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# Evaluation of the Cracking Resistance and Fracture Energy of Sustainable Asphalt Mixtures Containing Reclaimed Asphalt Pavement

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**Keywords**
Reclaimed asphalt pavement, cracking resistance, Asphalt mixture, Fracture energy, Marshall

**Abstract:** Asphalt pavement production and construction needs substantial amount of energy and non-renewable materials. Therefore, using recycled materials seems necessary to create more sustainable asphalt concrete pavements. This article aims to examine the performance of sustainable asphalt mixtures incorporating reclaimed asphalt pavement and investigate and evaluate the cracking resistance of the produced mixtures. To achieve the study objectives, an experimental program was designed for the hot asphalt mixtures using four different bitumen contents (4.5, 5.0, 5.5, and 6.0%), four RAP contents (20%, 40%, 60%, and 80%), in addition to a control mix (without RAP). The Marshall Test method was used to investigate the volumetric and mechanical properties of the prepared asphalt mixtures containing RAP. The load-displacement analysis was performed to investigate and evaluate the indices of cracking resistance, fracture energy and fracture work density by using the Indirect Tensile Testing program. The results indicated that the volumetric and mechanical properties; stability, Stiffness, and density of the mixtures containing RAP are greatly similar to those of the hot asphalt mixture without RAP. The analysis of indirect tensile strength results indicated that the cracking parameters; $CT_{Index}$, $CRI_{Index}$ and $FST_{Index}$ containing 40% RAP are higher than those of the other RAP mixtures. Statistical analysis showed that Stiffness, stability, air void and flow of RAP mixtures were significant. Also, the fracture energy, indirect tensile strength and fracture work density of RAP mixes were not significantly different from the control mix except in some cases.

## 1. Introduction

The production and construction of asphalt pavement requires considerable quantities of energy and natural materials. It is therefore necessary to utilize recycled materials to establish a more sustainable asphalt concrete pavement [1]. Asphalt pavement recycling is considered a technology for re-use of paving structures that have suffered permanent

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deformations and structural damage. Reclaimed Asphalt Pavement (RAP) ranks among the most recyclable materials globally [2]. RAP is considered one of the most significant types of sustainable asphalt pavement, as it reduces energy consumption, conserves natural resources, and lowers emissions. It minimizes environmental impact while meeting all performance criteria and adhering to established standards. In order to pursue the principles of sustainable development, it is defined as a solution to fulfill current requirements without compromising future generation's ability to meet their own needs [3].

Mulatu et al. studied the Moisture Susceptibility, Marshall Stability, and Rutting of 64 mix designs, investigating seven RAP ratios: 5%, 15%, 25%, 35%, 45%, 55%, and 65% by weight of crushed aggregate [4]. Their findings showed that increasing RAP content decreased the tensile ratio while still meeting standard limits and ensuring resistance to deformation and moisture damage. They also observed that replacing 45% of natural aggregate with RAP met volumetric, flow, and stability specification requirements. Additionally, heating RAP material improved compatibility, binder dispersion, and mix densification [5]. Gao et al. concluded that mixing duration significantly impacts the blending and dispersion of hot mixtures containing RAP. They determined that longer mixing times improved the performance of recycled asphalt mixtures, with optimal durations being 90 seconds in the laboratory and 60 seconds in the mixing plant [6].

Numerous variables, such as inadequate mix design, heavy traffic loads, moisture effect, and the aging of the asphalt binder in the mixture, can lead to cracking in asphalt pavement [7]. Because they contain stiff or very old asphalt binders, recovered materials like reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) can make cracking worse. Throughout the pavement's service life, mixtures with high amounts of these recycled materials are more likely to shatter because they are often stiffer and more brittle [8], [9]. Researchers have developed several testing methods, including the Disc-shaped Compact Tension (DCT), Texas Overlay Tester (OT), Semi-Circular Bending (SCB), and Indirect Tension Test (ITS), to assess the cracking resistance of asphalt mixtures To evaluate the cracking resistance of asphalt mixtures, researchers have created a number of testing techniques, such as the Disc-shaped Compact Tension (DCT), Texas Overlay Tester (OT), Semi-Circular Bending (SCB), and Indirect Tension Test (ITS) [10]. The indirect tensile test (ITS), one of these tests, was carried out in accordance with ASTM D8225 to assess the asphalt mixtures' cracking properties. A number of factors, such as the ITS cracking test's capacity to assess performance, testing uniformity, ease of specimen preparation, testing speed, and low equipment cost, all played a role in the decision [11]. Parameters including fracture work, fracture energy (FE), fracture work density (FWD), Cracking Resistance Index (CRI), and Cracking Tolerance Index (CTI) are computed using the load-displacement data gathered from these tests [10].

Generally, Hot Mix Asphalt (HMA) mixtures are produced using virgin materials. However, approximately four million tons of recovered asphalt material are not incorporated into annual production, and the ongoing pavement grinding or milling processes do not utilize this recovered material [3]. In recent years, there has been a global shift toward the adoption of green asphalt, with one key approach being the utilization of reclaimed asphalt pavement (RAP).

## 2. Objectives and Methodology

This article aims to investigate and evaluate the cracking resistance and fracture energy indices of sustainable asphalt mixtures incorporating reclaimed asphalt pavement RAP. Another objective of the study is to evaluate the volumetric and mechanical properties of the produced mixtures. To achieve the study objectives; a laboratory program was designed to overcome the circumstances of the study goals. The laboratory testing program included two basic parts: the indirect tensile test for cracking resistance and fracture energy investigation and the Marshal testing method for volumetric and mechanical properties evaluation. Test samples of asphalt mixtures with varying RAP 0, 20, 40, 60, and 80% percentages were made using four different asphalt cement percentages: 4.50, 5.00, 5.50, and 6.00 of the sample weight. About 60 test samples were examined using three samples of each of the four distinct asphalt cement percentages and five different RAP percentages.

## 3. Materials and Methods

### 3.1 Natural Aggregates

A dolomite stones as a coarse aggregate and siliceous sand as a fine aggregate as well as limestone mineral filler are used in this study The coarse aggregates were received as two sizes (Grade 2 and Grade 1), which have maximum nominal aggregate size of 19 mm and 9.5 mm, respectively. Whereas breaking sand and natural sand (pass 4.75 mm) obtained from Mania Crusher and Abo-Shalaby at Sharkia Governorate respectively. Limestone dust was used in preparing all of the investigated mixes and it was obtained from quarry 101 in Suez Governorate. Table 1 displays the natural aggregates properties.

### 3.2 Recycling Asphalt Pavement

Reclaimed Asphalt Pavement (RAP) materials are delivered from Banha-Zagazig road at station [25+200] in Sharkia, Egypt was utilized. The road asphalt surface layer's milling materials provided the sample of the recycled asphalt pavement. Determining the RAP binder content was conducted through solvent extraction following AASHTO T 164, revealing a 5.01% bitumen content in the specimen [12]. Fig. 1 shows the specimen of the recycling asphalt pavement and Table 1 illustrates the RAP properties.

### 3.3 Asphalt Cement

AC 60/70 is the usual asphalt grade used for asphalt pavement construction in Egypt, and it was obtained from Victory Laboratory in Suez. Table 2 shows the physical characteristics of the bitumen binder.

### 3.4 Rejuvenator Waste Engine Oil (WEO)

WEO is a common rejuvenator that used as recovery for the aged binder and improves the RAP mixes workability [13]. Choosing the right amount of rejuvenator is crucial since too much of it can cause stripping, adhesion, rutting, and heat cracking, while too little can cause the mixture to become stiff. [14]. **Ahmed Eltwati et al.** proposed three dosages of the waste engine oil: 5 %, 10 %, and 15 % by total weight of the binder[15]. **Ahmed Eltwati et al.** suggested three dosages of the waste engine oil: 6 %, 9 %, and 12 % by total weight of the binder [16]. The authors used 15% of WEO % by total weight of the binder [13]. 15% of WEO was employed as the rejuvenator to soften the aged binder. The utilized WEO had a specific gravity of 0.87 and contained 0.34% water.

