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# Evaluating the Impact of Reclaimed Asphalt Pavement on the Mechanical Performance of Hot Mix Asphalt

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**Abstract:** This study assessed the impact of integrating reclaimed asphalt pavement (RAP) and its moisture condition on the mechanical performance of hot mix asphalt (HMA). Using the standard Marshall method, mixtures with 0%, 10%, 20%, 30%, 40%, and 50% RAP were prepared, and for each mix, the optimum asphalt content (OAC) was found. Two moisture states of RAP (oven-dried and saturated surface-dried) were examined to assess its sensitivity to residual moisture. The results showed that adding more RAP to the mix lowered the OAC from 5.22% (control) to 4.87% (50% RAP), reflecting the influence of the aged binder. When the RAP levels were higher, the Marshall stability was enhanced, and the flow decreased, which meant that the mixture was stiffer. However, at high RAP levels, stiffness often exceeded the allowed limits. RAP mixtures showed increasing tensile strength values up to 20% RAP, but decreased at higher levels. Residual moisture in RAP greatly affected mechanical performance. Specimens prepared with saturated RAP were less stable, had higher flow, and had a much lower indirect tensile strength than dry specimens, which was exacerbated after 20% RAP. Up to 20% RAP can be used without lowering the quality of the mixture, as shown by the fact that RAP levels and moisture conditions, as well as volumetric ($V_a$, VMA, VFA) and mechanical parameters, meet SCRB R/9 2007 and ASTM performance standards. Suggestions include managing RAP moisture by properly stacking it, either by covering it or using conical-shaped stockpiles.

**Keywords:** *Reclaimed Asphalt Pavement; Hot Mix Asphalt; Marshall Stability; Indirect Tensile Strength; Residual Moisture.*

## 1. Introduction

The production of hot mix asphalt that includes reclaimed asphalt pavement (RAP) is becoming increasingly popular around the world because it offers better economic, environmental, and performance benefits. RAP is a sustainable choice because it uses materials that would have gone to landfills. This method not only reduces the need for new, virgin materials, thereby protecting natural resources, but it also lowers the overall cost of HMA production and minimizes environmental impacts, such as greenhouse gas emissions and waste [1-3]. In the United States alone, the use of RAP prevented the exploitation of approximately 82 million tons of natural aggregate and bitumen in a single year [4]. Economically, the incorporation of RAP lowers the overall cost of HMA production, with studies indicating that material cost savings can reach up to 30% when using a 50% RAP blend, and combined costs can be reduced by 50–70% in high-content applications [1, 5]. Furthermore, RAP minimizes environmental impacts, such as greenhouse gas emissions, as research by Arshad et al. [1] and Qiao et al. [6] highlights that high-RAP mixtures can reduce energy consumption and $CO_2$ emissions by approximately 30–35% compared to conventional mixtures.

Adding RAP to asphalt mixtures helps keep or even improve the mechanical properties of HMA. Research indicates that recycled mixtures frequently meet or exceed the performance criteria of conventional asphalt, particularly regarding rutting resistance, tensile strength, and volumetric stability [7, 8]. However, to get the best performance, you need to pay attention to properties like the percentage of RAP, the quality of the aged binder, and how well new and recycled materials work together [9, 10].

Many studies have investigated how RAP content affects HMA performance by using different ways to measure its mechanical and volumetric properties. For example, Arshad et al. [1] conducted a lab test of asphalt mixes with RAP contents from 0% to 35% and found no significant differences in volumetric properties, stability, or stiffness between the control and recycled mixes. Their findings indicated that the recycled mixes exhibited comparable performance to traditional HMA regarding resilient modulus and rutting resistance.

In the same way, Ghofran & Hasan [2] assessed how RAP affects warm asphalt mixes. They found that adding up to 30% RAP makes the mixture more stable, stronger, and better at bonding. Their results show that adding RAP makes the mixture's mechanical properties stronger without weakening its performance. Mu'tasim et al. [7] examined the impact of RAP percentages reaching 75% on asphalt stability and flow values, observing that optimal stability was achieved at 75% RAP with 4% asphalt content, indicating enhanced resistance to deformation.

