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# Appraising the synergistic use of recycled asphalt pavement and recycled concrete aggregate for the production of sustainable asphalt concrete

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A R T I C L E  I N F O

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A B S T R A C T

Material obtained from the demolition of concrete structures and milling of flexible pavements has the highest potential for recyclability. This study aimed to evaluate the performance of hot mix asphalt with the concurrent use of recycled asphalt pavement (RAP) and recycled concrete aggregate (RCA). Contents of RAP and RCA were varied from 0% to 50% by fixing the total recycling materials percentage to 50%. Penetration grade 40/50 virgin binder and waste engine oil (WEO) as rejuvenator were used in the present study. A series of tests, such as Scanning electron microscopy (SEM), Marshall stability, indirect tensile strength test, IDEAL CT, uniaxial compression test, and resilient modulus test, were carried out to assess the performance of the prepared recycled asphalt mixtures. SEM images revealed the presence of the medium to fine particles on RCA indicating the rough surface texture. Except RAP10 (10% RAP plus 40% RCA) and RAP50 (50% RAP) mixes, all mixes had Marshall stability value greater than the control mix, the highest for RAP40 (40% RAP plus 10% RCA) mix followed by RAP0 (50% RCA) mix. In the case of resilient modulus, the effect of RAP is more pronounced till 40% resulting in an almost linear increase in values. Also, RAP40 exhibited the highest rutting and fatigue resistance. As far as moisture sensitivity is concerned, all the mixes performed satisfactorily as the tensile strength ratio (TSR) was greater than 80%. Overall, the major factors affecting the performance of recycled mixes were surface roughness, stiffness of the aged binder and rejuvenator.

## 1. Introduction

With the growth in population and urbanization, rapid progression in road infrastructure using natural resources possess drastic environmental burdens [1,2]. As of 2023, out of the global road network, over 80% of the pavements are surfaced with the use of asphalt binder and natural aggregates. From the perspective of Iraq, almost all the road infrastructure in the current financial year has been granted for asphalt pavements instead of concrete technology. These issues are coupled with the increased prices of crude oil, as

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well as the government's pressure to construct eco-friendly and sustainable pavements [3]. To overcome the apprehensions, pavement industries are actively looking for an alternative material that can suffice the need or can be used as a substitute for pavement materials without compromising performance.

In Iraq, the turning from the concrete pavements along with the demolition of old asphalt pavements generates a significant amount of solid waste, resulting in the formation of large stockpiles. The material obtained from the demolition of asphalt and concrete pavements is generally referred to as recycled asphalt pavement (RAP) and recycled concrete aggregate (RCA), respectively. The accumulation of RAP and RCA amounts to billions of tonnes and remains unutilized for years, leading to severe environmental and social concerns [4]. As per the past reports, RAP and RCA allowed for the reuse and recycling of asphalt pavements is quite limited [5]. The probable reason may be the need for the processing of recycled material, lack of experience, and the concerns associated with the performance of reconstructed pavements. Although the use of these materials (RAP and RCA) facilitates environmental, social, and economic benefits [6,7], their use in asphalt pavements still involves various engineering challenges and research uncertainties in terms of mechanical performance and durability. The presence of cement and stiff asphalt binder over the aggregates in RCA and RAP material, respectively, influences the overall performance of the asphalt pavements [8–10]. Due to these reasons, RAP and RCA were commonly adopted in base and subbase layers [11–14]. Nevertheless, final performance depends on the properties of the already coated cement/asphalt binder, aggregate type, and their proportions [15–20]. Also, the performance of asphalt pavements inevitably varies with the use of these materials in an undefined proportion and hence their selection (individual quantity of RAP and RCA) is not straightforward.

Naser et al. [21] stated that the volumetrics and stability of the asphalt mixtures are predominantly affected by the dosage of RAP and RCA. Higher RCA and lower RAP content increased the optimum binder content (OBC) and vice-versa. Either 25% RCA and 75% RAP or 50% RCA and 50% RAP was found to be the best combinations that could meet the desired aggregate properties and are very similar to natural aggregates used for the construction of asphalt pavements [22]. In a study conducted by Purohit et al. [23], the combination of RAP and RCA resulted in 22%− 28% higher stability values compared to control asphalt mixtures, regardless of the base asphalt binder. This is attributed to the better interlocking due to the presence of rough textured and porous surface RCA in asphalt mixtures [24]. The asphalt mixture prepared with RAP and RCA not only improved the stability but also lowered the flow values (maximum 19% decrement). The authors [23] attributed the presence of stiff asphalt binder on the RAP for lower flow values. This shows the synergistic effect of RAP and RCA in asphalt mixtures. Although the inclusion of RAP and RCA in asphalt mixtures slightly lowered the moisture sensitivity, the TSR value was higher than the minimum desired value (80%) [23].

Various studies explored the performance of asphalt mixtures with different percentages of RAP and RCA as shown in Table 1. It can be seen that a significant amount of work has been done on the individual effect of RAP and RCA, showing their feasibility and effectiveness in improving the overall performance in terms of rutting, cracking, and moisture damage. However, very few studies have examined the coupled behavior of RAP and RCA on the performance of asphalt pavements. As per the author's knowledge, a study compiling all the key aspects such as rutting, cracking, and moisture sensitivity of RAP and RCA inclusive asphalt mixtures is still unknown. This forms the motivation for carrying out the present study.

## 2. Research significance and objectives

Recently, the increase in pavement material prices coupled with the increase in environmental awareness has driven a strong movement toward the adoption of sustainable construction. Owing to the abundant availability, the synergistic use of RAP and RCA in asphalt concrete could be one of the possible ways to reduce environmental burdens and encourage sustainable development following the recommendations of the United Nations Climate Change Conference 2022.

