Effect of Recycled Aggregates and Polymer Modified Bitumen on the Marshall Properties of Hot Mix Asphalt- A Case Study

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Abstract

The engineering infrastructures after serving their purpose are usually demolished and dumped in the surroundings as per existing local guidelines particularly due to a lack of disposal strategies. In addition to wasting engineering resources, this practice pollutes the environment. Therefore, the current study looked at the usage of demolished engineering wastes for useful engineering purposes in order to minimize paving expenses as well as environmental pollution. The prime objective of this study is to evaluate the conventional asphalt mixture in terms of Marshall mix design, and consensus properties, and compare results with those obtained for asphalt mixture containing recycled aggregates from demolished wastes. The conventional asphalt mixtures were prepared with conventional materials, and the modified asphalt mixtures were prepared with varying proportions of recycled coarse aggregates, ranging from 0% to 75%, and tested as per the procedure outlined in ASTM D1559. The findings revealed that the stability of the mixes showed a decreasing trend with the increase in the proportion of recycled aggregates. This decline in stability is attributed to the debility in interlocking properties in asphalt mixture particularly due to poor surface friction, texture, and surface free energy of the recycled aggregate. Additionally, the percentage of air voids and voids filled with mineral aggregates increased. However, the laboratory findings indicated that the modified mixes at 25% recycled aggregate content exhibited comparable performance to conventional asphalt mixes, providing improved environmental advantages through the recovery and reuse of waste concrete aggregates. These findings highlight the potential of utilizing recycled aggregates in hot mix asphalt as a sustainable approach in asphalt pavement construction.

Keywords—Hot Mix Asphalt, Optimum Bitumen Content, Polymer Modified Bitumen, Recycled Concrete Aggregates, Marshall Stability and Flow

1 Introduction

The use of recycled concrete aggregates (RCA) in asphalt pavements has attracted considerable attention worldwide. This research focuses on understanding the interaction between RCA and asphalt in hot mix asphalt (HMA). By incorporating RCA in HMA, the environmental impact is reduced through the recovery of waste concrete aggregates, resulting in reduced landfill load. Evaluating the performance and physical properties of RCA-modified HMA compared to conventional mixes is essential to determine its efficacy [1]. The use of RCA in asphalt mixtures presents several potential advantages, such as enhanced mechanical performance, reduced energy consumption, and cost savings [2]. The potential utilization of recycled aggregates (RA) derived from construction waste in HMA was investigated, specifically focusing on the incorporation of 40% 3/4-inch RCA and 30% 3/8-inch RCA. The performance of asphalt concrete produced from these RCA blends successfully met the requirements set by municipal regulations. Additionally, the inclusion of various types of reclaimed concrete

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materials, such as tile and brick, served as a means to assess the suitability of utilizing these materials as aggregates in HMA [3]. There were four different aggregate types used: 100% igneous crushed stone (ICS) (control mix), 100% recycled building materials (RBM), and 50% fine RBM plus 50% coarse and fine ICS. The optimum combination was found to be C-RBM and F-ICS [4]. The HMA incorporating quarry waste materials exhibits reduced resistance modulus, volumetric properties, and creep values compared to HMA composed solely of natural materials [5]. Marble and andesite quarry wastes have the potential to be employed as binder layers in asphalt pavements designed for light to medium traffic conditions. Extensive testing, including Marshall stability and flow, flakiness index, impact value, freezing and thawing, and abrasion tests, was conducted on the samples to assess their performance [6]. Asphalt concrete, a widely used pavement material, has the potential to incorporate glass waste as an alternative ingredient. The performance of glass-modified asphalt concrete was assessed through various tests, including moisture damage, adhesion, light reflection, water permeability, and compaction [7]. The performance of HMA incorporating RCAs was evaluated. Key aspects studied include volume and weight indices, resistance to permanent deformation, fatigue performance, and water stability incorporating [8,9]. The HMA-RCAs exhibit higher asphalt content than natural gravels, which increases with the RCA dose. This is due to the absorption of more asphalt in RCAs through their pores and microfractures. Accurate determination of asphalt content in HMA-RCAs is important for achieving desired performance in asphalt pavements [10-12]. Recycled fine and coarse aggregates are utilized in construction due to their significant role in cement mortar [13], offering a large specific surface area [14] and high oil absorption [15]. These properties make RCA a valuable component in various construction materials, including asphalt mixtures. Minimizing the amount of recycled fine aggregate is crucial in order to optimize the asphalt content in construction materials [16]. RCA from demolished structures like dams, buildings, and bridges is a significant global waste. It can be used as a partial replacement for fine and coarse aggregates in stone mastic asphalt (SMA) mixes. However, incorporating RCA in SMAs alters their performance due to higher porosity and absorption characteristics [17]. A specific aggregate source (limestone) and binder type (60/70-penetration grade) were employed to prepare HMA mixes containing varying percentages of RCA (0%, 35%, 70%, and 100%). The incorporation of RCA in HMA showed improved fatigue performance and reduced waste generation compared to virgin aggregates (VA) [18]. The use of RCA at varying rates (0%, 5%, 10%, 20%, and 30%) in HMA was examined. The findings demonstrated that the curing procedure positively influenced the Marshall Stability and moisture resistance properties of the HMA mixes [19]. The laboratory experiments demonstrated that the use of RCA in HMA resulted in comparable performance to conventional HMA mixes while offering notable environmental benefits [20]. The RCA percentages investigated were 0%, 20%, and 30%. Through rigorous evaluation of performance metrics and numerical analysis, it was determined that the optimal alternative was the HMA mixture containing 30% RCA [21]. The utilization of debris from collapsed bridges as a substitute for natural crushed stone aggregates in HMA offers a promising solution. The incorporation of this recycled material resulted in a reduction in voids, specific gravity, and air spaces within the mineral aggregates present in the HMA mixtures. Notably, the stability/flow ratio exhibited comparable values across all tested mixtures [22]. The mechanical performance of bituminous mixtures with recycled materials was evaluated using the reclaimed asphalt pavement (RAP) to new aggregate ratio, allowing for comparisons to fresh mixes. The results highlight the significance of optimizing the RAP content in bituminous mixtures to achieve desired performance characteristics [23].