Eloufy et al. [8] executed a comparative analysis of HMA and Half-Warm Mix Asphalt (HWMA) formulated with 70% RAP. Their study showed that HWMA-RAP worked just as well as or better than regular HMA. It had more Marshall stability and was less likely to rut and deform when the temperature changed. This finding is supported by other research on warm mix asphalt (WMA) technologies with RAP. For instance, a study on WMA with RAP contents up to 40% found that stability and indirect tensile strength increased with higher RAP percentages, with optimal stability achieved at 30% RAP [2]. Mohammed & Teba [3] also found that mixtures with up to 25% RAP met local performance standards while also providing significant economic and environmental benefits.

Comparative analysis of RAP and virgin mixtures is essential for evaluating the effectiveness of RAP utilization, yet inconsistencies in performance outcomes remain, particularly regarding moisture susceptibility. While the general consensus suggests that RAP content, binder type, and aggregate gradation are critical performance factors, findings on moisture damage are contradictory. Al-Rousan and Asi [11] found that RAP mixtures exhibited improved moisture resistance, with lower losses in indirect tensile strength compared to virgin mixes, attributing this to the stiffer nature of the aged binder. In contrast, Arshad et al. [12] reported that increasing RAP and warm-mix additive content actually increased the moisture susceptibility of the mixes, suggesting a potential weakness in the cohesive bond of recycled binders under certain conditions. Furthermore, Antunes et al. [13] noted that while aging hardens the mixture against permanent deformation, its effect on water sensitivity remains variable and dependent on the rejuvenation protocol. This lack of consensus highlights a significant gap in the literature, necessitating a focused analytical study to determine the optimal conditions for mitigating moisture-induced damage in RAP pavement layers.

## 2. Methodology and Materials

The primary objective of this study is to evaluate the impact of reclaimed asphalt pavement content and moisture conditions on the mechanical performance of hot mix asphalt. The experimental program methodically adheres to the flowchart depicted in Figure 1, outlining the procedure from material preparation to performance evaluation.

The materials for this study were obtained from the Qatawy Recycling Plant, a government-operated facility located in the south industrial area of Erbil city, which is the first factory in Iraq and the Kurdistan Region dedicated to recycling old road asphalt. The experimental program consisted of a series of tests conducted in accordance with ASTM standards to assess the mechanical properties of the HMA mixtures. These tests were conducted at the Erbil Construction Laboratory (ECL) and the asphalt laboratory at the highway engineering department of Erbil Polytechnic University . The laboratory results were also compared to the State Corporation for Roads and Bridges (SCRB R/9 2007) requirements for the binder layer.