Table 1: Properties of Aggregates

| Property | Coarse aggregate | | | Fine aggregate | | Criteria | Method |
|---|---|---|---|---|---|---|---|
| | Grade2 | Grade1 | RAP | NA | RAP | | |
| Bulk SG | 2.668 | 2.618 | 2.631 | 2.64 | 2.65 | - | ASTM C127/ C128 |
| Bulk SSD SG | 2.767 | 2.772 | 2.752 | - | - | - | ASTM C127/ C128 |
| Apparent SG | 2.707 | 2.673 | 2.675 | - | - | - | ASTM C127/ C128 |
| Water absorption (%) | 1.341 | 2.127 | 1.662 | - | - | < 5 | ASTM C127/ C128 |
| Water disintegrate (%) | 0.10 | 0.105 | 0.386 | - | - | | ASTM C127/ C128 |
| Los Angeles Abrasion (%) | 19.79 | 22.86 | 20.16 | - | - | < 45 | ASTM DC-131 |

Figure 1: Stockpile of Unprocessed RAP Milling

## 4. Experimental Work and Mix Design of Asphalt Mixtures

Table 3 displays the experimental program for the hot mix asphalt design and optimization. Specifically, experiments were achieved on various bitumen content from 4.5% to 6% at an increment rate of 0.5%, four various RAP content (20%, 40%, 60%, and 80%), and a reference mix (0% RAP). The tests were conducted in triplicates for each sample according to Egyptian Standards

[17] for five wearing surface mixes; R0, R20, R40, R60, and R80. The samples are defined by letters and numbers, so R0 is a reference sample consisting of 100% natural aggregates (NA) and 0% RAP. R20 is composed of 20 percent of RAP and 80 percent of natural aggregate (NA). The proportions of asphalt mixes and the codified names are shown in Table 3.

Table 2: Physical Characteristics of Asphalt Binder

| **Property** | **Value** | **Unit** | **Standard** |
|---|---|---|---|
| Penetration | 64 | mm | AASHTO T 49, ASTM D 5 |
| Rotational Viscosity at $135^0$C | 512 | CP | AASHTOTP48, ASTM 4402 |
| Softening Point $^0$C | 48 | $^0$C | AASHTOT53-09, ASTM D36-06 |
| Specific gravity | 1.02 | gm/cm$^3$ | ASTM D 70 |

Table 3: Mixtures Proportions and Codification

| Mix Type | RAP (%) | NA (%) | Asphalt Binder Content (%) | | | |
|---|---|---|---|---|---|---|
| | | | 4.5 | 5 | 5.5 | 6 |
| R0 | 0 | 100 | /// | /// | /// | /// |
| R20 | 20 | 80 | /// | /// | /// | /// |
| R40 | 40 | 60 | /// | /// | /// | /// |
| R60 | 60 | 40 | /// | /// | /// | /// |
| R80 | 80 | 20 | /// | /// | /// | /// |

Note: RAP composed of a 5.01% aged binder, /// = three sample

### 4.1 Aggregate Blending and Sample Preparation

With 20% grade 2, 28% grade 1, 37% crushed sand, 11% natural sand, and 4% filler, the mix design for RAP and natural mixes was carried out in accordance with Egyptian criteria. As indicated in Table 4, five hot asphalt mixtures were constructed with RAP ratios of 0, 20, 40, 60, and 80% [17]. The amounts of the new binder that should be added to the mixture are calculated and shown in Table 5. Equation (1) can be utilized to determine the bitumen content needed for the RAP and new aggregate mix gradation [18].

$$Pr = Pc - (Pa*Pp) \quad (1)$$

Where Pc is the percentage of total bitumen in the mix, Pp is the percentage of RAP in the mix, Pa is the percentage of aged bitumen in the mix as determined by the extraction test, and Pr is the percentage of new bitumen to be included in the mix including RAP.

The Marshall Mix design process was used to prepare the samples. The bitumen and natural aggregates were cooked separately at 170°C for one hour [13], while the RAP was preheated in an oven at 146°C for two hours [19]. With 0.5% increments, the bitumen content varied from 4.5% to 6%. The heated aggregate was mixed with bitumen to create the reference mix (R0). To guarantee direct contact with the aged binder, 15% WEO was added straight to the heated RAP in the case of RAP mixes. In order to encourage diffusion and reactivation of the aged binder, natural aggregates were added after the binder [20]. Following ASTM D6926 guidelines, the prepared asphalt mix was put in a mold and compacted using 75 blows per face [21]. The bitumen's rotational viscosity was measured in order to compute the compaction and mixing temperatures, which came out to be 0.28 ± 0.03 Pa.s. And 0.17 ± 0.02 Pa.s. respectively. The temperatures that resulted from mixing and compaction were 154 ± 1C and 147 ± 2C, respectively. Prior to additional analysis, the produced samples were lastly allowed to cure for twenty-four hours at room temperature. Marshall The HMA mixtures underwent flow and stability testing in accordance with ASTM D6927 guidelines [23]. ASTM D3203 [24] was used to estimate volumetric parameters such air voids (AV), while ASTM D2726 [25] was used to quantify the mix's bulk density.

Table 4: Gradation of the Design Aggregate Mixture

| **Sieve Size** | | **Design Gradation (JMF)** | **Specification Gradation (4C) [17]** | |
|---|---|---|---|---|
| (Inch) | (mm) | % Passing | Max. | Min. |
| 1" | 25 | 100 | 100 | - |
| 3/4 | 19 | 85 | 90 | 80 |
| 1/2 | 12.5 | 75 | - | - |
| 3/8 | 9.5 | 65 | 80 | 60 |
| No. 4 | 4.75 | 52 | 65 | 48 |
| No. 8 | 2.36 | 38.75 | 50 | 35 |
| No. 30 | 0.6 | 21.75 | 30 | 19 |
| No. 50 | 0.3 | 15.5 | 23 | 13 |
| No. 100 | 0.15 | 9 | 15 | 7 |
| No. 200 | 0.075 | 4 | 8 | 3 |

### 4.2 Indirect Tensile Strength (ITS) Test

Indirect Tensile Strength (ITS) tests were performed on cylindrical specimens prepared for the study. Marshall Equipment was used to apply vertical loads on the specimens at a loading rate of 50 mm/min parallel to their vertical diametric plane. [26]. The specimens usually failed by splitting along the loaded plane as a result of the consistent tensile stress created by this loading configuration, which was perpendicular to the load plane. The specimens, which had nominal diameters of 101.60 mm and heights of 50.80 mm, were made in accordance with ASTM D6926. For each RAP percentage, 15 specimens were prepared using the optimum bitumen content. The ITS values were calculated using Equation (2) [26]. The ITS test was also used to determine key parameters for evaluating the cracking resistance of both the reference mixture (R0) and RAP mixtures at 25$^0$C [27]. Figure 2 illustrates the ITS test setup configuration. Using the mathematical equations given in Equations (3) to (8), load-displacement data were gathered in order to compute the fracture energy, fracture work density, cracking tolerance index, and cracking resistance index. [10], [27]. Figure 3 presents the load- deformation data of the reference mixture (R0).

$$ITS = \frac{2000x\,P}{\pi x t x D} \quad (2)$$

Where ITS is the indirect tensile strength in kPa, P is the maximum load to failure in N, t is the specimen height in millimetres and D is the specimen diameter in millimetres.

$$FWD = \frac{Wf}{Vs} \tag{3}$$

$$Gf = \frac{Wf}{t*D} \tag{4}$$

Where FWD is the fracture work density in J/m$^3$, Wf is the fracture work in joule, Vs is the volume of specimen and Gf is the fracture energy in J/m$^2$.

$$CT_{Index} = \frac{t \times Gf \times L75}{62 \times |m_{75}| \times D} \tag{5}$$

$$|m_{75}| = \left| \frac{P85 - P65}{l65 - l85} \right| \tag{6}$$

$$CRI = \frac{Gf}{Pmax} \tag{7}$$

$$FST_{index} = \frac{Gf}{ITS} * 10^6 \tag{8}$$

Where $CT_{Index}$ is the cracking tolerance index, l65, l75, l85 are the displacements corresponding to 65%, 75% and 85% of peak load at the post-peak region in millimetres, P65, P85 are 65% and 85% of peak loads in kN, m75 is slope corresponding to 75% of peak load in the post-peak region in N/m, CRI is the cracking resistance index, $P_{max}$ is the peak load in kN and $FST_{index}$ is the Fracture Strain Tolerance index.

