- and 0.075-mm sieves which were sourced from a local quarry in Zango, Zaria, Kaduna state, Nigeria.

2.1.6 Filler

Quarry dust with particles passing a 0.075 mm sieve was sourced from a local quarry in Zango, Zaria, Kaduna state, Nigeria.

2.1.7 Reclaimed Asphalt Pavement (RAP)

Reclaimed asphalt used is milled aged pavement material that is stockpiled at in one of the Julius Berger Nigerian Limited sites at Dumbin Dutse, along Zaria-Kaduna Road.

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2.2 Methods

Physical and chemical properties tests were conducted on bitumen, mineral aggregates (fine and coarse aggregates, and filler), while Marshall test was conducted on the bituminous concrete mixes. All the testing except Fourier Transform Infrared Spectroscopy (FTIR) was conducted in the Department of Civil Engineering, Ahmadu Bello University in accordance with code specifications highlighted as follows;

2.2.1 Test on Bitumen

The test conducted on bitumen with their respective specifications are presented as follows; specific gravity test ASTM D70 (2019), flash and fire point test ASTM D92, (2018), ductility test (D ASTM, 2017), softening point test ASTM D36 (2014**),** penetration test (D5 ASTM, 2013). ASTM D5, (2019).

2.2.2 EPS-Modified Bitumen Preparation

Polymers can be blended with asphalt mixtures in two ways: dry and wet method. The dry method involves adding the EPS after introducing and integrating the bitumen with the aggregate in the final section of the mixing process. On the contrary, the wet mixing involves mixing the bitumen with the modifier before introducing it into the combination of reheated mineral aggregates. Thus, the heated aggregates are then coated with a "polymer-modified bitumen. A pre-condition for wet mixing is that the melting point of the modifier must be lower than that of bitumen in order to allow it mix properly. A study conducted by Ahmad and Ahmad, (2022) revealed that using the wet method to incorporate EPS as an additive into asphalt mixtures is feasible as EPS has a melting point of about 120°C lower than that of bitumen, thus, the wet mixing method was used in this study. The waste expanded polystyrene (EPS) was first cleaned to remove dirt and other contaminants and subsequently dried under ambient conditions. The dried EPS was then mechanically shredded into small particles to increase its surface area and facilitate its interaction with the bitumen. The required quantity of conventional bitumen was heated gradually to a blending temperature of 170 ± 5°C and maintained at this temperature throughout the modification process.

The predetermined quantity of shredded EPS that is, 4%, 6%, and 8% by weight of optimum binder content was gradually introduced into the heated bitumen under continuous mechanical agitation. The mixture was maintained at 170 ± 5°C and continuously mixed for 60 min to promote softening, dispersion and homogenization of the EPS within the bitumen matrix. Care was taken to maintain a relatively constant blending temperature and avoid excessive heating of the binder. The resulting homogeneous EPS-modified bitumen was subsequently used in the preparation of the asphalt mixtures containing the specified proportions of virgin aggregate and reclaimed asphalt pavement (RAP). Furthermore, an estimated effective dosage 15% WEO (by % of optimum binder content) was added to the mixture to serve as rejuvenator for the aged binder in RAP. This is based on the previous studies of Khan et al., (2021); (Mamun *et al.,* 2018; Nurul Hidayah *et al.,* 2014; Zaumanis, *et al.,* 2013). Before the introduction of the WEO to the mix, the WEO collected from automobile serving workshop was initially allowed to stand undisturbed for 24 hours to facilitate the gravitational settlement of coarse contaminants and suspended particles. The relatively clear oil from the upper portion of the container was carefully decanted and subsequently filtered through a fine filter to remove residual metallic particles, carbonaceous deposits, and other suspended impurities.

2.2.3 Test on Coarse Aggregates

Test conducted on coarse aggregates are; aggregate impact value/hardness test (BS 812 part 112, 1990), aggregate crushing value (BS 812 part 110, 1990), aggregate specific gravity (ASTM, C128, 2001), size and gradation analysis (BS 812-103.2, 1985) and water absorption (BS 812 2, 1995).

2.2.4 Test on Fine Aggregates

The tests conducted on the fine aggregates are; specific gravity (ASTM C127, 2005), sieve analysis (BS 812-103.2, 1985), and water absorption (BS 812 3, 1995).

2.2.5 Test on Mineral Filler

The tests carried out on quarry dust are; sieve analysis (BS 812-103.2, 1985) and specific gravity (ASTM C128, (2018).

2.2.6 Test on Reclaimed Asphalt (RAP)

The tests conducted on the reclaimed asphalt (RAP) are flakiness and elongation ASTM D4791 (2019) sieve analysis (BS 812-103.2, 1985), specific gravity test (ASTM C128, 2018), aggregate impact value/hardness test (BS 812 part 112, 1990), aggregate crushing value (BS 812 part 111, 1990), and absorption test (BS 812 2, 1995).