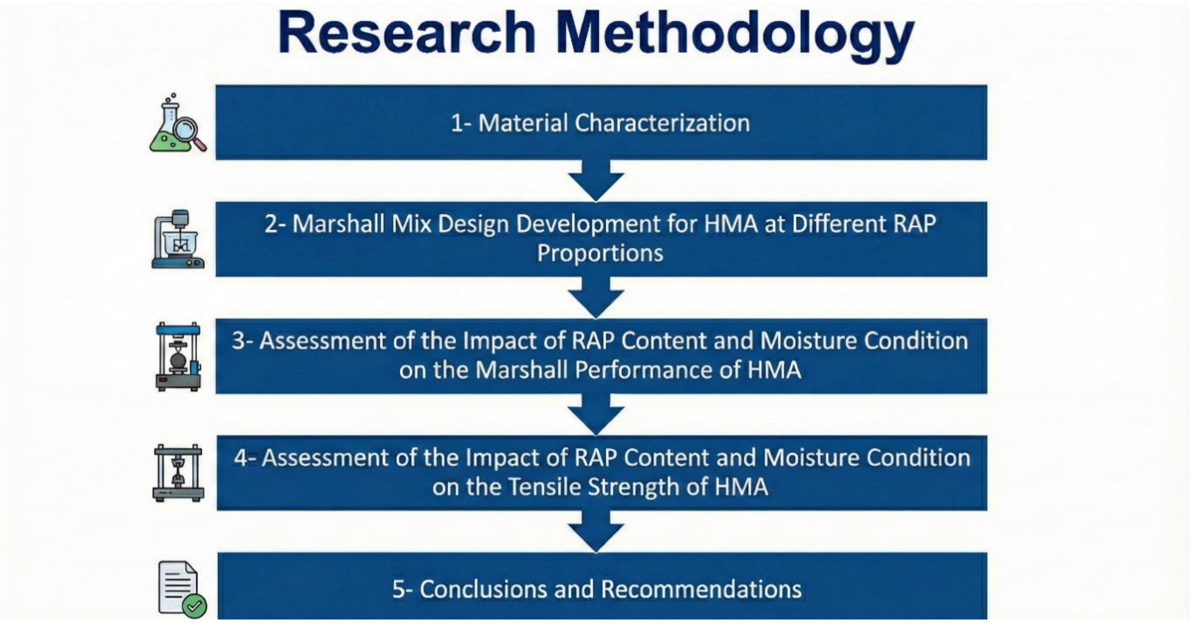


Figure 1: Experimental Program Flowchart

**2.1 Reclaimed Asphalt Pavement (RAP)**

The RAP material was taken from a 6 km stretch of local highway that was being fixed up between Erbil and Qushtapa (the old road from Erbil to Kirkuk). The Qatawy recycling plant stored the collected RAP and sorted it into coarse and fine parts. Table 1 shows a summary of the experimental results on RAP.

The ASTM D2172 (Test Method A) is used to determine the asphalt binder content in RAP mixtures. The binder content was determined using Equation (1).

[1] $$P_{b(RAP)} = \frac{W_i - W_f}{W_i} \times 100$$

Where

- $P_{b(RAP)}$: RAP asphalt binder content (%),
- $W_i$: Initial mass of the RAP (g),
- $W_f$: Final mass of the extracted aggregate, including aggregate and filler (g).

Figure 2: Asphalt Extraction Apparatus

Figure 3: Rotary Evaporator Apparatus

Table 1: Basic Properties of RAP Material

| Parameter | Result | ASTM Specification |
|---|---|---|
| Binder Content, $P_{b(RAP)}$ (%) | 4.8 | D2172 |
| Specific Gravity of Extracted Bitumen at 25°C, $G_{b(RAP)}$ | 1.04 | D70M-21 |
| Maximum Specific Gravity RAP Mixture, $G_{mm(RAP)}$ | 2.529 | D2041M-19 |
| Effective Specific Gravity of the RAP, $G_{se(RAP)}$ | 2.726 | |

**2.2 Virgin Asphalt Cement**

Virgin asphalt cement was obtained from the Halband oil refinery. For the control mix, a penetration grade of 40-50 was used because this grade is often chosen for its balance of stiffness and flexibility, which makes it suitable for the climate in the area. The basic properties of the virgin bitumen were examined and presented the results in Table 2.

Table 2: Basic Properties of Virgin Bitumen Grade 40-50

| Parameter | Result | SCRB R/9, 2007 Requirements | ASTM Specification |
|---|---|---|---|
| Penetration at 25 °C, 100g, 5 sec (0.1mm) | 44 | 40-50 | D5 |
| Ductility at 25°C, 5 cm/min (cm) | >100 | >100 | D133 |
| Flashpoint by Cleveland Open Cup (°C) | 271 | >232 | D92-24 |
| Specific Gravity at 25°C, $G_b$ | 1.03 | - | D70 |
| Softening Point by Ring & Ball (°C) | 54.1 | - | D36 |
| Absolute Viscosity at 135 °C (mPa·s) | 434 | - | D4402 |
| After Rolling Thin-Film Oven Test (ASTM D2872-22) | | | |
| Mass Loss (%) | 0.57 | <1 | D2872-22 |
| Retained Penetration (%) of Original | 63.6 | >55 | D5 |
| Ductility of Residue (cm) | 55 | >25 | D133 |