**Table 1**
A review of the performance of asphalt mixtures containing different percentages of RAP and RAC.

| Reference | RAP content | RCA content | Rejuvenator | Properties | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Marshall stability | Rutting | Fatigue | Moisture | Resilient modulus |
| [25] | 0%, 15%, and 30% | - | - | × | ✓ | ✓ | ✓ | × |
| [26] | - | 0%, 20%, 40%, and 60% | - | ✓ | ✓ | × | ✓ | × |
| [6] | - | 37% | - | ✓ | ✓ | × | ✓ | ✓ |
| [27] | 5%, 10%, 20%, and 30% | - | - | × | ✓ | ✓ | ✓ | ✓ |
| [28] | 0%, 30%, 40%, and 50% | - | RA-1, RA-2 and RA-3 | ✓ | ✓ | ✓ | ✓ | × |
| [29] | - | 0%, 35%, and 42% | - | × | × | ✓ | × | × |
| [30] | - | 0%, 15%, 30%, and 45% | - | ✓ | × | × | ✓ | ✓ |
| [23] | 30% and 40% (combined) | | - | ✓ | × | × | ✓ | × |
| [21] | 25%, 50%, 75% and 100% (RAP or RCA), 25:75, 50:50, 75:25 (RAP:RCA) | | - | ✓ | × | × | × | × |
| Present study | 0–50% | | WEO | ✓ | ✓ | ✓ | ✓ | ✓ |

The present study aimed to produce a 50% sustainable asphalt mixture by incorporating RAP and RCA. This is an experimental investigation that assessed the performance of several combinations of asphalt mixtures containing different percentages of RAP and RCA ranging from 0% to 50%. The Marshall mix design method was adopted to prepare the asphalt mixtures. The performance of all asphalt mixtures was evaluated based on different engineering aspects such as rutting, cracking, and moisture sensitivity. The influence of combined RAP and RCA proportions on the resilient modulus was also studied. In addition, scanning electron microscopy (SEM) analysis was carried out on VA, RCA, and RAP to understand their effect on the resulting performance. It is presumed that the present study would provide an estimation of RAP and RCA proportions for constructing a sustainable asphalt pavement with adequate engineering performance as per the standard specifications.

## 3. Material

### 3.1. Aggregate

Three types of aggregate were used in this research. Namely, virgin aggregate (VA), recycled concrete aggregate (RCA), and reclaimed asphalt pavement aggregate (RAP). The VA is a crushed quartz aggregate procured from the quarries located north of Baghdad. The RCA was brought from a concrete recycling factory in Alrathwanya district western north of Baghdad. Its source was the demolished T-wall barriers with an originally designed compressive strength of 30 MPa. The RAP was obtained from the milling of existing asphalt concrete pavement which is a highway on the army-canal in Baghdad. Due to different distresses on the highway it was decided by the municipality to mill the surface course and to construct a 5 cm depth asphalt concrete overlay. The milled surface course age was 15 years. After the samples of RAP were brought to the laboratory, an ignition test was performed as per the ASTM D6307 to determine the asphalt cement content in the RAP. Also, an extraction test (ASTM D 2171) was conducted for the RAP to determine the properties of the asphalt cement as well as filler content in RAP. The physical properties of the three types of aggregate were shown in Table 2.

### 3.2. Asphalt binder and Rejuvenator

The asphalt binder was supplied from Dora refinery in the Southwest of Baghdad, the physical properties as per the penetration grade are shown in Table 3. The tests conducted for the asphalt binder confirmed that its properties satisfy the specification requirement of State Corporation for Roads and Bridges (SCRB, R/9 2003) for the asphalt binder grade (40−50). The properties of aged asphalt binder extracted from RAP samples are shown in Table 3. The asphalt binder content in the RAP was 3.2% by weight of total mix. Since the consistency of the recovered asphalt binder revealed its hardened nature due to aging with time, it was decided to use a rejuvenator. In this study, waste engine oil (WEO) was used as a rejuvenator additive to alter the constituents and rejuvenate the aged asphalt. The content of WEO was fixed to 10% by weight of reclaimed asphalt binder. The properties of WEO are also listed in Table 3.

### 3.3. Mineral Filler

Ordinary Portland cement was used as the mineral filler. The chemical and physical properties of the Portland cement are shown in Table 4.

### 3.4. Mixing method and Specimen's legend

For the three types of aggregates, the various fractions of aggregate were separated into groups, as retained on each of the following sieves, 19, 12.5, 9.5, 4.75, 2.36, 0.3, and 0.075 mm and pan using dry sieve analysis. According to the aggregate gradation curve shown

**Table 2**
Physical Properties of Aggregates.

| Property | ASTM Design | Test Results | | | SCRB Specification |
|---|---|---|---|---|---|
| | | VA | RCA | RAP | |
| Coarse aggregate | | | | | |
| Bulk specific gravity | C-127 | 2.634 | 2.330 | 2.712 | |
| Apparent specific gravity | | 2.638 | 2.504 | - | |
| Water absorption, (%) | | 0.302 | 2.87 | 0.78 | |
| Percent wear by Los Angeles abrasion, (%) | C-131 | 17 | 28 | 20 | 30 max |
| Soundness loss by sodium sulfate solution, (%) | C-88 | 4.2 | 6.4 | 1.12 | 12 max |
| Fractured pieces, (%) | D5821 | 96 | 100 | 98 | 90 min |
| Fine aggregate | | | | | |
| Bulk specific gravity | C-128 | 2.563 | 2.278 | 2.645 | |
| Apparent specific gravity | | 2.612 | 2.408 | - | |
| Water absorption, (%) | | 0.809 | 4.12 | 1.48 | |
| Sand equivalent (%) | D2419 | 59 | - | - | 45 min |
| Clay lumps and friable particles, (%) | C-142 | 1.2 | - | - | 3 max. |

**Table 3**
Properties of asphalt cement and WEO.

| Asphalt binder | | | |
|---|---|---|---|
| Test | Result | | Specification limit (SCRB 2003/R9) |
| | Virgin Asphalt | Aged Asphalt | |
| Penetration at 25 °C, 100 gm, and 5 s (ASTM D5), dmm | 46 | 28 | 40–50 |
| Softening point R&B (ASTM D36), °C | 49 | 64 | —— |
| Specific gravity at 25 °C (ASTM D70) | 1.02 | 1.04 | —— |
| Flash point (ASTM D92), °C | 289 | 311 | Min. 232 |
| Ductility (ASTM D113), cm | 110 | 60 | Min. 100 |
| Residue from thin film oven test (ASTM D1754) | | | |
| Retained penetration, % of original (ASTM D5) | 54 | 60 | Min. 55 |
| Ductility at 25 °C, 5 cm/min, (ASTM D113), cm | 80 | 30 | Min. 25 |
| WEO | | | |
| Specific gravity at 25 °C, (ASTM D70) | 0.947 | | —— |
| Viscosity (ASTM D4402) at 38 °C, cSt. | 119 | | —— |