2.2.2 Marshall Mix Design

The Marshall mix design method was adopted for the preparation and evaluation of the compacted asphalt specimens in accordance with ASTM D6927 (2015). To determine the optimum binder content (OBC) of the control mixture, Marshall specimens were prepared using virgin aggregates at bitumen contents ranging from 5.0 to 7.0% at 0.5% increments. The Marshall stability and flow values, together with the volumetric properties, including air voids (VIM), voids in mineral aggregate (VMA), and voids filled with bitumen (VFB), were determined for each binder content. The OBC was subsequently determined as the average bitumen content corresponding to the specified criteria for maximum stability, maximum bulk specific gravity, and the target air-void content.

Following the determination of the OBC, RAP was incorporated into the hot mix asphalt at replacement levels of 25, 50, 75, and 100%, while EPS was incorporated at 4, 6, and 8% by weight of the bitumen. A full factorial experimental design was developed using Design-Expert software (Version 13) to investigate the combined effects of RAP and EPS contents on the Marshall and volumetric properties of the asphalt mixtures. The experimental design comprised a total of 36 specimens/runs. For each mixture, the constituent materials were thoroughly mixed and compacted using 75 Marshall blows on each face of the specimen, in accordance with the requirements for a wearing course subjected to heavy traffic.

3.0 Results and Discussions

3.1 Result on Bitumen

The results of physical properties conducted on Bitumen is presented in Table 1.

Table 1: *The physical properties obtained from the test on bitumen*

Tests	Results	Specifications	Code
Specific gravity test, at 25^{0}C, (g/cc)	0.98	0.97-1.02	ASTM D70, (2019)
Flash test (^{0}C)	325	Min. 232	ASTM D92, (2018)
Fire test (^{0}C)	355	Min. 232	ASTM D92, (2018)
Ductility at 25 ^{0}C, cm	110	Min. 100	ASTM D113, (2019)
Softening point (^{0}C)	57.5	*46-56	ASTM D36, (2014)
Penetration at 25^{0}C. 0.1mm	64	60-70	ASTM D5, (2017)

*Asterisk implies the result slightly deviates from the code specifications

3.2 Result on Mineral Aggregates

The results of physical properties conducted on the mineral aggregates are presented in Table 2 and Table 3.

Table 2: *Results of physical properties test on coarse aggregates*

Tests	Results	Specifications	Code
Specific gravity (g/cm³)	*2.85	2.55 - 2.75	ASTMC127, (2018)
Aggregate impact value (%)	25.57	0-30	BS 812 part112 (1990)
Aggregate crushing value (%)	23.1	0-30	BS 812 part110 (1990)
Absorption test (%)	0.4%	≤ 2	(BS 812 2, 1995)

*Asterisk implies the result slightly deviates from the code specifications

Table 2 above shows the physical property test carried out on coarse aggregate to which it satisfies the ASTM standard for coarse aggregate tests. Results from the test suggests they fall within the specifications needed for asphalt mix design.

Table 3: *Physical Property Result on Fine Aggregates*

Tests	Results	Specification	Code
Specific gravity	2.64g/cm³	2.5-3.0	ASTM C 128, (2020)
Sieve analysis	Cu>3, Cc>1<3		ASTM C 136, (2020)

The Table 3 above shows the result for test on fine aggregate; both the sieve analysis and specific gravity tests are satisfactory and meet the limitations for fine aggregates to be used in asphalt mix.

The results of physical properties conducted on Reclaimed asphalt (RAP) is presented in Table 4.

Table 4: *The physical properties of test carried out on RAP.*

Tests	Results	Specification	Code
Specific gravity (g/cm³)	2.56	2.55 - 2.75	ASTM C127, (2018)
Aggregate impact value (%)	26.1	0 - 30	BS 812 part112, (1990)
Aggregate crushing value (%)	23	0 - 30	BS 812 part110, (1990)
Absorption test (%)	0.4%	≤0.5	ASTMC127, (2018)

Table 4 above shows the physical property test carried out on RAP to which it satisfies the ASTM standard for RAP tests. Results from the test suggests they fall within the specifications needed for asphalt mix design.

3.4 Particle size Distribution Analysis of mineral Aggregates

The results of the particle size distribution obtained for the fine, quarry dust and coarse aggregates and RAP is presented in Figure 2 below.