**2.3 Virgin Aggregates**

The used virgin aggregate has been provided by Abu Shita Factory. The aggregates were sorted into different size groups, such as coarse, fine, and intermediate sizes. These materials were chosen because they are of high quality and meet the local HMA standards.

### 2.4 Mineral Filler

Limestone dust was the mineral filler used in this study, which was obtained from the Hatwan factory. It was sieved to achieve the right particle size, ensuring compatibility with the gradation blend. The properties of the virgin aggregates and mineral filler were measured and summarized in Table 3, and then were compared to the SCRB R/9 2007 requirements.

Table 3: Consensus Properties of Virgin Aggregate and Mineral Filler

<table>
<tr><th rowspan="2">Parameter</th><th colspan="6">NMAS</th><th rowspan="2">SCRB R/9, 2007 Requirement</th><th rowspan="2">ASTM Specification</th></tr>
<tr><th>19 mm</th><th>12.5 mm</th><th>9.5 mm</th><th>4.75 mm</th><th>2.36 mm</th><th>0.075 mm</th></tr>
<tr><td>LA Abrasion Value (%)</td><td colspan="2">17.44</td><td>15.6</td><td>15.4</td><td>-</td><td>-</td><td>< 35 for binder course</td><td>C131</td></tr>
<tr><td>Bulk Specific Gravity, $G_{sb}$</td><td>2.64</td><td>2.63</td><td>2.6</td><td>2.69</td><td>2.71</td><td>-</td><td>-</td><td rowspan="3">C127-24<br>C128-22<br>D854-23</td></tr>
<tr><td>Apparent Specific Gravity, $G_{sa}$</td><td>2.73</td><td>2.73</td><td>2.69</td><td>2.74</td><td>2.76</td><td>2.7</td><td>-</td></tr>
<tr><td>Water Absorption, WA (%)</td><td>1.30</td><td>1.40</td><td>1.35</td><td>0.72</td><td>0.60</td><td>-</td><td>-</td></tr>
<tr><td>Passing sieve No.200 (%)</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>98.30</td><td></td><td>C117-23</td></tr>
</table>

### 2.5 Marshall Mix Design

The target gradation for the binder course was designed by blending virgin aggregates, RAP, and mineral filler following SCRB R/9 2007 specifications. The mechanical size analysis was conducted according to ASTM C136M-19, and an initial gradation was developed through a trial-and-error process using Equation (2).

[2] $$P = A\,a + B\,b + C\,c + \cdots$$

Where

- *A, B, C* · · ·: The percentages of each aggregate that passes a given sieve size,
- *a, b, c...:* The proportions of each aggregate needed to meet the requirements for material passing the given sieve, where a + b + c + · · · = 1.

Later, the stockpile correction factors was used to change the initial gradation results for mixtures with different RAP inclusion levels (0%, 10%, 20%, 30%, 40%, and 50%) according to Equation (3). These changes considered that the total RAP content was higher than the aggregate content in RAP, which changed the combined gradation in the blended mix.

[3] $$RAP_{stockpile} = RAP_{blend} \times (1 - \frac{P_{b,RAP}}{100})$$

Where

- $RAP_{stockpile}$: Stockpile percentage of the RAP used in aggregate blending calculations (%),
- $RAP_{Blend}$: Total amount of RAP used in the mixture (%),
- $P_{b,RAP}$: Asphalt binder content of the RAP (%).

The result of the particle size distribution of virgin aggregates and RAP stockpile is presented in Table 4.