**Table 4**
Properties of mineral filler.

| Chemical Composition, % | | | | | | |
|---|---|---|---|---|---|---|
| CaO | $SiO_2$ | $Al_2O_3$ | MgO | $Fe_2O_3$ | $SO_3$ | L.O.I |
| 62.84 | 20.52 | 4.34 | 2.36 | 5.32 | 2.43 | 1.34 |
| Physical Properties | | | | | | |
| Specific Gravity | | Surface Area* ($m^2$/kg) | | Passing Sieve No. 200 (0.075) % | | |
| 3.12 | | 225 | | 96 | | |

* Blain air permeability method (ASTM C204)

in Fig. 1, which represents the mid-range of gradation for asphalt concrete wearing course as specified by the Iraqi State Corporation for Roads and Bridges (SCRB/R6 2003), the aggregate was combined in specimen preparing bowel to the desired weight depending on the specimen geometry and test type. At first, the RAP aggregate was placed in the mixing bowl and heated to 150 °C in a temperature-controlled oven, then the bowel was placed on a balance and the calculated amount of the WEO which was preheated to a temperature of 40 °C is applied on the RAP aggregate with the aid of a hand-held sprayer and mixed thoroughly for two minutes. Afterward, the rest of the pre-heated aggregate (VA and/or RCA) to a temperature of 150 °C is placed in the bowl and the blend was thoroughly mixed for two minutes.

Asphalt binder was also heated in a container to a temperature in the range of 150–155°C which yield binder viscosity within a range of 170 ± 20 c.St, the exact amount of asphalt cement was then poured into the mixing bowl. For two minutes, the content of the bowl was thoroughly mixed by hand on the hot plate. To ensure uniform compaction temperature, the bowl with its content was transferred to the oven and stored for 10 min at 140 °C. In this period, the compaction mold which was preheated to 100 °C is prepared. Thereafter the batched material was placed in the mold and compacted as per the requirement of the test type.

For ease of reference to the mixtures within the testing campaign of this research, the nomenclature and description for each mix type was shown in Table 5. In this study, 50% of virgin aggregate is replaced by RAP and RCA. For example, mix RAP40 means mix

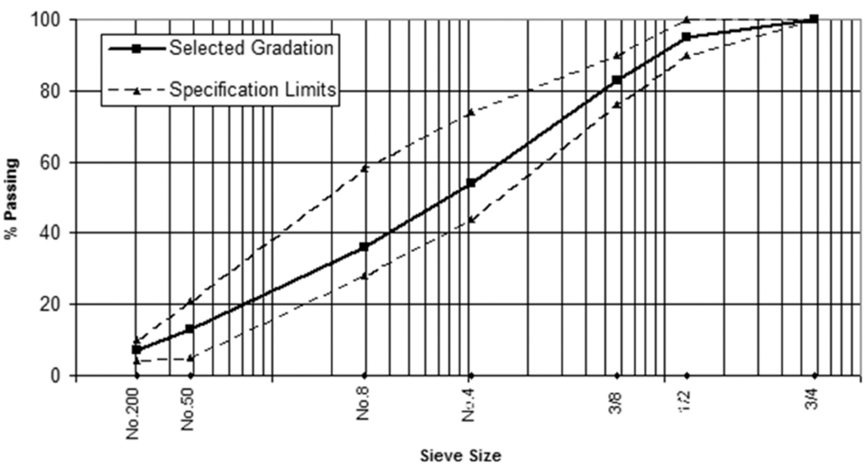


**Fig. 1. Aggregate gradation for wearing course.**

with 40% RAP and 10% RCA (by weight of total aggregate) and the rest of the aggregate is VA.

## 4. Mix Design

A complete mix design was conducted as per the Marshall method following the ASTM (D6927) by giving 75 blows using the automatic Marshall compactor on each side of the specimen. As outlined in AI's manual series No.2 (AI, 1981), the optimum asphalt content is determined by averaging the two values shown below:

- Asphalt content at maximum unit weight
- Asphalt content at maximum stability

For each mix type, six percentages of asphalt cement were tried starting from 4.2% by weight of total mix with an increment rate 0 f 0.3%. These are, 4.2%, 4.5%, 4.8%, 5.1%, 5.4%, and 5.7%. The obtained OACs are listed in Table 6. As the porosity of the RCA is more compared to VA and RAP, OAC increased with the increase in RCA content due to high asphalt cement absorption. Whereas for high RAP content (i.e., less RCA content), the OAC approaches CM. It is worth to mention that the original asphalt cement content in RAP which accounts for 3.2% should be subtracted from the quantity of asphalt cement while calculating the OAC.

## 5. Testing methods

### 5.1. Scanning electron microscope (SEM)

A scanning electron microscope (SEM) is a type of electron microscope that produces images of a sample by scanning the surface with a focused beam of electrons. Electrons interact with atoms in the sample, resulting in a variety of signals including information on the sample's surface topography and composition. For the purpose of this research work, SEM for the three types of aggregate; i.e., the VA, RCA, and RAP are used to provide three-dimensional surface topography as well as morphology of the crystalline structure of material which could be helpful in performance interpretations.

### 5.2. Marshall test

The resistance to plastic flow of the specimens was conducted via Marshall Apparatus following the ASTM (D6927). The Marshall stability is the maximum load the specimen can withstand until failure. The Marshall flow is the total vertical plastic deformation of the specimen. In addition, the air content and void content in mineral aggregate can also be obtained from the test according to the bulk specific gravity of specimens (ASTM-D2726–04) and the theoretical specific gravity of the mixes by component materials (ASTM-D2041). Specimens in the cylindrical molds were compacted at two ends with 75 blows on each end for exposure to high traffic conditions (>106 ESAL). Thereafter, they were demolded and immersed in water for 45 min before the Marshall tests. Each test was conducted on triplication.

### 5.3. Indirect splitting tensile strength

The moisture susceptibility of the asphalt concrete mixtures was evaluated following ASTM D 4867. The specimens of each mix were prepared following the Marshall procedure and compacted at two ends to achieve $7 \pm 1\%$ air void content. Six specimens were made for each mix. They were then split into two groups, three as the control were tested directly at 25 °C, while the other three (called conditioned) were subjected to a cycle of freezing and thawing exposure by conditioning at $-18 \pm 2$ °C for 16 h followed by other 24 h at $60 \pm 1$ °C before conducting the tensile test at the temperature 25 °C. In the indirect splitting tensile test, a compressive load was applied at a rate of 50.8 mm/min along the axis direction of the cylindrical specimens which were laid on their side surfaces. These specimens failed by splitting along the vertical diameter in the cross-section plane. The tensile strength is calculated according to Eq. (1). A tensile strength ratio (TSR), Eq. (2), is defined as the tensile strength of the conditioned specimens (ITSc) to that of the control ones (ITSd).