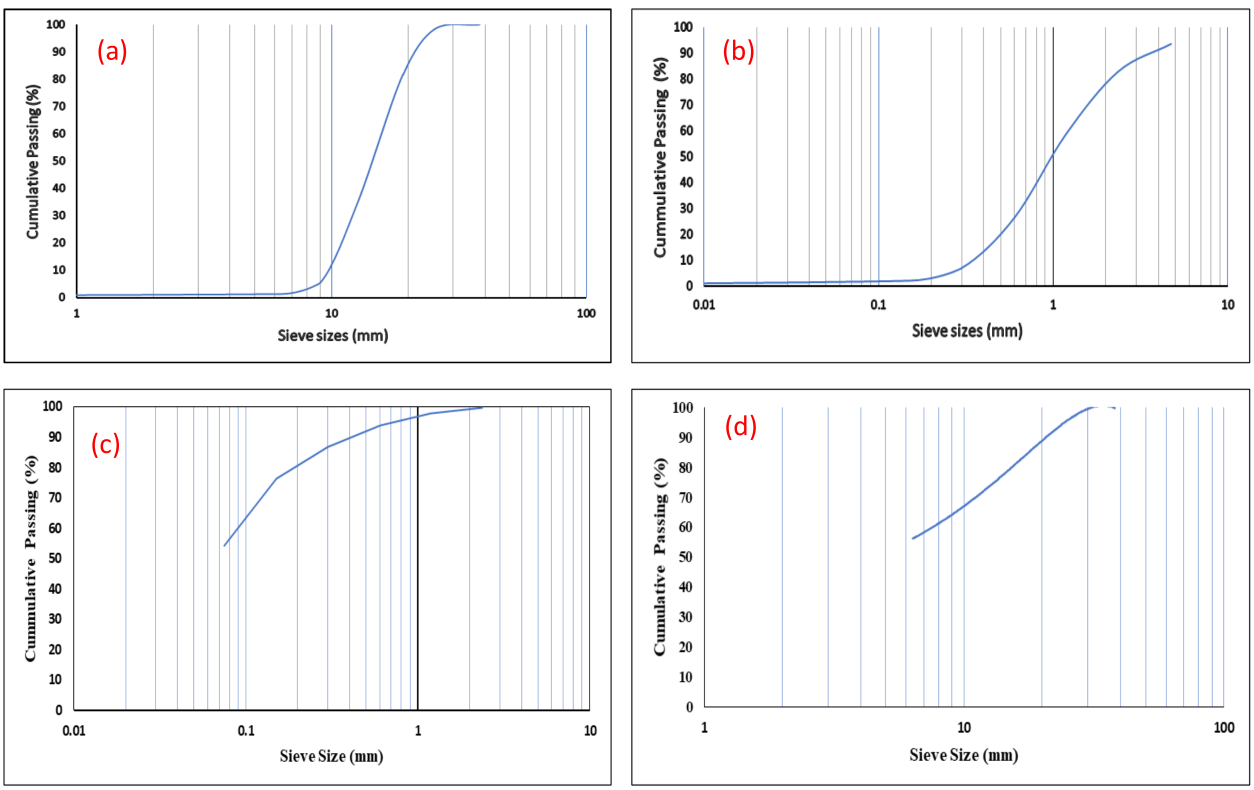

Figure 1: *Particle size distribution curves (a) coarse aggregates (b) fine aggregates (c) quarry dust (d) RAP*

From Figure 1, it can be deduced that the fine and coarse aggregates, RAP, and quarry dust are well-graded with particles of a wide range of sizes, indicated by a smooth, gradually rising curve. Consequently, they tend to be more stable and compactable satisfying the specifications of BS 812- 103.2, (1985). Thus, adjudged suitable for the production of bituminous mixtures.

3.5 Combined Aggregate Curve

Figure 2 shows the combined aggregate curve that was developed using the sum of particle size distribution of the coarse (granite and RAP), fine and filler aggregates on each sieve size. The Figure shows the blending of the materials which have been sandwiched between the envelope of the ranges of passing sieves sizes specified by the Nigerian General specifications for Road and Bridges; (NGSRB, 2016), hence, the aggregates used are within the limit of the codes and adjudged suitable for hot mix asphalt production.

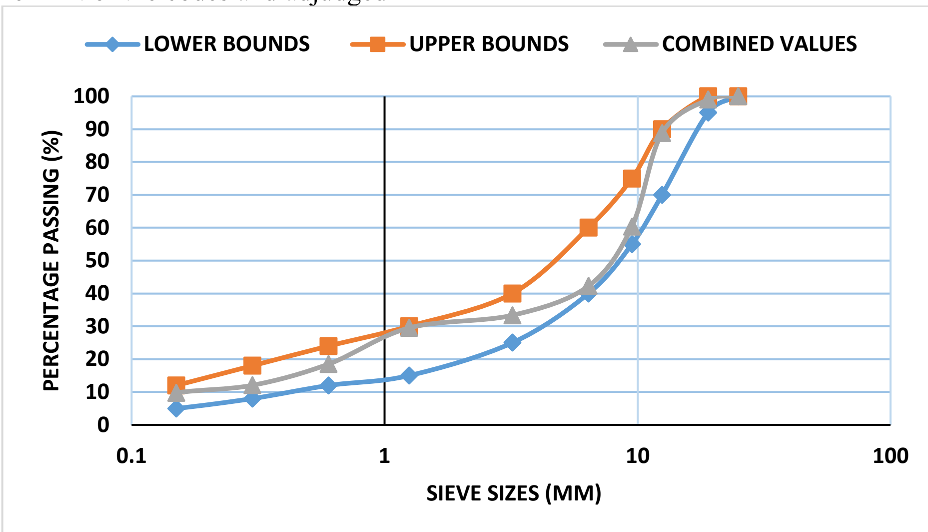

Figure 2: *Combined curve for mineral aggregates*

3.6 Marshall Mix Design - Optimum Bitumen Content

Table 5: *The results of the Marshall properties test carried out on bitumen.*

Bitumen Content	Stability (kN)	Flow (mm)	Quotient (kN/mm)	UW (g/cm^3)	VMA (%)	VFB (%)	VA (%)
5%	4.9	4.9	1.0	2.08	21.06	52.52	10
5.5%	6.4	4.6	1.39	2.13	21.10	53.46	9.82
6%	7.6	3.7	2.05	2.15	20.05	59.50	8.12
6.5%	6.6	3.9	1.69	2.10	19.74	63.12	7.28
7%	5.9	3.2	1.84	2.21	21.26	59.78	8.55