Table 5: Determining the necessary bitumen percentage based on the RAP content

| RAP Content. (%) | Total Bitumen in the Mix; (%) | Aged Binder of RAP; (%) | Virgin Bitumen; (%) |
|---|---|---|---|
| 0 | 4.50 | 5.01 | 4.50 |
| 20 | | | 3.50 |
| 40 | | | 2.50 |
| 60 | | | 1.50 |
| 80 | | | 0.50 |
| 0 | 5.00 | 5.01 | 5.00 |
| 20 | | | 4.00 |
| 40 | | | 3.00 |
| 60 | | | 2.00 |
| 80 | | | 1.00 |
| 0 | 5.50 | 5.01 | 5.50 |
| 20 | | | 4.50 |
| 40 | | | 3.50 |
| 60 | | | 2.50 |
| 80 | | | 1.50 |
| 0 | 6.00 | 5.01 | 6.00 |
| 20 | | | 5.00 |
| 40 | | | 4.00 |
| 60 | | | 3.00 |
| 80 | | | 2.00 |

### 4.3 Statistical Analysis

The mechanical and volumetric characteristics of the RAP mixes were analyzed using two-way ANOVA. To assess the degree and importance of the RAP's influence on the observed characteristics of the hot asphalt mixtures, this was done at the 5% level of significance. The ANOVA was conducted using the statistical program SPSS V16. For the first time, normality tests were used to confirm that all of the data had a 5% significance level of normalcy. A null hypothesis (Ho) was expected to create tested values with the same population mean, whereas an alternative hypothesis (Ha) was assumed to produce differing bitumen (AC) or RAP contents.

The cracking resistance characteristics of the RAP mixes were subjected to a one-way analysis of variance (ANOVA). The RAP effect's impact on the measured cracking resistance parameters of the hot mixes was assessed at the 5% level of significance. For the ANOVA, the statistical program SPSS V16 was used. The assumption that the mean value of these parameters for RAP mixtures was equal to the mean value of the control mix (R0) was the null hypothesis. In contrast, the alternative hypothesis (Ha) made a different assumption. The significance of the various test conditions was also assessed using a Tukey's post-hoc test.


Figure 2: Indirect Tensile Strength (ITS) Test Setup

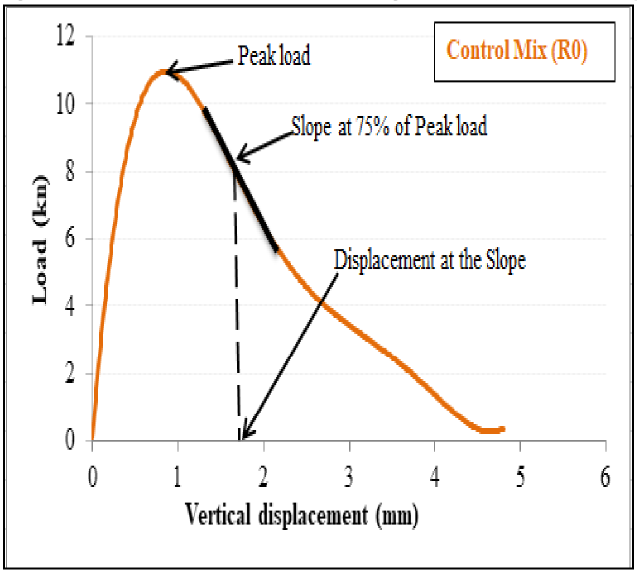


Figure 3: Load-Displacement Curve

## 5. Results and Discussion

### 5.1. Mechanical and Volumetric Properties

Figure 4 presents Marshall Stability values at various percentages of asphalt cement for the referenced mixture without RAP (R0) and the mixtures containing different contents of RAP content; 20%, 40%, 60%, and 80%. The impact of raising the bitumen content (AC), which typically causes the Marshall Stability to rise to the highest level of stability before falling once the bitumen content reaches its optimal level, is seen for all asphalt mixtures at all RAP content levels, which is consistent with the findings of (Azzam et al., 2016) [30].

Similar stability trends due to increase RAP content are also observed for mixtures with 5.5 – 6.0% Asphalt Content. The results show that the maximum stability of all mixtures was achieved at 5% Asphalt Content.

Results also indicated that mixtures containing 40% and 80% RAP produce stability as near as that for the referenced mixture (R0). The mixtures including 80% RAP achieve the lowest stability, while 40% RAP mixtures achieve the highest stability at all Asphalt Content. The analysis indicated that the obtained stability of RAP mixtures was improved by percentages ranging from 1.95% to 17.67% compared to the Egyptian specification value of 1100 kg. This indicated that the physical properties of the RAP aggregate are closest to those of natural aggregate. The WEO is also an effective rejuvenator capable of effectively enhancing the properties of the old bitumen. Figure 5 illustrates the combined influence of RAP and binder content on the mixture flow. The typical trend of increased flow with higher binder content was evident across all mixtures, regardless of RAP levels. Notably, the maximum flow for all mixtures occurred at a 6% asphalt content, exceeding the allowable range, except for mixtures containing 20% RAP. Flow values for all mixtures remained within the permissible range when asphalt content ranged from 4.5% to 5.5%, this finding is in agreement with (Ahmed Ebrahim et al., 2015) [3].

Figure 6 shows the Marshall Unit weight at varying bitumen percentages for the common mixture (R0) and mixtures with different RAP contents. For mixtures with 20% and 80% RAP, the unit weight displayed a rise-and-fall pattern as asphalt content increased, whereas mixtures with 40% and 60% RAP showed a consistent rise in unit weight. The standard mixture (R0) achieved a peak unit weight of 2.43 g/cm³ at 5.5% asphalt content. The lower specific gravity of RAP aggregates than natural aggregates likely contributed to the reduced unit weight in RAP mixtures. Additionally, the presence of aged binder in RAP contributed to the reduction of density. Figure 7 illustrates changes in air voids with increasing RAP and asphalt content. Air voids decreased as asphalt content increased, driven by improved lubrication, which facilitates greater compaction. This increase in asphalt content led to a reduction in VMA (voids in mineral aggregate) and an increase in VFA (voids filled with asphalt), collectively contributing to the observed decrease in air voids.