Traditionally, waste concrete aggregates or road milling aggregates have been dumped in landfills. Due to a shortage of landfills, environmental regulations, and costs, it is difficult to safely dispose of these materials. This led to the search for a new way to reuse demolition waste, such as recycling it. The recycling of concrete waste offers a solution to waste disposal issues while also reducing the need for quarrying VA. Its disposal has a substantial negative environmental impact. When these RCA are utilized in the right proportions in HMA, it enhances the desired properties of HMA while also being cost-effective and environmentally friendly. The aim of this case study is to investigate the effect of using RCA and polymer modified bitumen (PMB) on the Marshall properties of HMA. Literature suggests that the use of RCA and PMB can both have a significant effect on the Marshall properties of HMA. The beneficiaries of this research include the construction industry, researchers, and stakeholders involved in asphalt pavement design and production, who can benefit from the insights and recommendations provided to enhance the sustainability and performance of HMA mixtures.

2 Materials and methods

2.1 Materials

This study utilized coarse aggregates, including VA and RCA, in conjunction with PMB to investigate their effects on the Marshall properties of HMA. The VA specimens were procured from Margala Hill, while the RCA specimens were obtained from a 25 to 30-years-old building situated in Bannu, Pakistan. The PMB, which had a 60/70 penetration grade, was sourced from the Attock Refinery Limited Company and possessed a 2% reactive ethylene terpolymer (RET).

3 Tests performed

3.1 Tests on aggregates

The properties of the aggregates were assessed through several tests. The Los Angeles abrasion test was conducted according to ASTM C131-19a [24] to determine their resistance to abrasion and degradation. The specific gravity of the aggregates was determined using ASTM C127-19a [25]. Water absorption tests were performed in accordance with the same ASTM standard to measure the amount of water absorbed by the aggregates. ASTM C136-19 [26] was followed to conduct aggregate gradation analysis and determine the particle size distribution. ASTM C29/C29M-17a [27] was used to evaluate the uncompacted voids and measure the air voids present within the aggregates. These tests provided crucial information on the physical properties of the aggregates and their suitability for use in HMA.

3.2 Tests on bitumen

Various tests were conducted on the bitumen to assess its properties. The penetration grade test was performed following the AASHTO T49-20 [28] standard to determine the hardness of the bitumen. Ductility tests were carried out according to AASHTO T51-20 [29] to measure the bitumen's ability to stretch without breaking. The flash and fire point tests were performed following the AASHTO T48-20 [30] standard to determine the temperature at which the bitumen releases flammable vapors and catches fire. Additionally, the softening point test was conducted as per the AASHTO T53-20 [31] standard to measure the temperature at which the bitumen becomes soft. These tests, conducted in accordance with the AASHTO standards, provided crucial information about the consistency, durability, and temperature susceptibility of the bitumen.