**Table 5**
Mixes nomenclature and description.

| Mixture Nomenclature | VA Content, % | RAP Content, % | RCA Content, % |
|---|---|---|---|
| CM | 100 | 0 | 0 |
| RAP0 | 50 | 0 | 50 |
| RAP10 | 50 | 10 | 40 |
| RAP20 | 50 | 20 | 30 |
| RAP30 | 50 | 30 | 20 |
| RAP40 | 50 | 40 | 10 |
| RAP50 | 50 | 50 | 0 |

**Table 6**
OAC for the various mix types.

| Mix Type | CM | RAP0 | RAP10 | RAP20 | RAP30 | RAP40 | RAP50 |
|---|---|---|---|---|---|---|---|
| OAC | 4.8 | 5.1 | 4.95 | 4.90 | 4.8 | 4.8 | 4.8 |

$$ITS = \frac{2P}{\pi t D} \tag{1}$$

$$TSR = \frac{ITS_c}{ITS_d} \tag{2}$$

where, P is the ultimate applied load, t is the thickness or length/height of specimens, and D is the diameter.

### 5.4. Uniaxial repeated loading test

The uniaxial repeated loading tests were conducted for cylindrical specimens 101.6 mm (4 in) in diameter and 203.2 mm (8 in) in height using the pneumatic repeated load system. Two series of tests were conducted at a controlled temperature of 40 °C (104°F) to measure permanent deformation and a normal temperature of 20 °C (68°F) to measure resilient modulus. In these tests, repetitive compressive loading with a stress level of 0.137 mPa (20 psi) was applied in the form of a rectangular wave with a constant loading frequency of 1 Hz (0.1 s load duration and 0.9 s rest period), and the resilient deflection was measured at a time in the repetition at 50–100 to characterize the resilient modulus and the axial permanent deformation was measured under the different loading repetitions to characterize the permanent deformation.

The specimen preparation method for this test can be found elsewhere [31,32]. The permanent strain (εp) was calculated by applying the following equation:

$$\varepsilon_p = \frac{P_d \times 10^6}{h} \tag{3}$$

where.
εp = axial permanent microstrain.
pd = axial permanent deformation.
h = specimen height.

The permanent deformation test results for this study are represented by the linear log-log relationship between the number of load repetitions and the permanent microstrain with the form shown in Eq. (4) below, which was originally suggested by [33].

$$\varepsilon_p = aN^b \tag{4}$$

Where.
εp = previously defined.
N = number of stress applications.
a = intercept coefficient.
b = slope coefficient.

The resilient strain, εr, and resilient modulus Mr, were calculated using the Eqs. (5) and (6):

$$\varepsilon_r = \frac{r_d \times 10^6}{h} \tag{5}$$

$$M_r = \frac{\sigma}{\varepsilon_r} \tag{6}$$

Where.
rd = axial resilient deflection.
h= specimen height.
σ = axial stress.

1. Indirect Tensile Cracking Test (IDEAL-CT)

The IDEAL-CT is a relatively new testing method to evaluate the fatigue cracking of asphalt concrete mixture at an intermediate temperature which could range from 5 °C to 35 °C, depending on local climate. Due to its simplicity (no instrumentation, cutting, gluing, drilling, or notching of specimens), practicality (minimum training needed for routine operation), and efficiency (test completion less than 1 min), It has gained more popularity. During this test, as per the ASTM D 8225, a cylindrical specimen is subjected to monotonic loading with a rate of 50 mm/min applied in a vertical direction along the diametric axis of the specimen, and both the load and displacement are measured during the entire duration of the test. Marshall specimens are used with a dimension of 101.6 mm (4 in.) in height and 63 mm (2.5 in.) in height that compacted to an air void level 7 ± 0.5% using 41–59 blows for Marshall compactor at each face of the specimen. The test temperature is fixed at 25 °C, for each testing condition 3 replicate specimens were tested. Fig. 2 shows a typical load-displacement curve that is generated from the IDEAL-CT output.

The $CT_{Index}$ of an asphalt mixture is calculated as per the following equation

$$CT_{index} = \frac{t}{62} \times \frac{i_{75}}{D} \times \frac{G_f}{m_{75}} \times 10^6 \quad (7)$$

Where, Gf is the failure energy calculated as an area under the curve divided by the cross-sectional area of the specimen, m75 is the absolute value for the post-peak slope of the load-displacement curve at the point where the load in the post-peak region reduces to 75% of the peak load, and i75 is the deformation tolerance at 75% of the peak load.

## 6. Results and discussion

### 6.1. SEM analysis

SEM analysis at a magnification level of 5 kX was used to compare the external morphology (texture) and the crystalline structure of the VA, RCA, and RAP. The results are displayed in Fig. 3. It is evident that the difference exists in the morphology of the three types of materials. The virgin aggregate (VA) shows a more intact microstructure of relatively large crystal phases with small quantities of varied fine crystalline particles having the appearance of fragments. They collectively reveal the quartz mineral which primarily consists of silica but contains some impurities. More homogeneous crystalline medium is the salient feature for the SEM of VA in comparison to other materials. The SEM of RCA aggregate shows a porous crystal structure with a noticeable size of fractures between the crystal phases. Also, the cement mortar with medium to fine size particles exist on the RCA crystal's surface that makes them have a rough surface texture. Based on the SEM photos presented in Fig. 3, it is obvious that the RCA has less density than the VA. The SEM for RAP showed the asphalt cement binder covered the surface of quartz aggregate, all particles are included in the bulk of the material. Apparently, the most uniform material in all the presented SEM is the RAP since there no particles are visible that would not be associated with the bulk of the material matter which reveals the interconnected nature of the skeleton of this type of aggregate particle when used in the mixture.

### 6.2. Marshall and volumetric properties

The Marshall stability results for the mixes are shown in Fig. 4. In comparison between the CM (control mix) and mixes with RCA aggregate denoted as RAP0, the latter exhibits 22.8% higher stability than the former, this is owing to the fact that RCA has rougher surface texture which can provide better interlock between aggregate particle to resist the applied stress. It was also observed that stability increases with the addition of RAP to the mixes and peaked at 40% of RAP. Further increase in RAP, i.e., 50%, the stability value falls down due to the WEO's oily effect, which makes it easier for aggregate particles to slide over each other during loading and softens asphalt cement. Based on the flow results shown in Fig. 5, there is a tendency to produce more flexible mixes when the RAP content increase from 0% to 40%, the highest flow value (3.55 mm) for RAP40 is lower than the CM. The existence of RCA in these mixes provides high interlock between the aggregate particles resulting in low flow value.