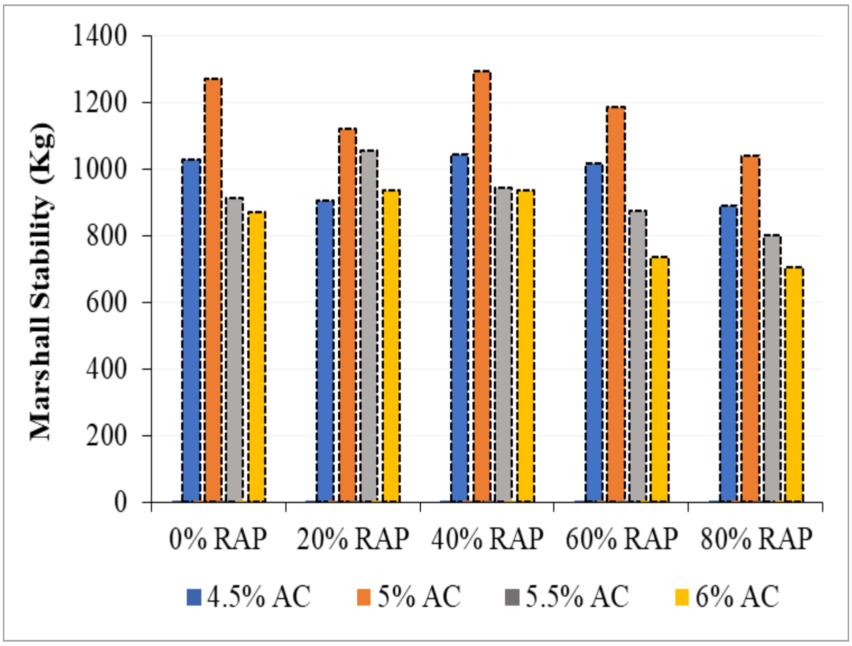


Figure 4: Marshall Stability with different RAP Percentages

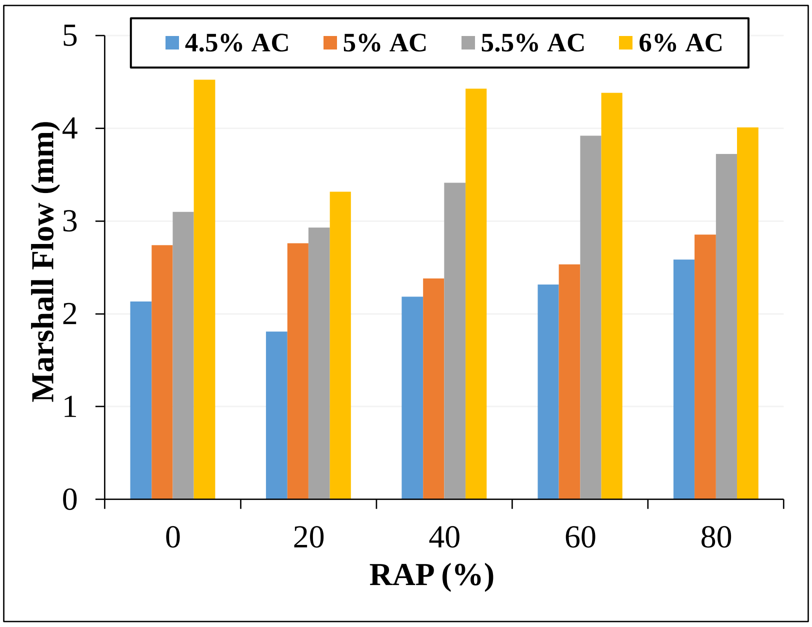


Figure 5: Effect of RAP Content on Marshall Flow Values

Figure 8 presents the stiffness of various asphalt mixtures with varying amounts of RAP and bitumen content. Marshall Stiffness of asphalt mixture is defined as the ration of stability per flow values; and it is considered an indication of a stable mixture under the effect of traffic loadings. The results showed that the highest stiffness for the standard mixture (R0) and mixtures with 20% RAP occurred at 4.5% asphalt content, while mixtures containing 40%, 60%, and 80% RAP reached their maximum stiffness at 5% asphalt content. Additionally, mixtures with 40% RAP and 5% asphalt content were 17% stiffer than the common mix (R0) and further increasing the RAP content beyond 40% resulted in a reduction in stiffness. The stiffness values improved as RAP content increased from 20% to

40%. Specifically, the mixtures with 20% RAP at 4.5% asphalt content and 40% RAP at 5% exhibited the highest stiffness, surpassing 500 kg/mm. It was also noted that the RAP mixtures with higher stiffness corresponded to the lowest flow values.

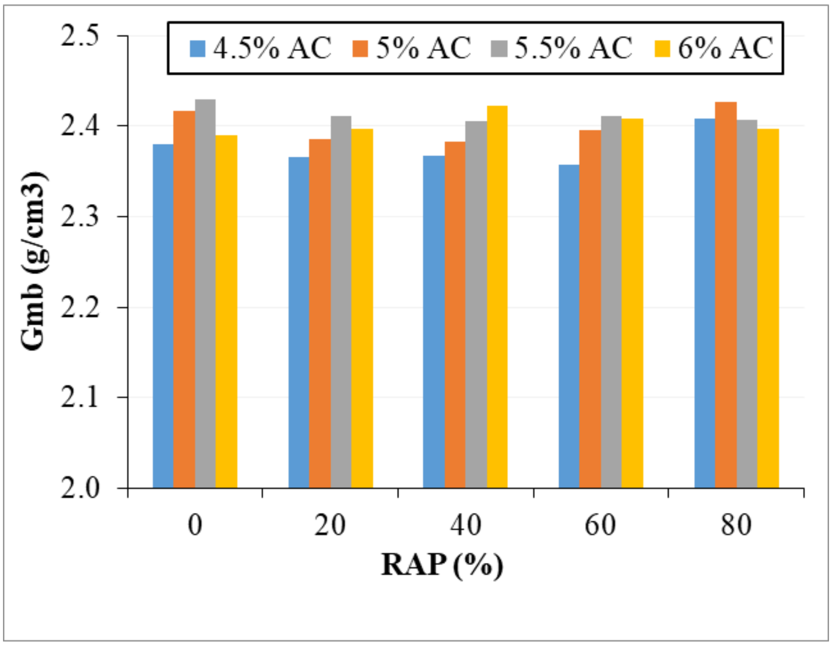


Figure 6: Impact of RAP Content on Bulk Density

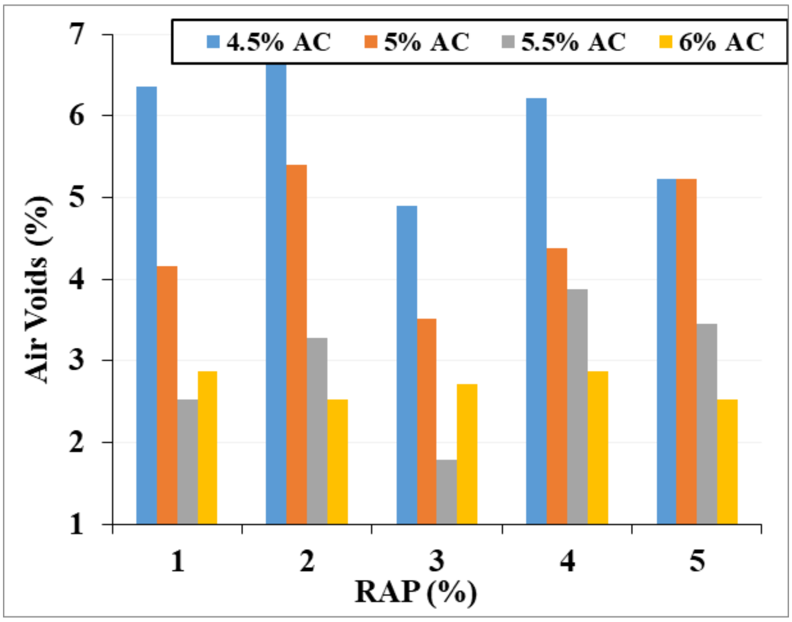


Figure 7: Influence of RAP Content on Air Voids

Table 6 and Figure 9 present the mechanical and volumetric properties of asphalt mixtures containing Reclaimed Asphalt Pavement (RAP) at optimum asphalt content. Optimum Asphalt Content (OAC %) values range from 5.27% to 5.40%, meeting the criteria of 3-7%. This indicates consistent binder content in all mixes. Stability decreases as RAP content increases, from 1200 kg for R0 to 940 kg for R80. Mixtures R20, R40, and R60 meet the minimum stability criterion of >1100 kg. [17], but R80 does not. Flow values (2.85-3.20

mm) are within the acceptable range of 2-4 mm, indicating good deformation resistance for all mixes, this finding is in agreement with (Ahmed Ebrahim et al., 2015 and Julide Oner et al., 2015) [3], [18]. Bulk Specific Gravity (Gmb) values slightly increase with RAP content, indicating denser mixtures at higher RAP levels. The air voids decrease from 4.25% (R0) to 3.20% (R60) but increase slightly to 4.00% (R80). All values remain within the acceptable range of 3-5%, this finding is in agreement with (Hossain Khan et al., 2021) [13]. Marshall Stiffness decreases as RAP content increases, from 367 kg/mm for R0 to 303 kg/mm for R80. All values meet the minimum stiffness criterion.