TABLE 1: Mix design for OBC

Sieve #	%ages	3.5%	4%	4.5%	5%
12.5	17.5	202.65	201.6	200.55	199.5
9.5	12.5	144.75	144	143.25	142.5
4.75	20	231.6	230.4	229.2	228
2.36	20	231.6	230.4	229.2	228
200	20	231.6	230.4	229.2	228
300	5	57.9	57.6	57.3	57.0
Pan	5	57.9	57.6	57.3	57.0
Total	100	1158 gm	1152 gm	1146 gm	1140 gm

3.3 Sample Preparation

The research utilized the Marshall mix design method to prepare samples containing RCA. Different mix proportions were used in the study, involving various percentages (0%, 25%, 50%, and 75%) of RCA blended with virgin aggregates (VA). The coarse portion of RCA was partially replaced by VA based on the total weight of the aggregates in each mixture. A control specimen with 0% RCA (100% VA) was utilized as a control mix. The mix design details for specimen preparation are outlined in Table 1 and Table 2. The aggregates, including RCA, and fillers were dried at 110±0.5ºC for 2 hours prior to weighing and placement. Binder content in the HMA varied from 3.5 to 5% of the aggregate weight. Weighing the needed amount of PMB and heating it for one hour at 160 ºC. The binder was well blended with the aggregates until fully coated. Next, the filler was added to the mixture and thoroughly mixed for 5 minutes at a temperature of 160°C. Following this, the samples were conditioned at 150°C for 4 hours. Subsequently, the compacting process was carried out at a temperature of 145°C using a Marshall compactor, with 75 blows applied on each side.

3.3.1 Marshall stability test procedure for optimum bitumen content

The Marshall stability (MS) test was performed to assess the asphalt's strength properties, encompassing stability, flow, unit weight, and bitumen content. Marshall specimens were prepared in accordance with AASHTO standard requirements, utilizing PMB at varying percentages of 3.5%, 4%, 4.5%, and 5% to establish the optimum bitumen content (OBC). The specific mix design for OBC is presented in Table 1.

3.3.2 Mix design for control samples and varying percentages of RCA

This study looked at four different asphalt concrete mixtures. The control mix was an asphalt concrete mixture that contained no demolished aggregates. RCA was utilized as a substitute aggregate in the other mixtures. The asphalt mixtures were prepared using the Marshall mix design method, compacting cylindrical samples with dimensions of 101.6 mm diameter and 40 mm thickness, subjecting them to 75 compaction blows on each side. The standard techniques for compaction and evaluation of Marshall samples, including bulk specific gravity, were applied [32]. The Marshall specimens were prepared in two groups. The first group of specimens consisted of varying binder concentrations to assess the OBC. The HMA mechanistic properties were tested in the second series, which was made at the OBC. At least three samples were obtained for each aggregate blend and asphalt binder level to ensure that the findings were repeatable [33]. Table 2 lists the replacements in detail, as well as the OBC of mixes. Using RCA as aggregate in asphalt mixtures clearly enhances the OBC. The OBC was calculated to be 4.48%, with the remaining aggregate weight being 1146.24 grams. All mix designs used the same OBC value. A total of 24 samples were prepared for each mixture in order to determine the OBC, which was followed by multiple tests to examine and identify the best results.

3.4 Determination of Volumetric Properties of Asphalt Mixtures

Air voids (V_a), voids in mineral aggregates (VMA), and voids filled with asphalt (VFA) are key parameters utilized for evaluating the performance of asphalt concrete mixtures. The volume properties of the asphalt determine how well it performs in usage. In this investigation, the volume parameters of the asphalt sample are utilized. These characteristics are detailed below.

3.4.1 Percent Air Voids in the Compacted Mixtures

The volumetric measurement of air voids in an asphalt sample is expressed as the percentage of V_a. It represents the total volume of air contained within the compacted mixture of aggregates in the asphalt [36]. After the aggregates have been covered with bitumen, little pockets or packets of air form between the particles in an asphalt sample. Dense-graded asphalt mixes commonly incorporate a controlled volume of air voids to facilitate optimal traffic compaction. This design consideration ensures that the asphalt mixture can effectively accommodate future compaction or loading, allowing the binder to freely flow into voids generated by subsequent compaction processes. The amount of air pockets in an asphalt surface determines its durability. Low air spaces cause the squeezing of bitumen out of the asphalt following compaction, while high air voids cause damage and deformations or water admittance. The lower the density of the asphalt mix, the more air pockets there are. The following formula can be used to compute the percentage of V_a:

$$V_a = \frac{(G_m m - G_m b}{G_m m} * 100 \tag{1}$$

where V_a = Air Voids Percentage in compacted asphalt mixture $G_m m$ = Maximum Theoretical Specific Gravity of Loose Asphalt Mixture $G_m b$ = Bulk Specific gravity of Compacted Asphalt Mixture

3.4.2 Voids in Mineral Aggregates in Compacted Asphalt Mixture

VMA refers to the aggregate void space, including air voids and bitumen volume, which affects the performance and durability of asphalt mixtures. The vacuum gaps between particles in a compacted asphalt mixture are referred to as VMA [36]. The VMA can be calculated as follows:

$$VMA = V_a + V_b \tag{2}$$

where
V_a = Air voids (%)
V_b = Volume of Bitumen (%)