The optimum bitumen content was found to be 7%, which was calculated by taking the average of bitumen content at median air void, maximum stability, and maximum bulk density.

Bitumen content at median air void = 7%,
Bitumen content at maximum stability = 6%,
Bitumen content at maximum bulk density = 7%

Optimum binder content = $\frac{7+6+7}{3}$ = 6.67% approximately 7%

It satisfies the requirements for wearing course bitumen content in the Nigerian general specification code for roads and bridges, as it falls between 5 and 8%.

3.7 Effect of EPS and RAP to Marshall and Volumetric Parameters

The result of the Marshall and volumetric analysis of sample with varying RAP and EPS content is presented in Figures 3 through 9 below.

3.7.1. Stability

The Marshall stability test evaluates how well asphalt mixtures withstand traffic stress. Higher stability values reflect denser mixtures that are more resistant to deformation (Kadhim et al., 2025). Figure 3 below is a plot of stability at varying RAP content and EPS modifications.

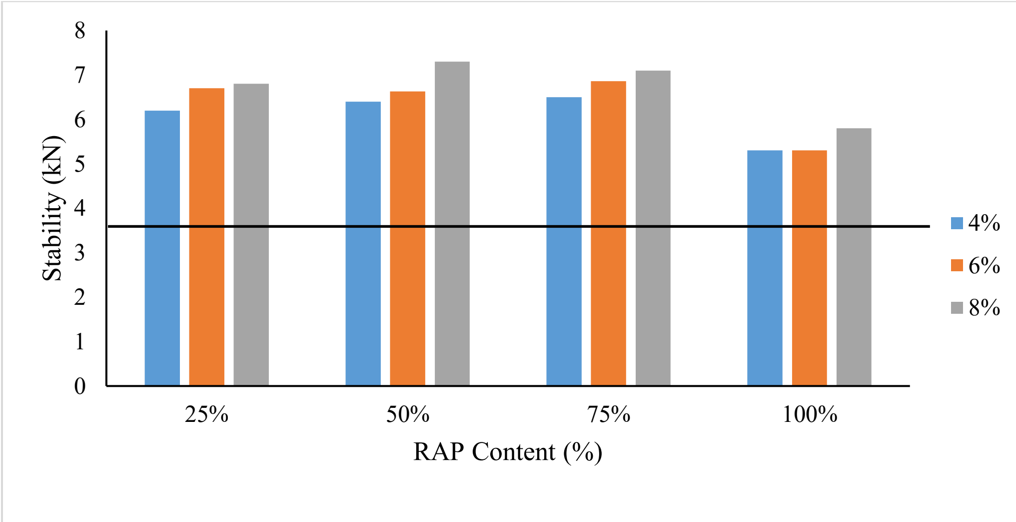

Figure 3: *Variation of stability with RAP at EPS-modified bitumen contents*

Figure 3 shows that Marshall stability increased with higher expanded polystyrene (EPS) content in the mixes (8% EPS modification gave maximum stability at each RAP variation). The is due to that fact that EPS improves cohesion and bonding properties of the asphalt mix, consistent with previous studies Falderika and Bahtiar (2022), Murana et al. (2020), and Abd Taih (2011). Stability also increased with increase in RAP content at each EPS modification point until beyond 75% RAP content, where a decrease in stability was observed. The initial increase may be attributed to the presence of stiffer aged bitumen and fine particles contained in the RAP, which enhance the stiffening effect and fill the voids within the mixture, thereby improving densification and resulting in increased Marshall stability. Additionally, the application of rejuvenator (waste engine oil) is effective in recovering the attributes of the aged/oxidized bitumen which in turn offers improved cohesion properties and compaction, thus, reduction in air void. However, beyond 75%, a point of saturation was reached, and a decrease in stability was observed. This could also be due to an excess fine and too much aged binder, making the mix overly stiff, less workable, hence, proper compaction wasn't achieved, resulting in increased air voids and reduced cohesion. The Marshall stability values obtained across all RAP contents and EPS modification levels were greater than 3.5 kN, thereby exceeding the minimum Nigerian specification requirement (NGSRB, 2016).

3.7.2. Marshall Flow

Marshall flow, on the other hand, is a measure of deformation (both elastic and plastic) of HMA during the stability test. The flow test indicates whether the asphalt mixture contains an excessive amount of binder (Kadhim et al., 2025).