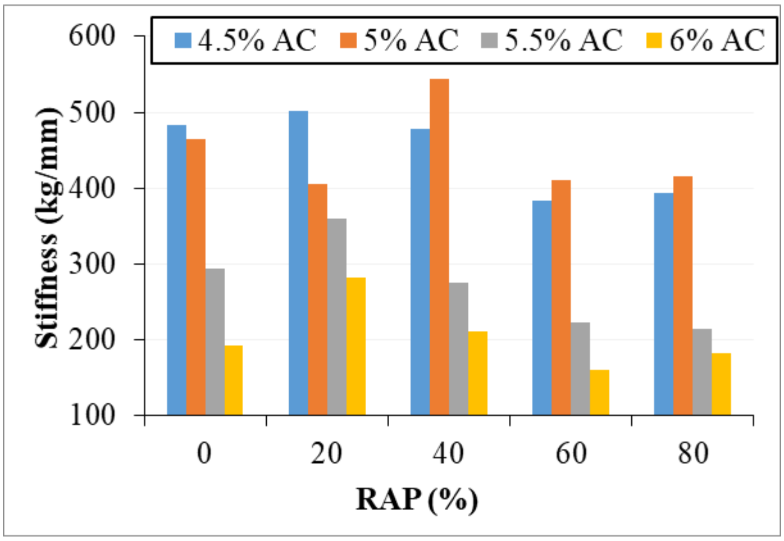


Figure 8: Variations of Stiffness Values with Increase in RAP Contents

Table 6: Volumetric and Mechanical Characteristics of Asphalt Mixtures Containing RAP

| Parameter/Mix | R0 | R20 | R40 | R60 | R80 | Criteria 4C [17] |
|---|---|---|---|---|---|---|
| OAC (%) | 5.30 | 5.40 | 5.39 | 5.27 | 5.35 | 3 - 7 |
| Stability (kg) | 1200 | 1100 | 1110 | 1120 | 940 | > 1100 |
| Flow (mm) | 3.00 | 2.85 | 3.10 | 3.20 | 3.10 | 2 - 4 |
| $G_{mb}$ (gm/cm$^3$) | 2.438 | 2.395 | 2.400 | 2.406 | 2.420 | - |
| A.V (%) | 4.25 | 3.70 | 3.20 | 4.10 | 4.00 | 3 - 5 |
| VMA (%) | 13.25 | 14.28 | 14.40 | 14.04 | 13.48 | > 13 |
| Stiffness (kg/mm) | 367 | 386 | 358 | 350 | 303 | ≥ 275 |

## 5.2 Cracking Resistance

### *5.2.1 Load–Displacement Relationship*

Figure 10 presents the load–displacement relationships resulted from the Indirect Tensile Strength tests (ITS) for both control mix (R0) and mixtures containing 20%, 40%, 60% and 80% percentages of RAP. As shown on the Figure, the trend of relationship can be divided into three stages; the first stage is elastic phase in which the relationship in the initial loading is almost straight line and the displacement is linearly increased as the load is increased. The second stage represents a strain-hardening stage in which the displacement increases with an increase in load up to reach the maximum load value before the specimen failure. The displacement increases with the increased load nonlinearly at a slower rate of applied load than that in the first stage. The last stage is the strain-softening in which the displacement was increased rapidly with a small increase in the effected load up to the specimen failure.

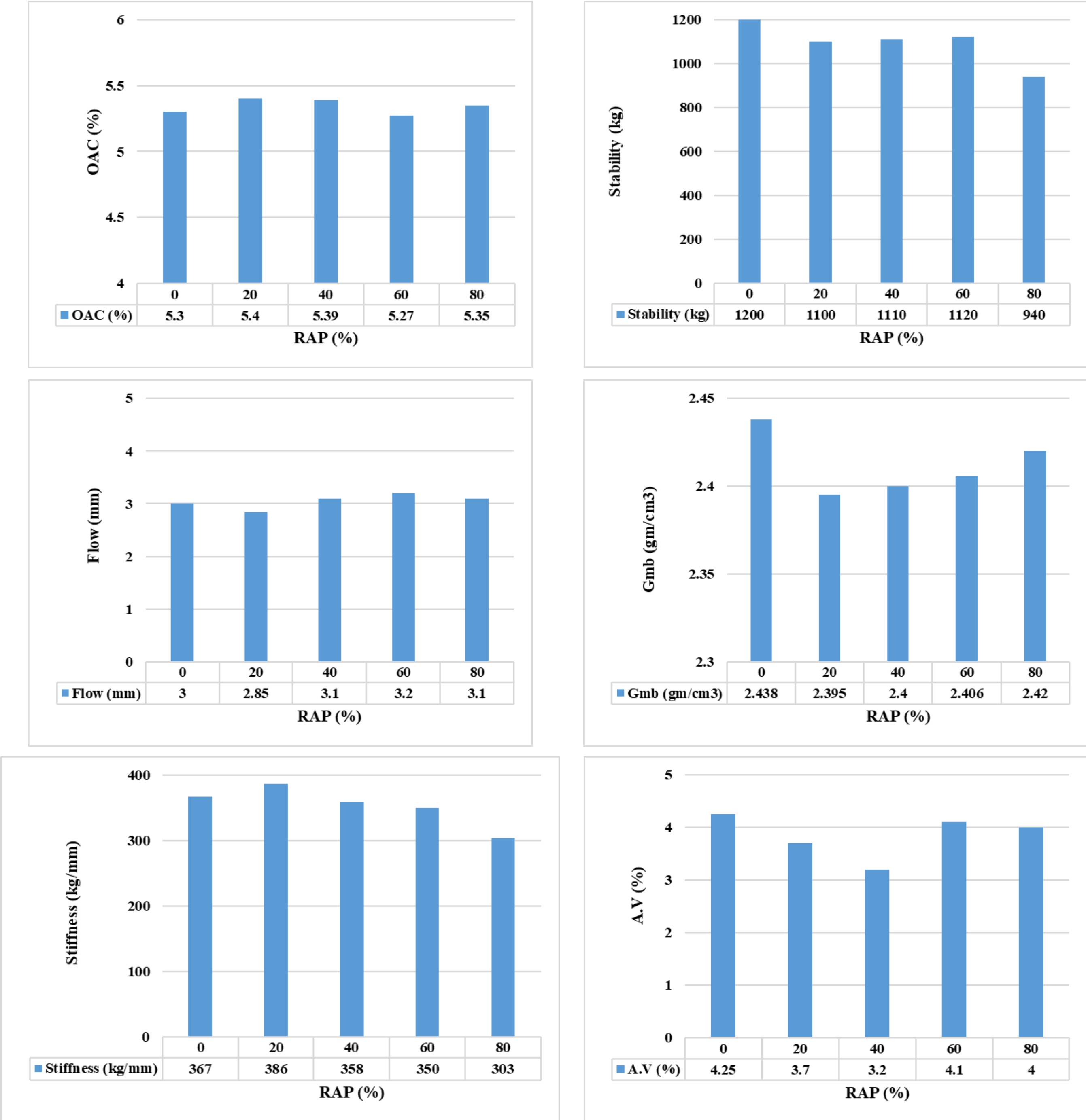

Figure 9: Marshall Properties of Asphalt Mixtures

From Figure 10, the control mixture needs a higher peak load and Gf values than RAP mixtures. As the RAP content increases, peak loads show a clear decreasing trend. All mixtures show similar initial slope in the elastic region. The virgin mix (R0) exhibits more ductile behaviour with a gradual post-peak decline. Higher RAP content mixtures show more brittle behaviour with steeper post-peak drops. This trend is consistent with the findings of previous studies, which have reported that the incorporation of RAP leads to a reduction in the ductility and toughness of asphalt mixtures (Jiangmiao Yu et al., 2024) [28]. The more brittle behavior observed in mixtures with higher RAP content can be attributed to the aged binder in RAP, which is typically more brittle and less cohesive compared to virgin binder (Xiong Xu et al., 2022) [29].