As noticed from Fig. 6, for all the mixtures in the range of the RAP contents, there is a trend to increase the bulk density of mixes with increasing the amount of RAP. It could be attributed to the WEO rejuvenator.

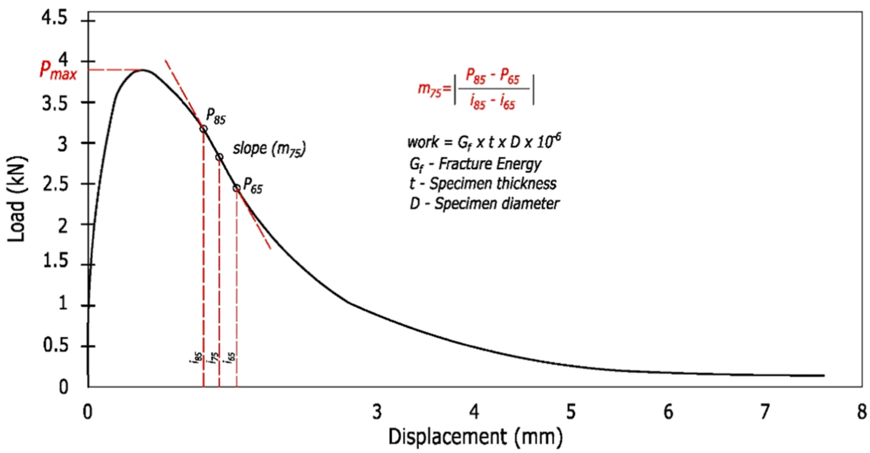


**Fig. 2. Typical load-displacement curve and test parameters for IDEAL-CT.**

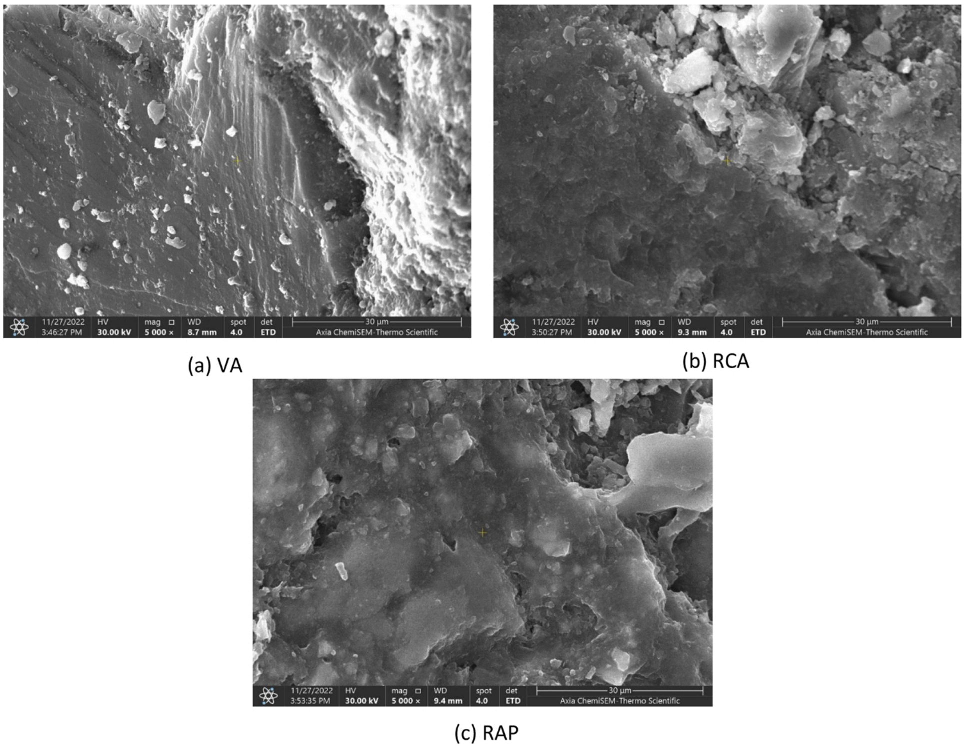


**Fig. 3.** SEM Images of the VA, RCA, and RAP.

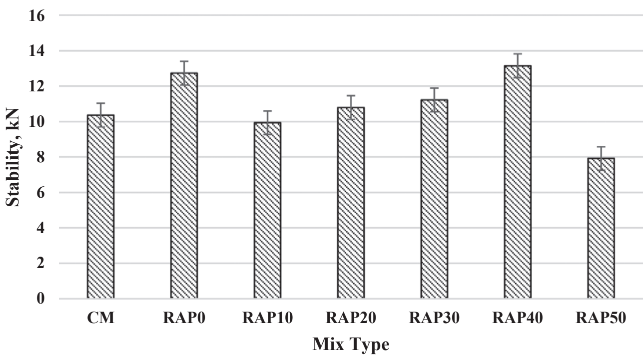


**Fig. 4.** Effect of mix types on Marshall stability.

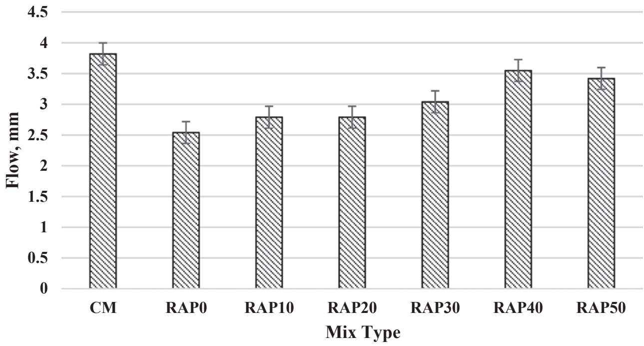


**Fig. 5.** Effect of mix types on Marshall flow.

As is obvious, soft asphalt binder fills in the particle voids and reduces their volume, indicating an increase in the bulk density of the asphalt mixture. Based on the obtained results, RAP40 and RAP50 mixes were even denser than the CM. In conjunction with this result, as demonstrated in Fig. 7, the trend observed for the effect of RAP content on air voids values (AV%) is exactly opposite. The higher the RAP content lower the AV%, due to RAP's capability to produce dense mass as opposed to RCA, which has a rough surface that makes it harder for aggregate particles to slide each other.