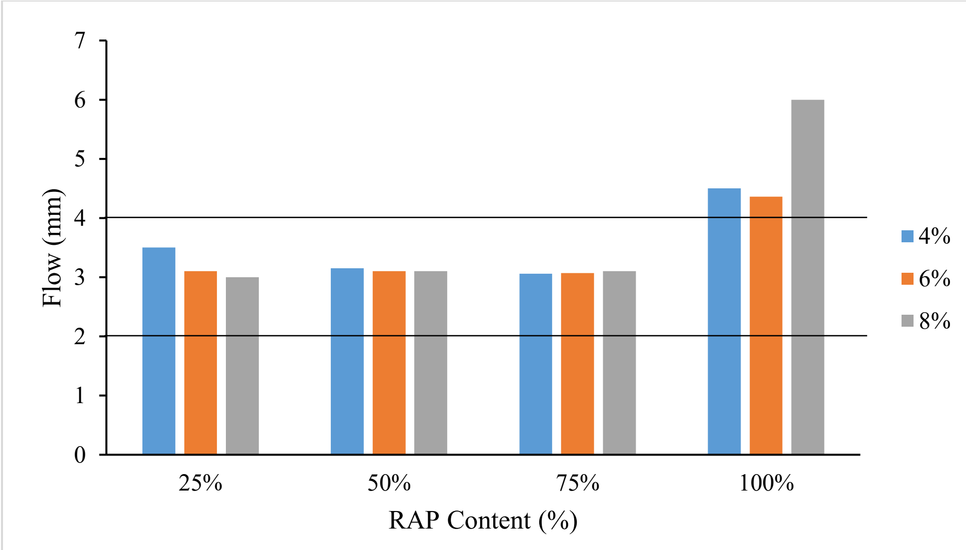

Figure 4: *Variation of flow with RAP at EPS-modified bitumen contents*

The results shown in Figure 4 suggests that as the expanded polystyrene incorporated in the mix increases at different RAP contents, a corresponding decrease in the flow value was observed, except at 100% RAP content. The decrease in flow could be due to the effect of aged, oxidized bitumen (higher asphaltenes, lower maltenes), contained in RAP that is capable of stiffing the mixture and EPS that is capable of acting as a rigid filler, thereby lowering binder viscosity and penetration, which ultimately reduces the flow of the mixture (Ali, Joni, & Al-Rubaee, 2024; Anwar et al., 2021). The flow results obtained at all EPS contents and RAP upto 75% are within the 2 to 4mm specified by the Nigerian general specification for roads and bridges (NGSRB, 2016).

3.7.3. Marshall Quotient (MQ)

Marshall Quotient**,** a measure of performance indicator (resistance to permanent deformation such as rutting) for hot mix asphalt concrete mixtures, is calculated as the ratio of Marshall stability to flow. The higher MQ, the stiffer and stable is the mixture and ability to resist deformation while lower MQ indicates is more flexible but the cumulation of stresses can lead to rutting. In asphalt design, a balance is usually sought to stability and durability in the asphalt mixture in service.

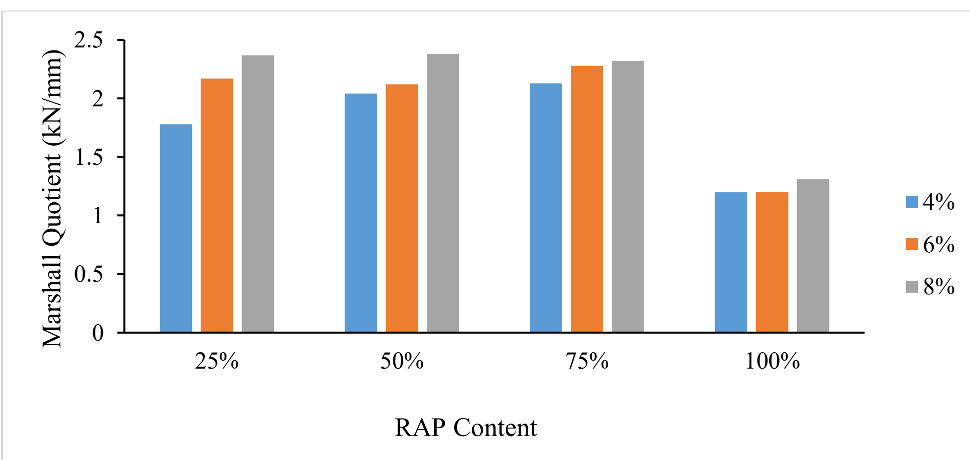

Figure 5: *Variation of Marshall Quotient with RAP at EPS-modified bitumen contents*

Figure 5 shows that the Marshall Quotient (MQ) increases with the addition of EPS across all RAP contents. This rise in MQ can be attributed to the enhanced elasticity and binding capacity that EPS, as a thermoplastic polymer, imparts to the bitumen. This in turn improves binder–aggregate cohesion and strengthen resistance to deformation under loading, resulting in higher stability and reduced flow. Consequently, the MQ values increase with EPS content. This assertion agrees with the previous studies by (Motlagh et al., 2012; Murana et al., 2021).