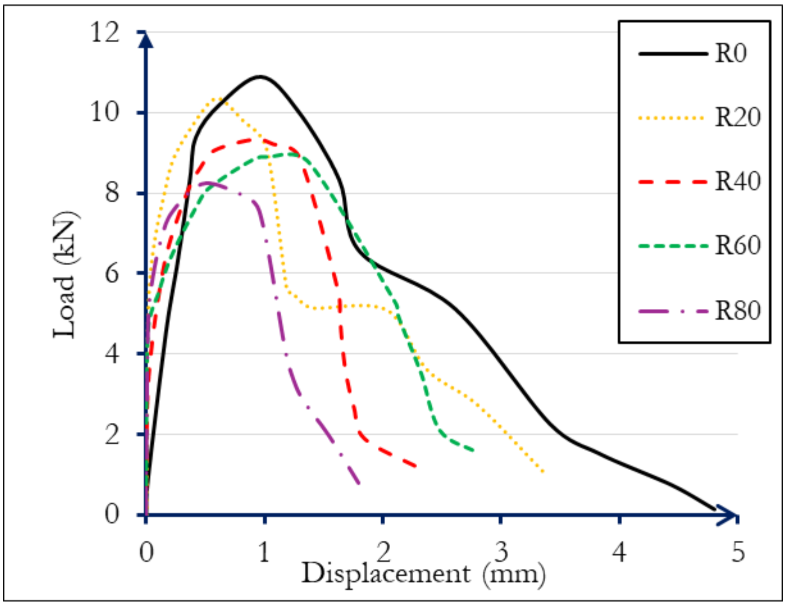


Figure 10: Load – Displacement Relationships

Figure 11 presents the results of indirect tensile testing for each RAP percentage average of three samples. The ITS of mixtures containing RAP decreases with the increase in RAP percentages, which is in line with the findings of other researchers who have observed a reduction in the tensile strength of asphalt mixtures with higher RAP content (Azzam et al., 2016) [30]. The figure shows that the ITS value of the control mix (0% RAP) is 1027 kpa, representing 100%, whereas the IT'S of other mixes is attributed to the control mix. The ITS values for mixes containing RAP represent about 95.72, 98.05, 76.92, and 77.22 % of CAM for 20%, 40%, 60%, and 80% RAP ratios, respectively. It shows that the ITS values for mixes containing 40% RAP are nearest to ITS values for CM. Higher RAP percentages mean more aged binder, reducing overall mix flexibility. This aged binder is typically more brittle and less able to form strong cohesive bonds. Figure 12 presents the results of maximum vertical displacement (ΔD) for both the control mixture (R0) and mixtures containing different percentages of RAP. The figure shows that the ΔD of mixtures incorporating RAP decreases with the increase in RAP percentages. The ΔD value of control mixture (R0) is 1.253 mm whereas the ΔD values for mixes containing 40, 60 and 80% RAP are lower than the ΔD value of the common mix.

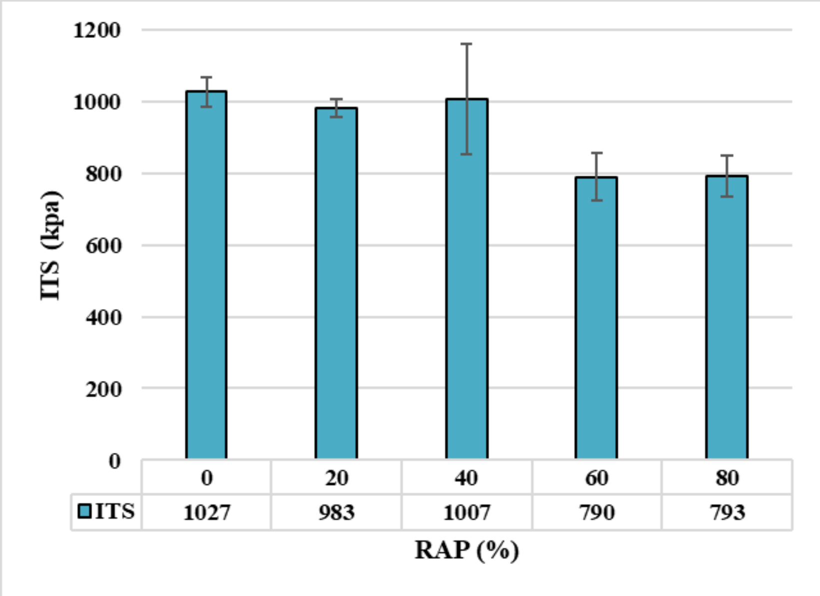


Figure 11: Indirect Tensile Strength

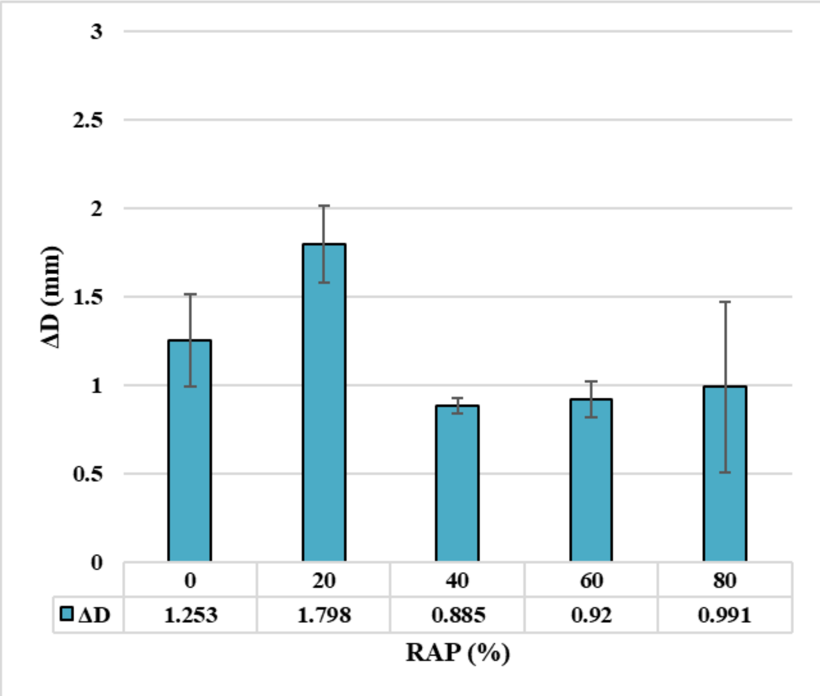


Figure 12: Vertical Displacement

### 5.2.2 Fracture Energy (FE) and Fracture Work Density (FWD)

Figure 13 presents the results of fracture energy for both the control mix (CM) (0% RAP) and mixtures containing different percentages of RAP. The FE value of the CM is 3706 J/m2. The FE of mixtures containing RAP decreases with the increase in RAP percentages, indicating a reduction in the ability of the mixtures to absorb energy before failure. This is consistent with the findings of previous studies, which have reported that the incorporation of RAP leads to a reduction in the fracture energy of asphalt mixtures (Weimin Song et al., 2023) [31]. It is concluded that the mixture containing 20 and 40% RAP gains the desired strength other than studied RAP mixtures, representing about 74.95 and 72.21% of CM, respectively.

The Fracture Work Density (FWD) of asphalt mixtures is shown in Figure 14. The FWD decreases as the RAP percentage increases, signifying reduced fracture energy and ductility of the asphalt mixtures with higher RAP content. At 0% RAP, the asphalt mixture exhibits the highest FWD (46 kJ/m³), reflecting the best ability to resist cracking and deformation. At 20% RAP, the FWD slightly decreases to 43 kJ/m³, showing a minimal reduction in fracture work capacity. As the RAP content increases to 40%, 60%, and 80%, the FWD values drop progressively to 32, 27, and 19 kJ/m³, respectively. It indicates a significant reduction in the material's ability to absorb energy before fracturing. The decrease in FWD with higher RAP content suggests that adding RAP makes the asphalt mixture more brittle, compromising its cracking resistance. This is in line with the results of earlier research, which indicates that adding RAP lowers the fracture energy of asphalt mixes (Ali Foroutan et al., 2023) [32].