The percentage voids in mineral aggregate (VMA %), which is the percentage of void spaces in the compacted mixture, including the air voids and the volume occupied by the effective asphalt content, is shown in Fig. 8. It is evident that the VMA decreases with the increases in RAP content. As the compaction effort for all the mixes is the same, aged binder in RAP will not be able to infiltrate through the voids due to high stiffness resulting in high bulk density and hence low VMA. The CM showed the lowest VMA as compared to the mixtures containing RAP. However, since the specification requirement for the VMA is more than 14%, all the mixes are satisfying the requirement of the volumetric property, VMA.

### 6.3. Resilient modulus

The elastic property for the mixes as characterized by resilient modulus (Mr) is shown in Fig. 9. It's obvious that there is a distinct trend in Mr as the RAP content increase (i.e. the RCA content decrease). The relation is approximately linear up to 40% of RAP with a constant of proportionality of about 134.75 MPa for each 10% increment in RAP content, but further increases in RAP content reverse this relation. Also, with the inclusion of 40% of RAP, a significant change of about 10% in Mr values could be noticed compared to the CM. Due to the existence of RAP and WEO, a dichotomic effect is observed i.e. the softening effect of WEO and the hardening effect of RAP. It could be inferred that up to 40% RAP content, there is an increase in the stiffness of asphalt concrete mixture resulting in high Mr values. Further increase in RAP content beyond 40%, the softening effect of WEO is predominant resulting in low stiffness of mixes and hence lower Mr value.

### 6.4. Moisture susceptibility

Based on the data shown in Figs. 10 and 11, it appears that the examined RAP contents as well as RCA contents have an influence on the moisture susceptibility of the asphalt concrete mixes. RAP0 mix i.e. the mix with RCA content of 50% (0% RAP content) showed the highest ITSd value (1385 KPa) which is even more than CM. This increase in tensile strength is mainly due to the surface roughness of the RCA particles which generate a strong bond between the binder and aggregate, which helps in withstanding the tensile stress along the diametral axis of the specimen while testing. Also, ITSd increased with the increase in RAP content till 30%. Further increase in RAP content reveals inverse relation with ITSd. As revealed by the TSR values, all the mixes showed lower moisture damage since their TSR values are higher than the minimum acceptable limit for the TSR which is 80%. Better performance against moisture damage is associated with the use of RAP0 mixes due to the strong bond between aggregate and asphalt cement. For other mixes, the increment in RAP content up to 40% rise the resistance to moisture damage beyond which there is a reduction in such resistance revealing the incoherent bonding between the RAP and virgin ingredient of the mixture. As compared to the CM, the TSR for the mixes of RAP0 and RAP40 are improved by 7.22% and 4.8%, respectively.

### 6.5. Permanent deformation

The results of the permanent deformation test in terms of permanent strain versus the number of load applications (N) for the variety of mixes are shown in Fig. 12, log scales are used to present the relation in a straight line. The line could be defined in terms of intercept (a), (i.e. the permanent strain at N = 1) and the slope (b), (i.e. the accumulation rate of permanent strain over N load applications). These two parameters, together can define the ability of asphalt concrete specimens to resist permanent deformation, the lower the two values the better the mix in rutting resistance. The discrepancy is a silent feature in the intercept values as demonstrated in Fig. 13, so mixes are sorted into three groups namely, CM, RAP0, and mixes RAP10 to RAP50. Considering the average intercept for

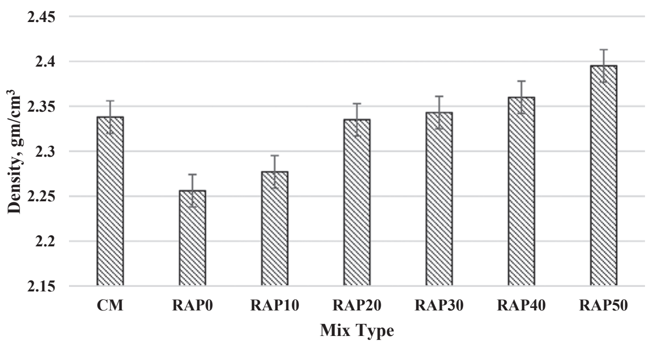


**Fig. 6.** Effect of mix types on Bulk density.

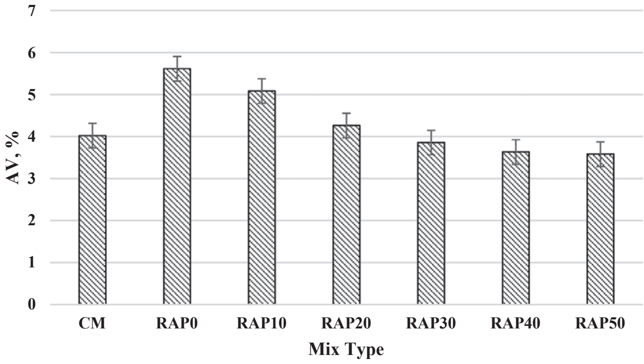


**Fig. 7.** Effect of mix types on air voids.

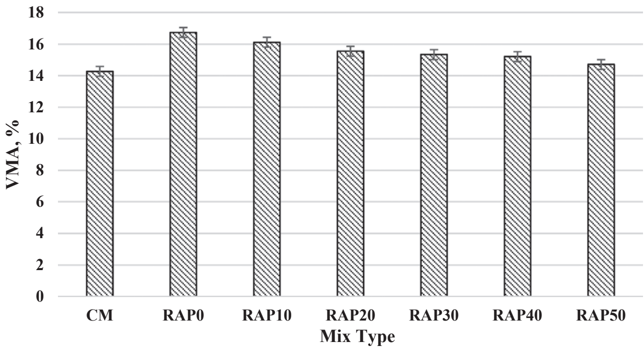


**Fig. 8.** Effect of mix types on voids in mineral aggregate.

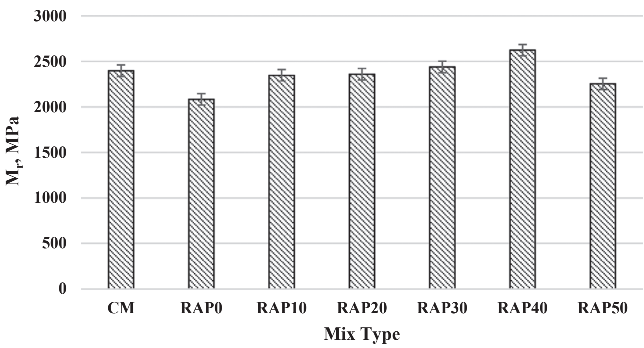


**Fig. 9.** Effect of mix types on Mr.

each group, 401, 320, and 308 microstrains, respectively, reveals slight convergence between the mixes with RCA and RAP regarding their resistance to rutting which, in general, is better compared to CM. This behavior could be attributed to the rigidity of specimens against further densification which is the primary mechanism of rutting offered by the two types of mixes compared to CM as previously exhibited in Fig. 5 for the flow values.