Table 4: Result of the Particle Size Distribution by ASTM C136M-19

| | | % Passing for Each Aggregate Stockpile with given *NMAS* | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Sieve size (mm) | Sieve size (in.) | 19 mm | 12.5 mm | 9.5 mm | 4.75 mm | 2.36 mm | 0.075 mm | $RAP_{stockpile}$ % |
| 25 | 1" | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 19 | 3/4" | 93.4 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 92.0 |
| 12.5 | 1/2" | 18.1 | 91.7 | 100.0 | 100.0 | 100.0 | 100.0 | 79.0 |
| 9.5 | 3/8" | 2.6 | 12.3 | 97.8 | 100.0 | 100.0 | 100.0 | 67.0 |
| 4.75 | No.4 | 0.0 | 4.0 | 11.8 | 95.6 | 100.0 | 100.0 | 41.0 |
| 2.36 | No.8 | 0.0 | 0.0 | 7.0 | 48.2 | 96.4 | 100.0 | 33.0 |
| 0.3 | No.50 | 0.0 | 0.0 | 0.0 | 8.1 | 25.7 | 100.0 | 7.0 |
| 0.075 | No.200 | 0.0 | 0.0 | 0.0 | 0.0 | 6.0 | 98.3 | 4.0 |

The adjusted design gradation for each RAP proportion mix was compared with the SCRB R/9 2007 specifications shown in Table 5.

Table 5: Asphalt Mixture Gradings Specifications According to SCRB R/9 2007

| Sieve Size | mm | Type I | Type II | Type IIIA | Type IIIB |
|---|---|---|---|---|---|
| | | Base Course | Binder or Leveling Course | Surface or Wearing Course | |
| | | % passing by Weight of Total Aggregate + Filler | | | |
| 1 ½ in | 37.5 | 100 | | | |
| 1 | 25.0 | 90-100 | 100 | | |
| ¾ | 19.0 | 76-90 | 90-100 | 100 | |
| ½ | 12.5 | 56-80 | 76-90 | 90-100 | 100 |
| 3/8 | 9.5 | 48-74 | 56-80 | 76-90 | 90-100 |
| No. 4 | 4.75 | 29-59 | 35-65 | 44-74 | 55-85 |
| No. 8 | 2.36 | 19-45 | 23-49 | 28-58 | 32-67 |
| No. 50 | 0.300 | 5-17 | 5-19 | 5-21 | 7-23 |
| No. 200 | 0.750 | 2-8 | 3-9 | 4-10 | 4-10 |
| Asphalt Cement (% weight of total mix) | | 3-5.5 | 4-6 | 4-6 | 4-6 |

The adjusted gradation curves, as shown in Figure 4, demonstrated that the blended aggregate gradations for the control mix and the RAP-modified mixtures meet the required limits.