The indirect tensile test describes the determination of the cracking indices; "cracking tolerance index (CT index), cracking resistance index (CRI index), and (FST index)" determined from the load-displacement curve [10]. These parameters can be used to evaluate the resistance of asphalt mixtures to cracking. Figure 15 shows the CT index of sustainable asphalt mixtures at 25 °C. The CT index decreases significantly as the RAP percentage increases. The highest CT index (93) is observed at 0% RAP, demonstrating the superior cracking tolerance of asphalt mixtures without any RAP. At 20% RAP, the CT index drops to 74, and it continues to decrease to 57, 44, and 20 for RAP contents of 40%, 60%, and 80%, respectively. The minimum CT Index of 20 is often used as a baseline for acceptable cracking performance, though higher values are desirable for improved durability [33]. It indicates a reduction in the cracking tolerance of the asphalt mixtures with higher RAP content. This decline suggests that increasing RAP compromises the flexibility and resistance of the asphalt to cracking.

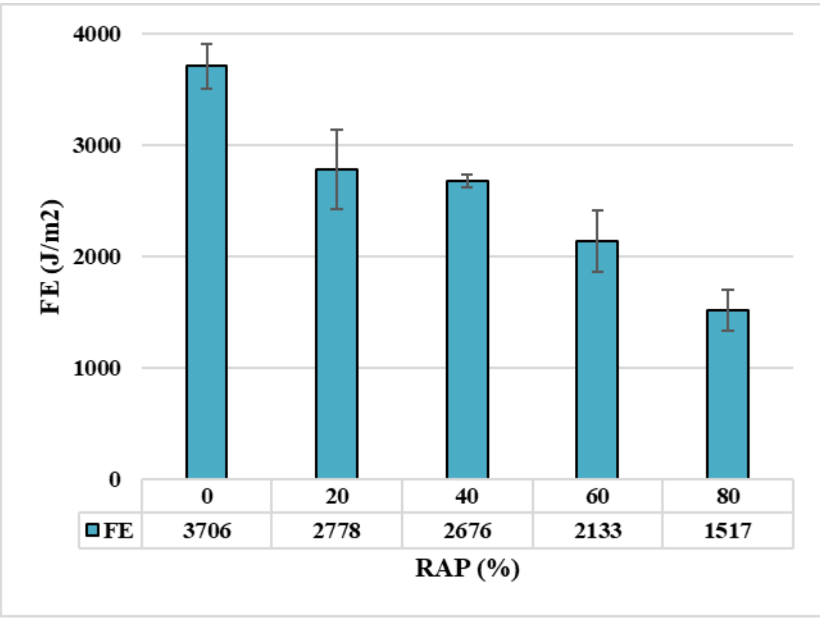


Figure 13: Fracture Energy

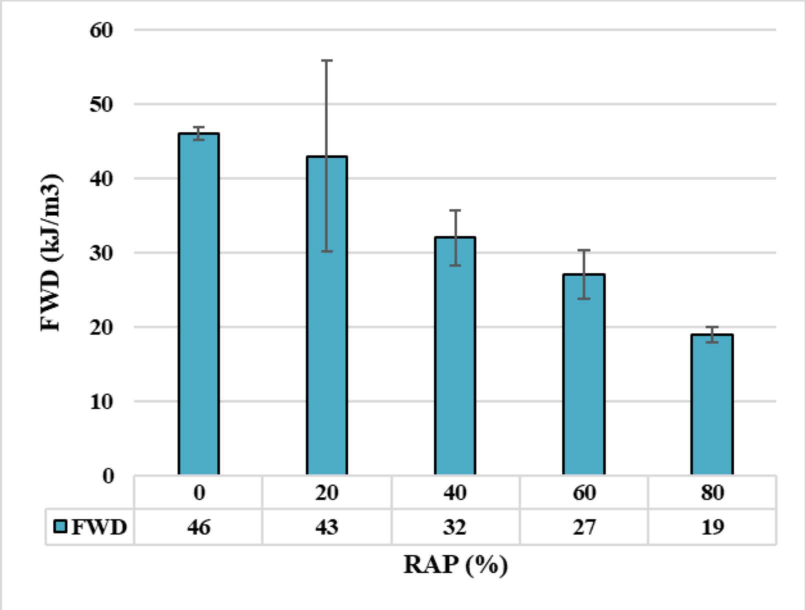


Figure 14: Fracture Work Density

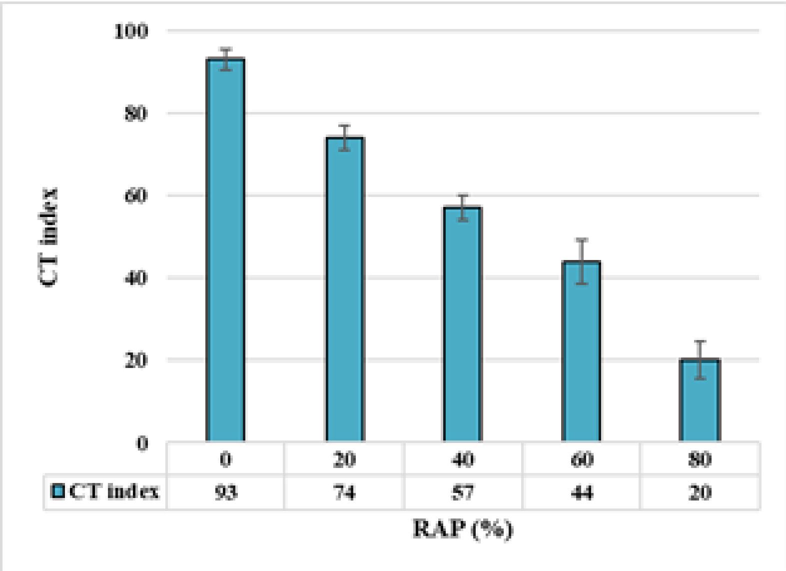


Figure 15: Cracking Tolerance Index

Figure 16 illustrates the Cracking Resistance Index (CRI) of sustainable asphalt mixtures at 25 °C. The CRI decreases as the RAP percentage increases, indicating a decline in the cracking resistance of the asphalt mixtures with higher RAP content. The asphalt mixture without RAP achieves the highest CRI value of 341, showing the best cracking resistance. At 20% RAP, the CRI decreases to 269, while a slight recovery is observed at 40% RAP (287). However, as the RAP content rises to 60% and 80%, the CRI further declines to 240 and 184, respectively. The results suggest that while moderate RAP content (20-40%) may still provide acceptable cracking resistance, higher RAP percentages (60% and above) significantly reduce the asphalt's resistance to cracking. Figure 17 indicates that the FST index parameters of most of the RAP mixtures are lower than those of the control mixture

(R0). Thus, the cracking resistance of RAP mixtures is decreased with the increase in RAP percentages.

These results are in line with those of earlier research, which found that adding RAP lowers asphalt mixes' resilience to cracking (Baoshan et al., 2010) [34]. The aged binder in RAP has a lower viscosity and cohesiveness than virgin binder, which reduces the mixture's resistance to cracking. This is the reason for the decrease in cracking resistance.