3.4.3 Voids Filled with Asphalt in Compacted Asphalt Mixture

The term VFA refers to the empty spaces within mineral aggregates that are occupied by the asphalt content in an asphalt mixture. The formula for the computation of VFA is as under:

$$VFA = (\frac{V_b}{VMA}) * 100 \tag{3}$$

where
VFA = Voids Filled with Asphalt %)
VMA = Voids in Mineral Aggregates (%)
V_b = Bitumen's % content in Compacted Mixture (%)

4 Results and discussions

4.1 Gradation Curve

Figure 1 shows the selected gradation of aggregates alongside the prescribed gradation criteria outlined in the National Highway Authority (NHA), 2020 [37]. The test results are shown in Table 3, demonstrating that both VA and RCA complied with the specifications set by ASTM. To meet the requirements specified

TABLE 2: Mix Design for control and varying percentages of RCA

Sieve #	%age	VA (0%)	RCA (25%)	VA (75%)	RCA (50%)	VA (50%)	RCA (75%)	VA (25%)	Total (gm)
12.5	17.5	200.59	50.4	150.44	100.29	100.29	150.44	50.14	200.59
9.5	12.5	143.28	35.82	107.46	71.64	71.64	107.46	35.82	143.28
4.75	20	229.248	57.312	171.936	114.62	114.62	171.93	57.318	229.248
2.36	20	229.248	57.312	171.936	114.62	114.62	171.93	57.318	229.248
200	20	229.248	57.312	171.936	114.62	114.62	171.93	57.318	229.248
300	5	57.312	14.328	42.984	28.656	28.656	42.98	14.33	57.312
Pan	5	57.312	14.328	42.984	28.656	28.656	42.98	14.33	57.312
Total	100	1146.24	286.56	859.68	573.12	573.12	859.68	286.56	1146.24

by NHA, the aggregates underwent sieving processes. The NHA holds responsibility for overseeing the construction and maintenance of the nation's primary road networks in Pakistan.

4.2 Results of bitumen tests

Table 4 presents the results of the bitumen tests, showing the performance of the tested samples against established standards and limits. The penetration grade test assessed the consistency of the bitumen, with the obtained values falling within the acceptable range specified by the AASHTO standards. The ductility test measured the elongation properties of the bitumen and demonstrated its ability to meet or exceed the minimum requirements outlined in the standards. Furthermore, the flash and fire point tests determined the temperatures at which the bitumen exhibited flammability, and the results indicated compliance with the specified safety thresholds. Lastly, the softening point test evaluated the bitumen's resistance to deformation under heat, and the recorded values were found to be within the acceptable range according to the standards. These comparisons with the standard limits provide valuable insights into the quality and suitability of the tested bitumen samples for various road construction applications.

4.3 Optimum Bitumen Content

Afterward, HMA samples were prepared using the Job Mix Formula (JMF) by incorporating different percentages of RCA- 25%, 50%, and 75% - in comparison to HMA made solely with VA. The JMF is a specific recipe used for producing asphalt mixtures with specific characteristics. It specifies the proportions of materials based on testing and analysis to meet performance criteria. It guides asphalt plant operators for consistent and high-quality production [36]. The total weight of the aggregates used in the mixture was measured to be 1146.24 grams. To achieve the desired properties, the OBC of 4.48% was determined. As a result, the total weight of the Marshall samples was adjusted to 1200 grams. This experimental setup enabled a thorough comparison of the properties of HMA samples containing different percentages of RCA with those made only with V_A. The detailed characterization and evaluation of these samples provide valuable insights into the performance and suitability of utilizing RCA in HMA production.

4.4 Marshall stability

The resistance of a mixture to permanent deformation is referred to as "stability." As a result, mixes with high MS results are desired in concept. However, it must be remembered that overly high stability values may result in difficult-to-compact mixes in the field [39]. Figure 2 illustrates the MS values for different binder content percentages, including RCA. The MS test was conducted following the guidelines and standards outlined in ASTM D1559 [40]. As the amount of RCA in HMA mixes increased, MS values decreased. The slopes of the MS curves indicated that the MS values decreased slightly when the RCA content was 25%. However, with an RCA content of 50% or 75%, the slopes became steeper, and the reduction in MS values was significantly greater. The stability value for heavy traffic loads should be more than 1000kg [36]. The MS value for 4.48% binder and 0% RCA (100% VA mixture) was 1146.66kg, while the lowest level was 829kg for 4.48% binder and 75% RCA. As a consequence, all of the specimens will be able to reach the required standard. When the asphalt content is increased, it leads to the formation of thicker bitumen films around the aggregates, effectively filling the voids within the mixture with an adequate amount of binder. As the RCA content increased, the contacts between aggregates decreased dramatically, resulting

TABLE 3: Physical properties of coarse aggregates

Tests	Apparatus	ASTM standard	VA (%)	RCA(%)	Specifications [38]
Uncompacted voids	Volumetric Flask	C 1252	39	47	45 (min)
Water Absorption	Water Absorption Test	C 127	1.03	2	2 (max)
Fractured particles	Fracture Test Apparatus	D 5821	100	115	100 (min)
Loss Angeles Abrasion	Los Angeles Abrasion Machine	C 131	12	17	15 (max)