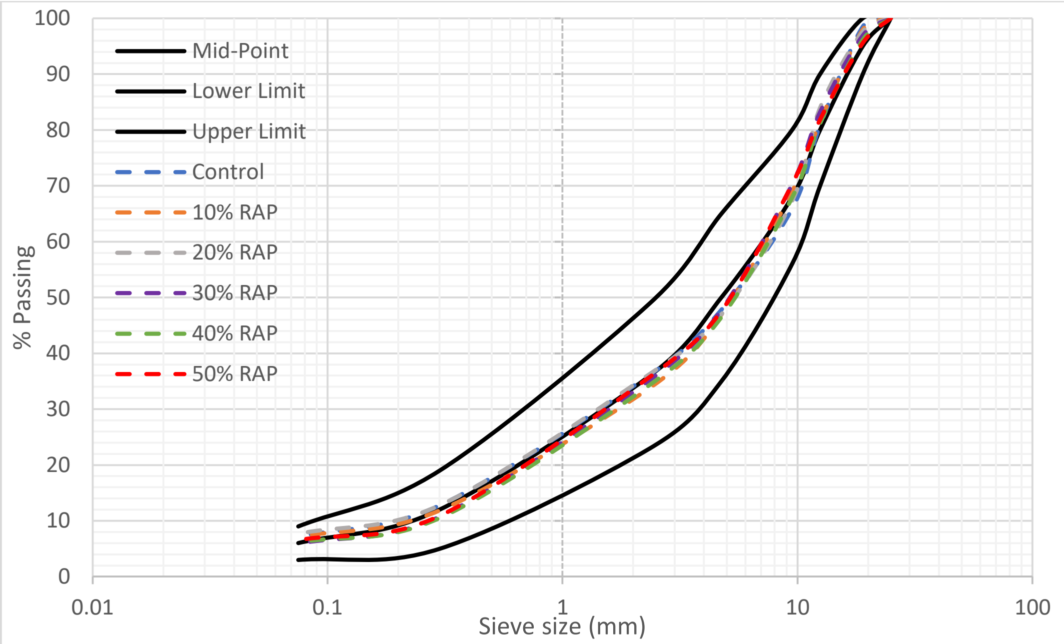


Figure 4: Adjusted Design Aggregate Gradation Curve for Control and RAP Mixtures

The selection of an appropriate binder grade depends on several factors, such as climate and expected traffic loading at the project site. The American Association of State Highway and Transportation Officials (AASHTO) M323 recommends the following:

Table 6: AASHTO M323 Binder Selection Guideline for RAP Mixtures

| Recommended Virgin Asphalt Binder Grade | RAP Percentage |
|---|---|
| No change in binder selection | < 15 |
| Select a virgin binder one grade softer than normal | 15 to 25 |
| Follow recommendations from blending charts (Figure 3) | > 25 |

ASTM D4402M-23 outlines the procedure for measuring the absolute (dynamic) viscosity of asphalt binders using a rotational viscometer. After determining the absolute viscosity of the recovered RAP binder at 60°C, the proper virgin binder grade to be used for each RAP proportion was determined by first selecting the target viscosity of the final blended binder. Note that the target was grade 40-50 with absolute viscosity of 4,000 ± 800 poises at 60°C (140°F), which was used for the control mix.

Figure 5: Container for Viscosity Test

Figure 6: Brookfield Viscometer

Figure 7 was used to find the proper virgin binder viscosity for each RAP inclusion level. After that, the derived virgin binder viscosities were turned into penetration grades. So, AC-40 (penetration grade 40–50) was used for blends with 0% and 10% RAP, AC-30 (50–60) for blends with 20% and 30% RAP, and AC-20 (60–70) for blends with 40% and 50% RAP. Table 7 shows viscosity ranges according to the common standard ASTM D3381.