Moreover, as shown in Fig. 13, there is a distinct trend for the relation between the slope and the RAP content, as the RAP content increases from 0% to 40%, the slope value is decreased by about 21.7% indicating better performance against rutting. After which the slope value acts inversely proportional to RAP content. Additionally, specimens with 0 RAP have the highest slope value, but in conjunction with the somewhat low intercept value for this type of mix, the resistance to permanent deformation at the N value higher than 5000, is better than that of RAP 50 as illustrated in Fig. 12. In contrast, considering both parameters, a and b, and taking into consideration all the investigated specimens, RAP40 showed some superiority with regard to the rutting distress in asphalt concrete pavement.

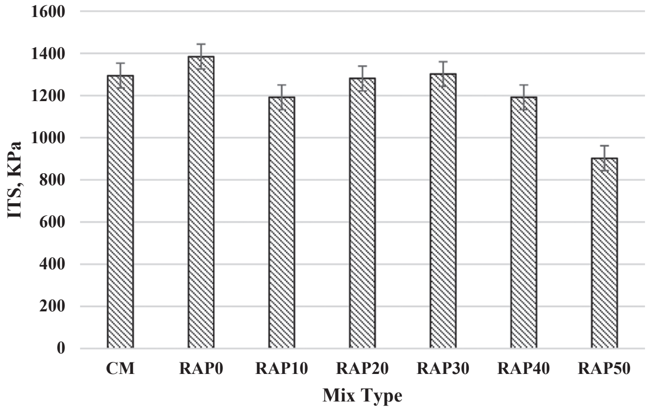


**Fig. 10.** **Effect of mix types on $ITS_d$.**

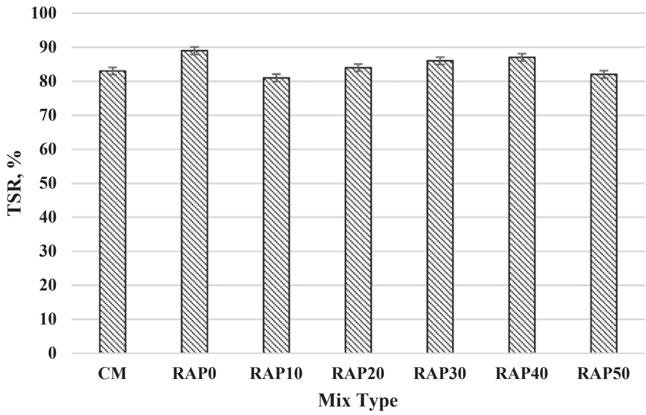


**Fig. 11.** Effect of mix types on TSR.

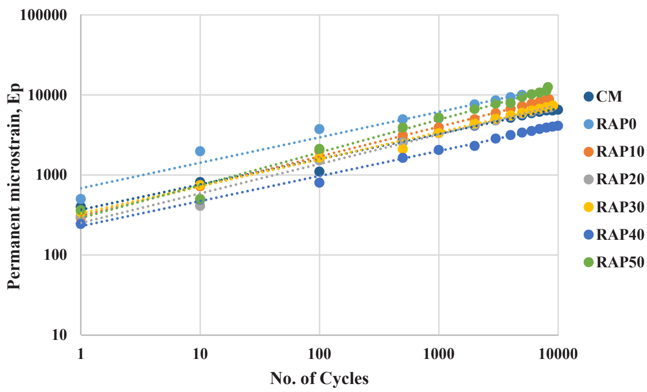


**Fig. 12.** Permanent microstrain vs load repetition for different mix types.

### 6.6. *Fatigue cracking*

The results of the CT Index along with the values of Gf and m75 for different types of mixes are presented in Figs. 14, 15 and 16, respectively. Although the calculated value of the CT Index reveals the ability of asphalt concrete specimens to resist fatigue cracking, but the inspection for the two main parameters (m75 and Gf) used in CT Index calculation is essential. The m75 is a measure of the cracking propagation rate, while the Gf is a measure of the resistance to fracture initiation. High resistance to crack initiation (high Gf value) and high resistance to crack propagation (low absolute m75 value) are ideal characteristics of good performance against fatigue