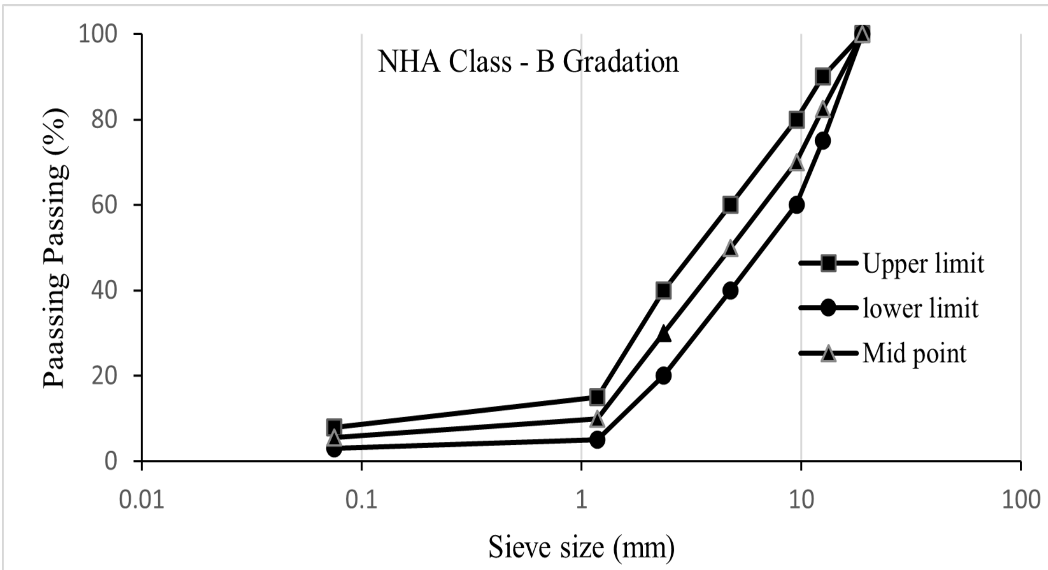

Fig. 1: NHA Class-B Gradation

in reducing in MS values. The Marshall stability of varying percentages (0, 25, 50 and 100) % of RCA are shown in Figure 2.

4.5 Marshall Flow

Marshall flow is the vertical deformation that occurs in an asphalt specimen during Marshall stability testing. It is measured from the beginning of loading until stability starts to decrease. The high flow value indicates that the mix is highly plastic, which will eventually lead to rutting failure in the pavement. Large voids and insufficient binder might also contribute to the low flow value, which could lead to pavement failure sooner [41]. ASTM D1559 [40] was used to conduct the flow test. The Marshall stability of the asphalt mixture is dependent on the binder, filler, coarse aggregate, fine aggregate, and air voids [42]. Figure 3 shows the flow values for various proportions of RCA and binder content. As the RCA content increases, there is a corresponding increase in the flow values. The optimal flow values for producing asphalt mixtures suitable for heavy traffic volumes typically range between 8 and 14 mm [36]. The maximum flow was 8.30mm in an asphalt mixture including 0% RCA and 4.48% binder, while the lowest flow was 7.75mm in 75% RCA mixes with 4.48% binder. When RCA is compared to VA, the results are assumed to be owing to the increased porosity and absorption of RCA.

4.6 Voids in mineral aggregates

Figure 4 depicts the relationship between VMA values and the content of RCA for different proportions. As the percentages of RCA in conventional mixes increased, a noticeable increase in VMA was observed, as indicated by the values obtained from the graphs. This observed correlation highlights the direct relationship between the proportion of RCA and the volumetric properties of asphalt mixtures, specifically the significant expansion of void spaces within the mineral

TABLE 4: Results of PMB

Tests	Apparatus	AASHTO standards	Results	Recommended Ranges
Softening point (ºC)	Brass Ring and a Steel Ball	T-53	55	46-56
Flash Fire point (ºC)	Cleveland Open Cup	T-48	318	235
Penetration Grade @ 25 ºC , 1/10 of mm	Penetrometer	T-49	56	60-70
Ductility @ 25ºC, cm	Ductilometer	T-51	108	100+