3.7.4. Unit Weight

Asphalt unit weight, also known as density, refers to the mass per unit volume of asphalt mixture, typically measured in units such as kilograms per cubic meter (kg/m³).

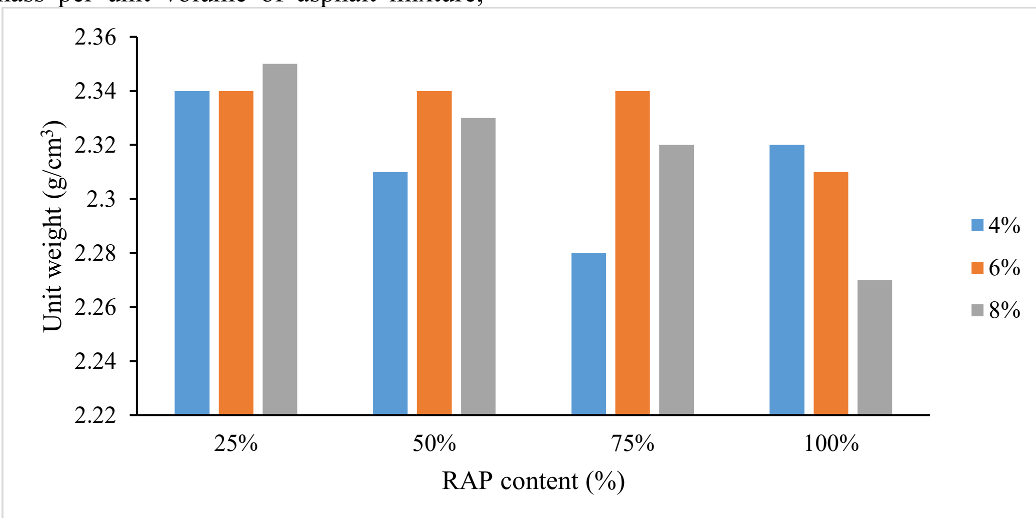

Figure 6: *Variation of unit weight with RAP at EPS-modified bitumen contents*

From Figure 6, it can be observed that the unit weight varied with both RAP content and EPS modification level, with no consistent linear trend. At 25% RAP, the mixtures exhibited relatively high unit weights (approximately 2.34–2.35 kg/m³), indicating good compaction and relatively dense packing. As RAP content increased to 50% and 75%, the unit weight generally decreased, particularly for the 4% EPS mixture, which may be associated with the lower density of RAP/EPS-modified constituents and increased internal voids. At 100% RAP, the 8% EPS mixture recorded the lowest unit weight (approximately 2.27 kg/m³), suggesting that higher EPS content may have promoted greater void formation and reduced mixture density. Overall, the results indicate that increasing RAP and EPS contents can influence mixture density through changes in aggregate packing, binder characteristics, and void structure. Though a reduction of unit weight was observed as the RAP contents increases, all the values UW values obtained at different RAP content and EPS modification exceeds that of the control mix.

3.7.5. Voids in Mineral Aggregates (VMA)

Voids in Mineral Aggregates (VMA) refer to the volume of intergranular void space between the aggregate particles in a compacted asphalt mixture, including the space filled by the asphalt binder and air voids. It is a critical parameter in asphalt mix design because it directly influences the durability, strength, and performance of the pavement (Shuaibu et al., 2021).