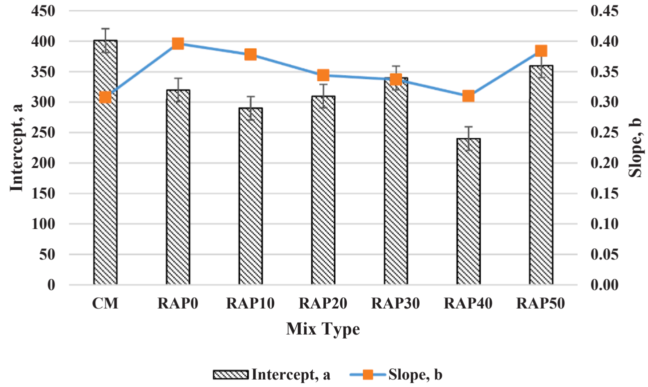


**Fig. 13.** Effect of mix types on permanent deformation parameters.

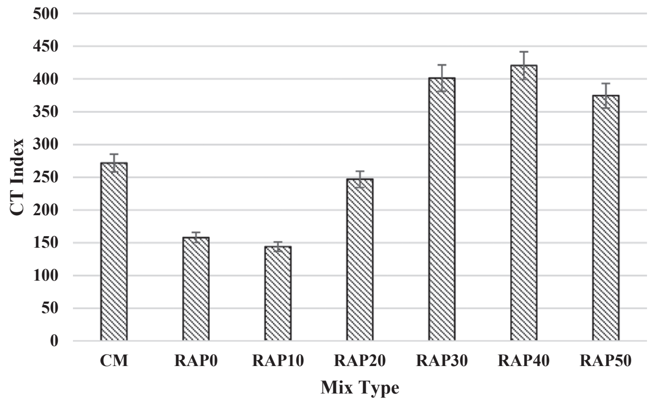


**Fig. 14. Effect of mix types on CT index**.

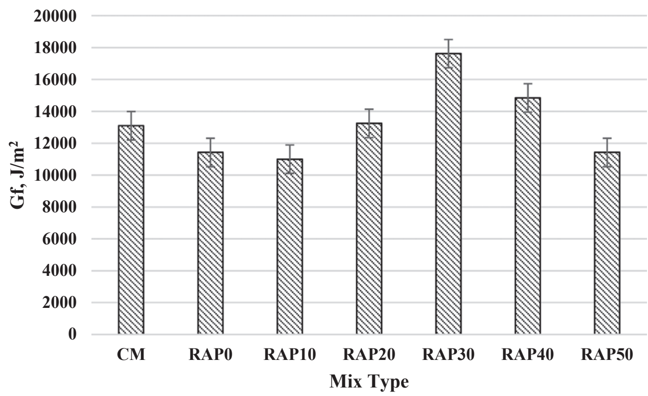


**Fig. 15. Effect of mix types on Fracture Energy**.

cracking, thereby in consequent, a high CT Index value.

Based on the CT Index results, it is obvious there is a general trend of increase in fatigue resistance as the RAP content increased from 10% to 40%, which indicates that the addition of rejuvenator (WEO) restored as well as improved the cracking resistance for these mixes. But the trend changes as the RAP content increases more (i.e. 50%), suggesting the addition of WEO could not be effective in offsetting the effects of adding the highest percentages of RAP on cracking resistance. Interestingly, the RAP40 offers the best resistance to fatigue cracking which accounts for 54.4% higher than the CM, this could be attributed to the lowest m75 value belonging to the RAP40 mix.

Although the CTindex results can effectively discriminate between different mixtures with different percentages of RAP, reporting

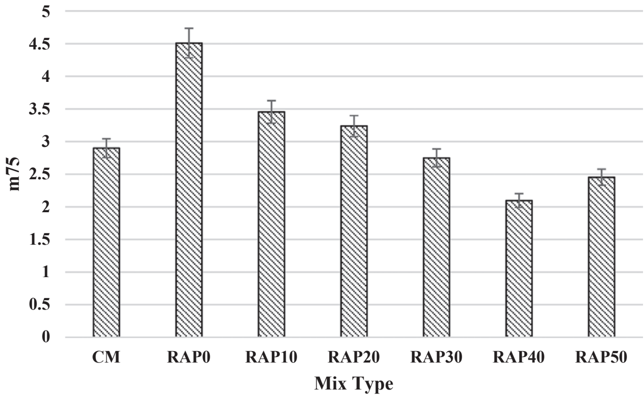


**Fig. 16.** Effect of mix types on post-peak slope.

m75 and Gf parameters demonstrate the advantage as opposed to the CTindex alone when comparing mixtures. Although the improving trend for the mixes with increased RAP content from 10 to 40 is obvious through the increase in CT index values (shown in Fig. 14) and decreases in m75 values (shown in Fig. 16), but the Gf results are somewhat different from them. The highest fracture energy is belonging to the mixes with 30% RAP content (i.e.20% RCA), meaning that it has a higher resistance to crack initiation as compared to other mix types. Also, it is worth to mention that the mixes with 50% RCA and 40% RCA showed the lowest resistance to crack initiation as well as propagation, resulting in low CT index values.

## 7. Conclusions

Several advantages associated with using recycled materials make it unavoidable to include them in the construction sector. Thus, the key objective of the present study is to evaluate the simultaneous effect of RAP and RCA on the performance of hot mix asphalt. Mixes with varying percentages of RAP and RCA from 0% to 50% have been studied. Waste engine oil (WEO) was used as a rejuvenator, considering the high percentages of RAP. Marshall mix design was adopted in the present study. The following conclusions were drawn based on extensive laboratory testing:

- SEM images showed a homogenous large crystalline medium in the case of VA, a porous crystalline structure with medium to fine particles in the case of RCA, and no visible particles in the case of RAP. The presence of fine and medium particles on the surface of RCA imparts a rough surface texture.
- Although using RCA (50%) increased the Marshall stability by 22.8%, adding RAP (10%) decreased the value. Furthermore, the stability value increased with increasing the percentage of RAP to 40% and then again decreased with further increments. Overall, the RAP40 mix had the highest stability and RAP50 was the lowest due to the softening effect of the rejuvenator.
- RAP50 and RAP40 mixes exhibited higher density than the control virgin mix due to the softening of the aged binder by the WEO rejuvenator. Air voids and voids in mineral aggregate (VMA) increased with the inclusion of RCA (50%) and then decreased continuously with the increase in the percentage of RAP.
- Resilient modulus values increased linearly with the increase in the percentage of RAP for 0–40% (134.75 MPa increment for every 10% increase in RAP), signifying the influence of the aged binder. However, at the 50% RAP, the rejuvenator was more predominant than the aged binder resulting in a lower resilient modulus value.
- All the mixes tested in the present study had more than 80% TSR values. The strong bond between the aggregate and binder due to the rough surface texture resulted in the highest moisture resistance for RAP0.
- Due to the linear relation between the permanent strain and the number of cycles (when used in log scale), line intercept and slope are used to define the permanent deformation of mixes. No clear trend was observed with the use of these parameters. In the case of the slope, the control mix had better rutting resistance followed by the RAP40. But the control mix had the highest intercept value. Therefore, considering the two parameters together RAP40 performed better against rutting.
- In terms of fatigue resistance, RAP40 had the highest CT index value followed by RAP30 and RAP50. But concerning fracture energy, RAP30 showed the highest value followed by RAP40 and RAP20 mixes. RAP50 had a lower fracture energy value than the control mix. Also, from the perspective of m75, RAP40 had the lowest value (better resistance) followed by RAP50 and RAP30. Considering all parameters, RAP40 can be concluded as the best-performing mix against cracking.

Important factors observed to affect the performance of mixes with both RCA and RAP were found to be the surface roughness of RCA, stiffness of the aged binder in RAP, and rejuvenator. From this study, it can be concluded that 40% RAP and 10% RCA results in better performance in terms of rutting, fatigue, moisture, resilient modulus, and stability.

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## Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

## Data Availability

No data was used for the research described in the article.

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