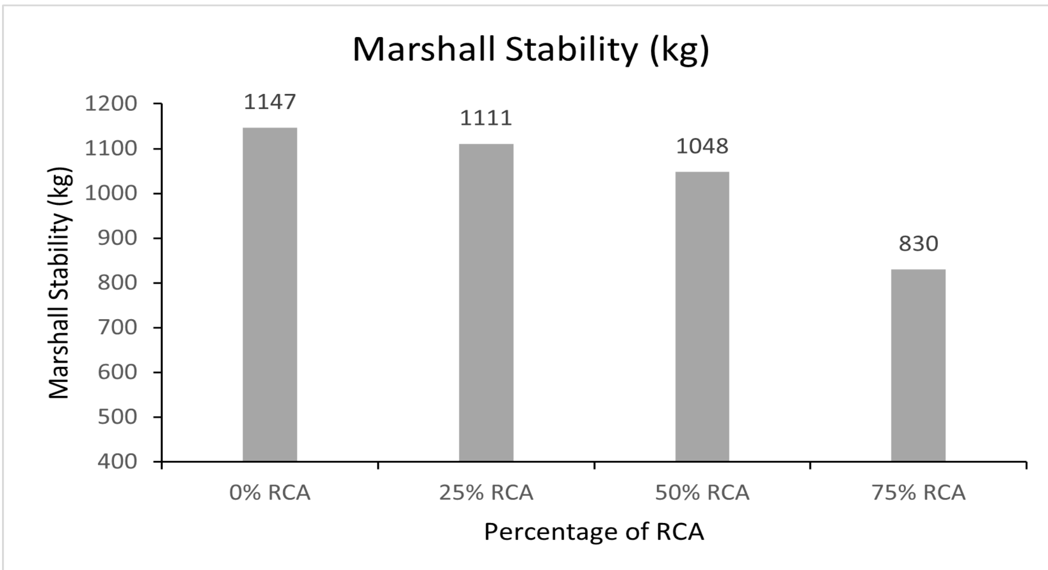

Fig. 2: Marshall Stability Comparison of combined samples

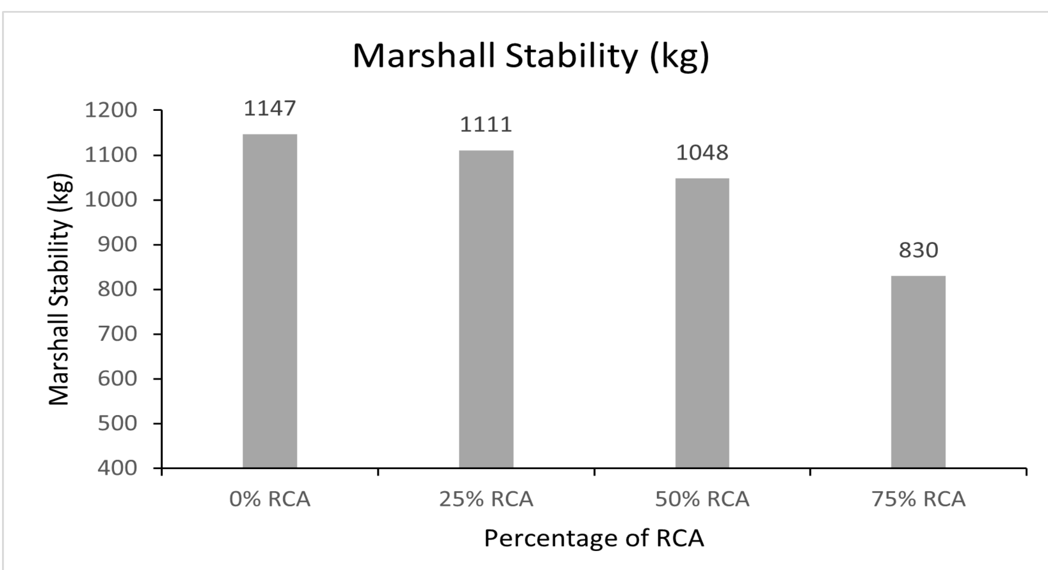

Fig. 3: Marshall Flow Comparison various RCA percentages

aggregate. VMA values in asphalt mixtures are affected by air voids and the effective asphalt content. Increasing RCA content in conventional mixes leads to higher binder absorption, reducing effective binder content and increasing VMA values. In asphalt mixes, the nominal maximum aggregate size is typically 19 mm, which means the largest particles in the mix are up to 19 mm in size. This is one sieve size smaller than the maximum aggregate size of 12.5 mm. When the nominal maximum aggregate size is reduced to 12.5 mm, the VMA is measured to be 14% at a design air voids content of 4% [36].

4.7 Voids filled with asphalt

The VFA, which represents the portion of VMA filled with binder, is an important factor in designing high-performance and durable asphalt mixtures. There is a correlation between effective binder content and VMA. Aggregate gradation, material quality, and compaction methods influence VMA and VFA values. Figure 5 shows the measured VFA values at OBC for different percentages of RCA. It is evident from the graph that the VFA values of modified specimens increase as the RCA content rises, regardless of the binder amount. This increase in VFA is attributed to higher binder absorption in RCA mixes, which results in a reduction of the effective binder content in the asphalt mixtures. However, the VFA values ranging from 65% to 78% for compacted specimens with 75 blows (representing heavy traffic volume) fall within the acceptable range [36].