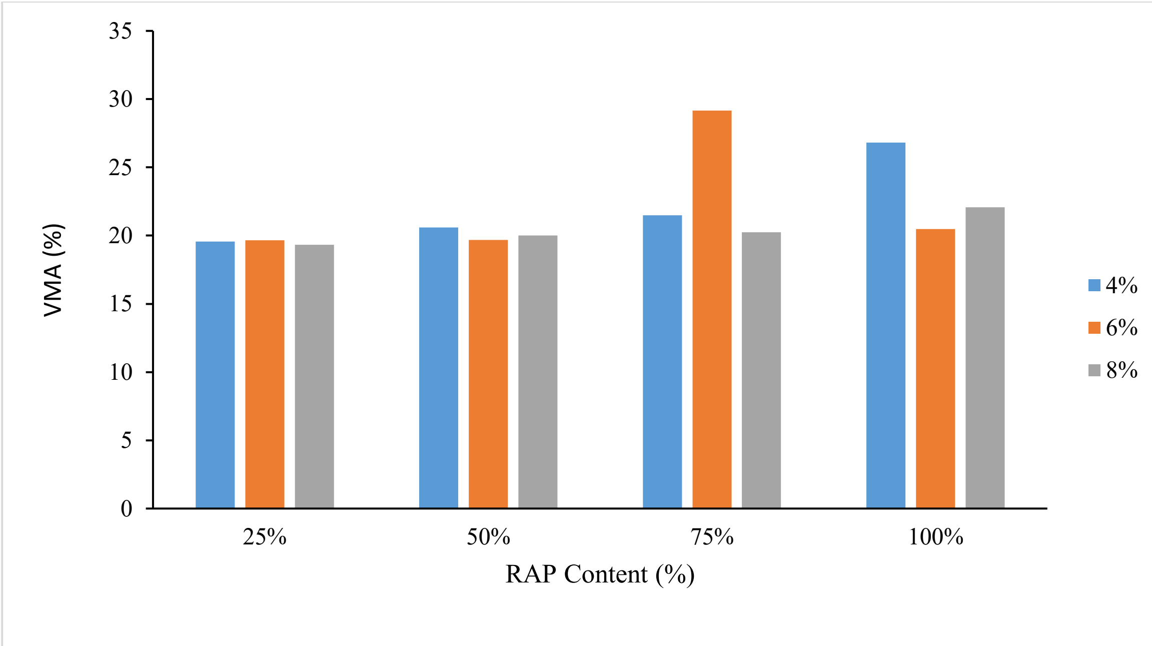

Figure 7: *Variation of VMA with RAP at EPS-modified bitumen contents*

Figure 7 revealed that the VMA values increase with increase in RAP content and decrease slightly with increase in EPS modification content. The increase in VMA as RAP contains increase could be as a result of the presence of oxidized/stiff binder in RAP which binds poorly with virgin bitumen, thereby, reduces aggregates lubricity, coating efficiency, and efficiency of compactive efforts, leading to higher voids. Also, the angular nature of RAP can hinder good packing of the aggregate leading to higher void. This agrees with the previous assertion of (Abd Ali *et al.,* 2024). However, the slight decrease in VMA observed as EPS increased that is seen between 25 – 50% RAP is as a result of enhanced binder elasticity and aggregate binding offered by EPS, thus, lowering the VMA. This agrees with the findings of Madhu et al., (2024). All the recorded VMA values the specifications of the Asphalt Institute (1997) which states a minimum VMA should be 13% considering nominal maximum aggregate size.

3.7.6. Voids filled with bitumen

In hot mix asphalt, the void filled with bitumen refers to the percentage of voids in a compacted asphalt mixture that is filled with bitumen. It is cardinal in determining the mixture's durability and resistance to deformation in service.

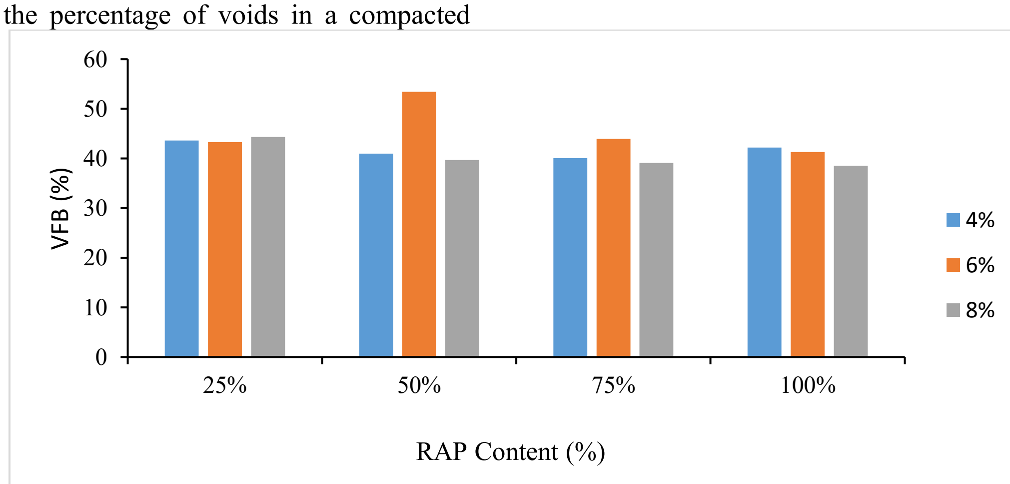

Figure 8: *Variation of VFB with RAP at EPS-modified bitumen contents*

Figure 8 shows the void filled with bitumen with varying RAP content and EPS modification. As RAP content increases, VFB generally decreases due to the aged/oxidized, stiff binder in RAP reducing effective binder activity to fill voids and mix flexibility. As RAP content continue to increase beyond 50%, the VFB continue to reduce and this could be due to insufficient coating causing poor compaction. Moreso, the reduction in VFB at higher EPS contents may be associated with changes in binder rheology and aggregate-binder interaction, which could influence aggregate packing, compaction and air-void development. The pronounced reduction at 100% RAP further suggests that the influence of EPS becomes more significant as the proportion of aged RAP materials increases**.** The maximum void filled with bitumen of 53.39 % obtained for all the mixtures were below the specified range of Nigerian specification of 75–85%, indicating that the mixtures contained a relatively low proportion of effective binder within the available voids in the mineral aggregate. This suggests that the mixtures may have relatively high air-void contents and/or inadequate filling of the aggregate void structure. From an engineering perspective, excessively low VFB may result in a mixture that is relatively dry and potentially more susceptible to permeability, oxidation and moisture-related deterioration, thus, poor durability. The failure of the mixtures to satisfy the specified VFB range suggests that further optimization of the binder content, WEO dosage, EPS modification level and/or compaction conditions may be necessary to achieve the desired volumetric requirements.