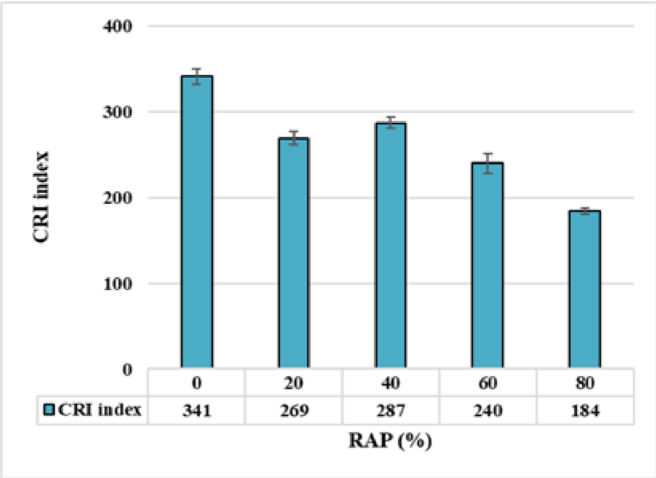


**Figure 16: Cracking Resistance Index**

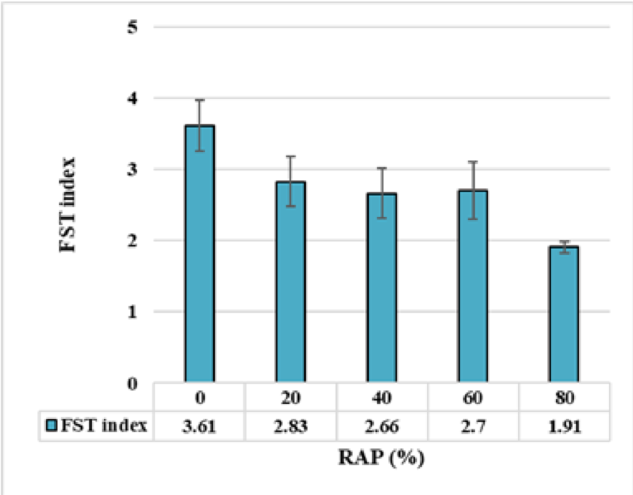


**Figure 17: Fracture Strain Tolerance Index**

### 5.3 Statistical Analysis

Table 10 displays the outcomes of an ANOVA test carried out for FE, IT'S, and FWD of hot mixtures at 250°C. Table 11 reveals that varying percentages of RAP exert a noteworthy influence on FE, IT'S, and FWD of asphalt mixtures. In the Tukey's post-hoc test, Ro is taken as the control mixture, and RAP mixtures are compared against it. As indicated in Table 13, with a few exceptions, the ITS, FWD, and FE of RAP mixes did not exhibit significant differences from Ro.

Table 10: One-Way ANOVA Results for Hot Mixtures at $25^0$C

| Dependent variable | | Sum of Squares | df | Mean Square | F | p-value | Sig. |
|---|---|---|---|---|---|---|---|
| ITS | Between Groups | 167533.333 | 4 | 41883.333 | 6.153 | 0.009 | Yes |
| | Within Groups | 68066.667 | 10 | 6806.667 | | | |
| | Total | 235600.000 | 14 | | | | |
| FWD | Between Groups | 1339.009 | 4 | 334.752 | 7.090 | 0.006 | Yes |
| | Within Groups | 472.142 | 10 | 47.214 | | | |
| | Total | 1811.151 | 14 | | | | |
| FE | Between Groups | 8346807.067 | 4 | 2086701.767 | 6.860 | 0.006 | Yes |
| | Within Groups | 3041760.667 | 10 | 304176.067 | | | |
| | Total | 11390000 | 14 | | | | |

Table 11: Tukey's Post-hoc Test for Hot Mixtures at $25^0$C

| Condition (I) | Condition (J) RAP | ITS (kPa) | | FWD (kJ/m$^3$) | | FE (J/m$^2$) | |
|---|---|---|---|---|---|---|---|
| | | p-value | Sig. | p-value | Sig. | p-value | Sig. |
| R0 | R20 | 0.964 | No | 0.999 | No | 0.998 | No |
| | R40 | 0.998 | No | 0.141 | No | 0.162 | No |
| | R60 | 0.035 | Yes | 0.087 | No | 0.101 | No |
| | R80 | 0.038 | Yes | 0.016 | Yes | 0.019 | Yes |

## 6. Conclusions

This study discussed the mechanical and volumetric properties of sustainable asphalt mixtures incorporating RAP and determining parameters to evaluate the cracking resistance and Fracture Energy for RAP mixtures. Based on the methodology and results analysis of this study, the following conclusions were drawn:

- HMA mixtures containing 80% RAP showed the lowest stability whereas those containing 40% RAP showed the highest stability for all AC content.
- The RAP mixes' stability increased from 1.95% to 17.67% when compared to the 1100 kg specification value, suggesting that WEO was a powerful rejuvenator that could improve the aged binder's qualities.
- Flow values are located within the required specifications range at 4.5-5.5% AC, whereas flow values are outside the required specifications range when AC > 5.5%.
- Common mixture has a maximum unit weight of 2.43 gm/cm$^3$ at 5.5% AC. The lower specific gravity of the RAP aggregate relative to the natural aggregate can be considered among the main reasons for the drop in unit weight of RAP mixtures.
- The RAP mixtures with higher stiffness exhibited the lowest flow.
- All the RAP and control asphalt concrete mixture met the design criteria except for 80% RAP HMA. The 60% RAP mixture failed to meet the minimum stability requirements.

- ITS values for mixes containing RAP decrease with the increase in RAP content. A reduction in the ITS values may be caused by a reduction in the stiffness of these mixtures due to the addition of WEO to the RAP mixtures.
- The FWD, FE, CRI and $CT_{Index}$ values of the mixture containing 40% RAP are higher than those of other RAP mixtures. It can be concluded that the mixture containing 40% RAP achieved desired strength, whereas the remaining RAP mixtures.
- Based on the outcomes of the study, it is recommended to study the effect of the different loading rates, and the moisture sensitivity of asphalt mixtures.

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# تقييم مقاومة التشقق وطاقة الكسر لمخاليط الأسفلت المستدامة التي تحتوي على الأسفلت المعاد تدويره


## الملخص

يحتاج إنتاج وإنشاء الرصف الأسفلتي إلى كمية كبيرة من الطاقة والمواد الطبيعية غير المتجددة. لذلك، يبدو أن استخدام المواد المعاد تدويرها ضروري لإنشاء أرصفة أسفلتية أكثر استدامة. الهدف من هذه البحث هو فحص أداء الخلطات الأسفلتية المستدامة التي تحتوي على ركام معاد تدويره (RAP) بالإضافة إلى فحص وتقييم مقاومة الخلطات الأسفلتية للشروخ. ولتحقيق أهداف الدراسة، تم تصميم برنامج تجريبي الخلطات الأسفلتية الساخنة باستخدام أربعة محتويات مختلفة من البيتومين (٤,٥ و ٥,٠ و ٥,٥ و ٦,٠ ٪)، وأربعة محتويات مختلفة من الركام المعاد تدويره (٢٠ RAP ٪ و ٤٠ ٪ و ٦٠ ٪ و ٨٠ ٪)، بالإضافة إلى الخلطة الأسفلتية المرجعية (بدون RAP). تم استخدام طريقة اختبار مارشال للتحقيق في الخصائص الحجمية والميكانيكية للخلطات الأسفلتية. تم قياس الحمل والازاحة لفحص وتقييم مؤشرات مقاومة الشروخ وطاقة الكسر وكثافة حمل الكسر باستخدام اختبار الشد غير المباشر. أشارت نتائج الدراسة إلى أن الخصائص الحجمية والميكانيكية للثبات وصلابة وكثافة الخلطات الأسفلتية المحتوية على الركام المعاد تدويره تتشابه إلى حد كبير مع تلك الخصائص للخلطة المرجعية. أشار تحليل نتائج مقاومة الشد غير المباشرة إلى أن معاملات التكسير ؛ مؤشر CT ومؤشر CRIومؤشر FST للخليط الذي يحتوي على ٤٠ ٪ RAP أعلى من خلطات RAP الأخرى. أظهر التحليل الإحصائي أن الصلابة والثبات ونسبة الفراغت الهوائية والانسياب للخلطات الأسفلتية المحتوية على RAP كانت ذات فروق معنوية. أيضًا، لم تختلف طاقة الكسر وقوة الشد غير المباشرة وكثافة عمل الكسر لخلطات RAP بشكل كبير عن الخلطة الأسفلتية المرجعية.