4.8 Air voids

Va vs. bitumen content is represented in Figure 6. Oven-cured mixtures have a greater Va content than non-cured mixtures. When a mixture has too many Va, it becomes less durable. As a result, oven-cured mixtures may be less durable than untreated mixtures. The Va content usually falls between these limits. Non-compliance with this criteria might, however, be caused by a mix design that contains more or less bitumen. The recommended Va content for asphalt pavement compaction should be between 7 and 3%. The interconnected voids of 8% or more allow air and moisture to penetrate the pavement, reducing its durability [36].

5 Study Limitations

This study mainly looked at the Marshall properties of the asphalt mixture. However, it's important to be aware of certain limitations that need to be considered. Firstly, the scope of the study was primarily confined to the Marshall stability and flow tests, and other critical performance indicators, such as rutting resistance, fatigue behavior, and moisture susceptibility, were not extensively investigated. These other properties have a crucial impact on the long-term performance and durability of asphalt pavements.

Furthermore, it should be noted that the findings of this study are specific to the particular combination of RCA and PMB used. The results may vary when different types of RCA are employed. Therefore, caution should be exercised when generalizing the outcomes of this study to different mix designs or material compositions.

6 Conclusions

This study provides experimental results on the use of RCA in conventional asphalt mixtures. The conclusions derived from the research findings are summarized in this section, taking into account the limitations of the materials and testing program used in this study:

- Increasing the concentration of RCA in conventional asphalt mixes resulted in higher bitumen absorption. This was due to the increased porosity of the recycled concrete and the adhering mortars on its surface. However, the enhanced performance of the RCA in conventional mixes was achieved by reducing binder absorption and improving adhesion between the RCA and other elements in the mixture.
- The proportioning of the aggregates with RCA at all specified percentages of 25, 50, and 75 resulted in a proper blending of the aggregates that met the specifications.
- Based on laboratory research, it can be stated that more than 25% and less than 75% RCA can be used in the construction of new roads with the VA.
- The optimal proportion of RCA to improve the stiffness, Marshall stability, flow, air voids, and bulk density of the asphalt mixture is found to be 25% by weight of the coarse aggregate. For 75% replacement of RCA the stability is still well above than its specified value (820 kg/cm2).
- The Marshall properties of conventional mixes with 25% and 50% RCA showed acceptable trends, indicating that they may easily fulfill the requirements for heavy traffic volumes. Low-traffic pavements should employ conventional blends comprising more than 50% RCA. When increasing the RCA concentration of asphalt mixes, however, caution should be used.

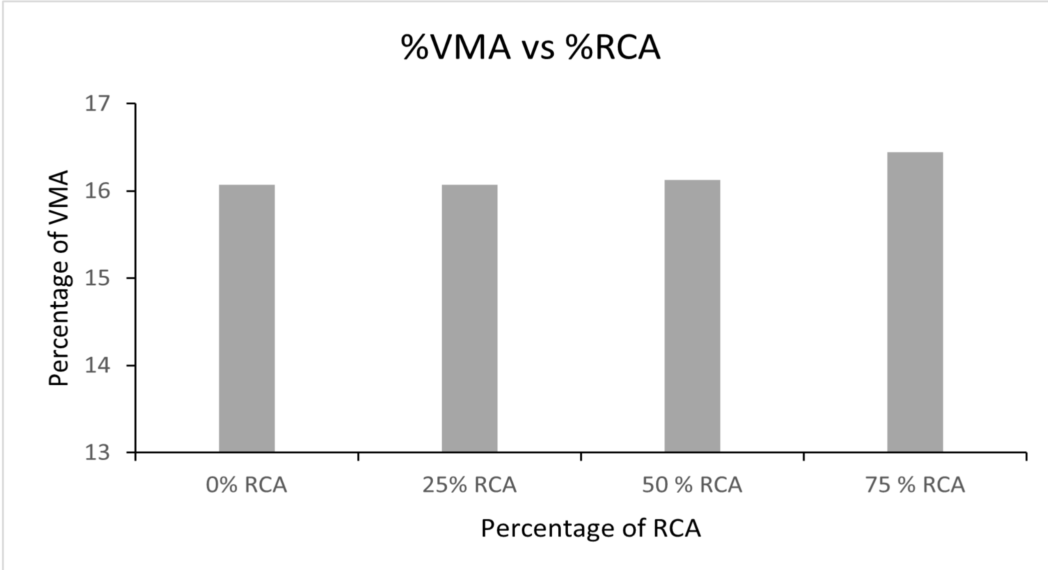

Fig. 4: Comparison of VMA (%) VS RCA(%)