3.7.7. Air Voids

Air voids are the percentage of the total volume of a compacted asphalt mixture that is occupied by air spaces between the aggregate particles coated with asphalt binder.

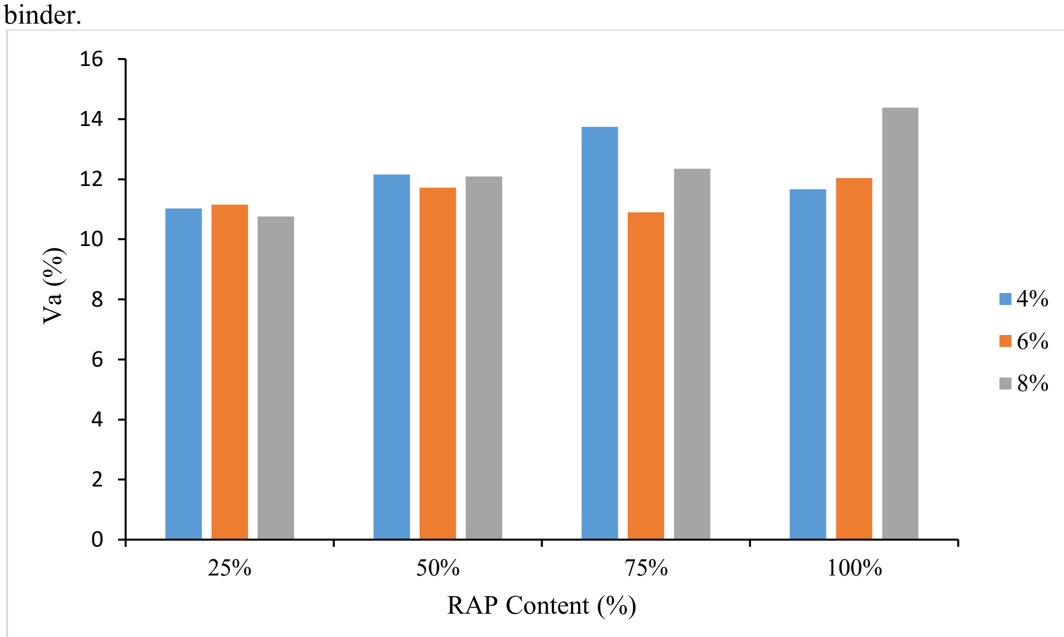

Figure 9*: Variation of Va with RAP at EPS-modified bitumen contents*

Figure 9 shows the variation of Va with RAP at EPS-modified bitumen contents. The air-void results indicate that all the investigated HMA mixtures exceeded the specified air-void range of 3–5%, with values ranging from approximately 10.7% to 14.4%. The relatively high air-void contents suggest that the mixtures did not achieve adequate densification during compaction. The increase in RAP content introduces aged and relatively stiff binder into the mixture, while EPS modification can further alter binder stiffness and workability. Although a fixed quantity of waste engine oil was incorporated as a rejuvenator, its constant dosage may have been insufficient to compensate for the increasing influence of aged RAP binder and EPS modification at higher RAP contents. Consequently, the binder may have had limited mobility during mixing and compaction, resulting in inadequate aggregate packing and retention of excessive air voids. The high air-void contents are also consistent with the relatively low VFB values obtained in the study. From a pavement performance perspective, excessive air voids can increase permeability and accelerate oxidative ageing and moisture-related deterioration, thereby reducing the durability and service life of the HMA. Therefore, the investigated mixtures, in their present formulation, do not satisfy the specified volumetric requirement and require further optimization of the binder content, EPS level, WEO dosage, aggregate gradation and/or compaction conditions.

4 Conclusions

In this research, the effects of different percentages of RAP and EPS in hot mix asphalt on the physical and mechanical properties were investigated with the use of waste engine oil as rejuvenating agent in the mix, the following conclusions were derived;

1. The results on the laboratory tests of the asphalt constituents confirm that it satisfies all the necessary physical requirements for asphalt mix specified in the standards i.e. (ASTM, AASHTO and BS), demonstrating its suitability for pavement construction. This indicates that the constituent materials are capable of withstanding applied stresses which demonstrates potential for long-lasting pavement performance.
2. Based on the comprehensive analysis of the Marshall Test results on the control mix, the optimum binder content for the asphalt mix was determined to be 7%. This value ensures adequate binding and durability striking a balance between stability, flow and voids while minimizing excess bitumen related problems to ensure satisfactory pavement performance.
3. The Marshall properties, including stability (> 3.5kN), flow (2-4mm), and Marshall Quotient (MQ), generally satisfied the specified requirements across the various RAP and EPS contents, except in some cases at 100% RAP. However, most of the volumetric properties did not fall within the specified code limits, with the exception of voids in mineral aggregate (>13%).

5 Recommendations

The findings of this study suggest that further optimization of the binder content, waste engine oil (WEO) dosage, EPS modification level, and/or compaction conditions may be necessary to achieve the desired volumetric characteristics and ensure compliance with the relevant specifications.

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