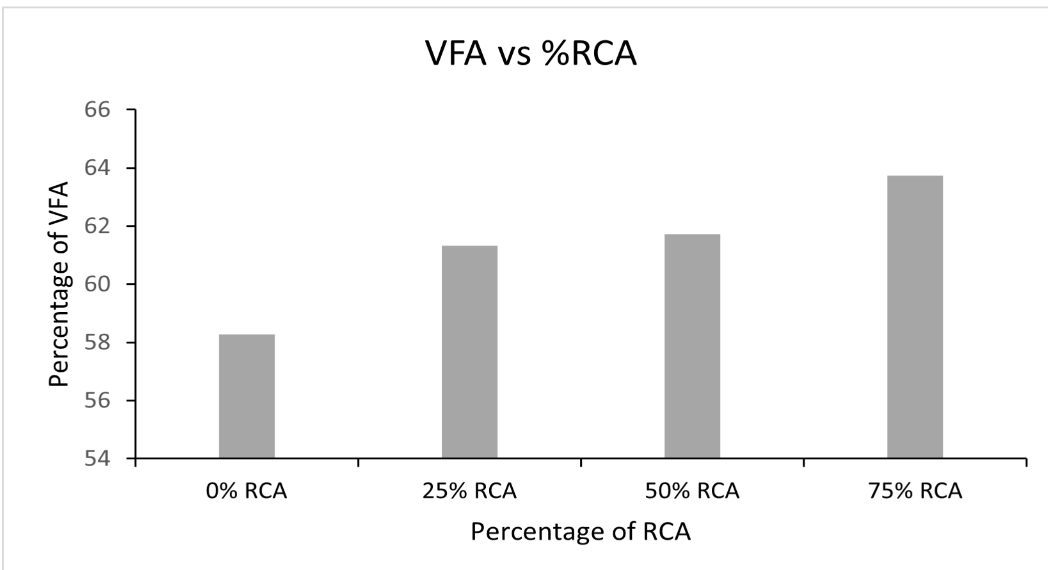

Fig. 5: Comparison of VFA (%) VS RCA (%)

- The RCA were mixed with VA as a coarse mixture, with the ratio based on the total weight of aggregates in the mixture. RCA reduces density values, independent of the amount of RCA in the mixture. In terms of stability, density, VFA, and VMA, conventional mixes with varied amounts of RCA performed poorly, whereas flow and air voids performed better. Because RCA aggregates have a higher porosity, lower specific gravity, and lower density than VA.

To comprehensively evaluate the performance of RET-modified pavements under vehicle-induced rutting, it is recommended to conduct additional testing using dual wheel track laboratory equipment. This testing method will provide valuable insights into the resistance of the modified pavements to rutting caused by repeated wheel loads, allowing for a more accurate assessment of their durability and performance. By incorporating dual wheel track testing into the research, a more comprehensive understanding of the effectiveness of RET-modified pavements can be gained, leading to improved design and implementation strategies for sustainable and resilient road infrastructure.

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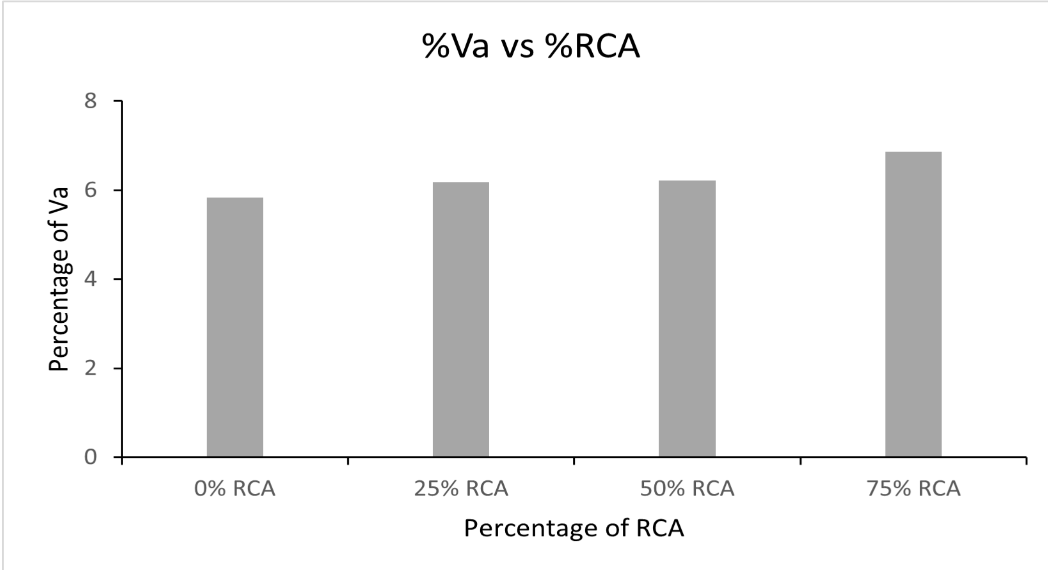

Fig. 6: Comparison of VA (%) VS RCA(%)

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