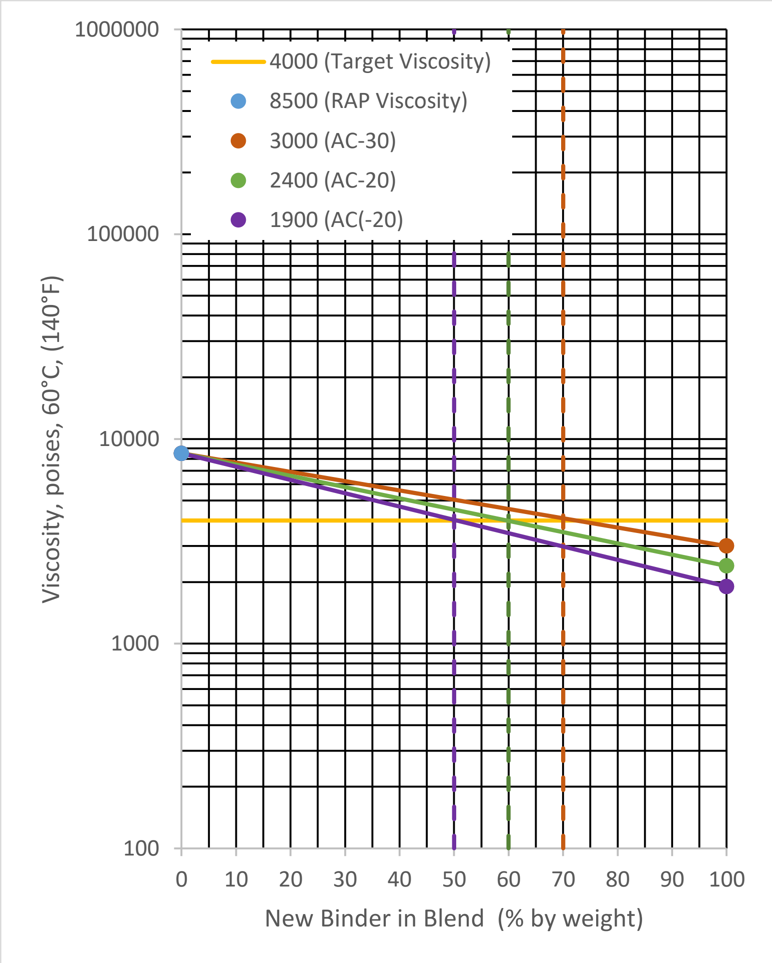


Figure 7: Blending Chart for Virgin Binder Selection

Table 7: Viscosity Ranges According to ASTM D3381

| Viscosity Grade | Viscosity Ragne at 60°C (Poises) |
|---|---|
| AC-20 | 1,600 – 2,400 |
| AC-30 | 2,400 – 3,600 |
| AC-40 | 3,200 – 4,800 |

Using the viscosity-temperature graph, the optimal temperatures for mixing and compacting was determined. The Asphalt Institute and other industry groups have set the following viscosity ranges:

- Mixing Temperature: Matches a viscosity range of 170 ± 20 mPa·s.
- Compaction Temperature: Matches a viscosity range of 280 ± 30 mPa.s.

RAP contains asphalt bitumen, which implies that it cannot be heated in the same manner as new material without altering its properties. Asphalt Hot-Mix Recycling (MS-20) [14] suggests that to offset the application of a lower temperature material, the virgin aggregate temperature should be increased by 0.5°C (0.9°F) for each percentage of RAP added to the mix. The virgin materials were heated up and mixed for 25 seconds. Then, the RAP was added and mixed for another 20 seconds. The total mixing time of 45 seconds was chosen to achieve the best possible homogeneity while preventing the binder from oxidizing and breaking down due to heat.

The specimens were prepared according to ASTM D6926. To keep the mixture from cooling too quickly during compaction, the steel mold with an inside diameter of 101.6 mm and 76.2 mm height, together with extension collar and base plate, was preheated. A mechanical Marshall compactor was used to put the mixtures into the mold and compact them. To make one Marshall specimen, about 1200 g of the mix is required. This will make a specimen that is about 63.5 ± 1.27 mm tall. Each specimen was hit 75 times on each side to simulate the compaction effort that happens when there is heavy traffic on the pavement. After being molded, each specimen was left to cool to room temperature for 24 hours before being taken out with an extraction device. After being compacted, the extracted samples were put in a water bath at 60°C for 30 to 40 minutes before the Marshall stability test, as described in ASTM D6927-22. The stability value obtained by specimens with a thickness other than 63.5 mm was corrected by multiplying the stability by the correlation ratios given in the Asphalt Institute MS-2, shown in Table 8.

Table 8: Stability Correlation Ratios- Asphalt Institute MS-2

| Volume of Specimen ($cm^3$) | Approximate Thickness of Specimen (mm) | Correlation Ratio |
|---|---|---|
| 471 to 482 | 58.7 | 1.14 |
| 483 to 495 | 60.3 | 1.09 |
| 496 to 508 | 61.9 | 1.04 |
| 509 to 522 | 63.5 | 1.00 |
| 523 to 535 | 65.1 | 0.96 |
| 536 to 546 | 66.7 | 0.93 |
| 547 to 559 | 68.3 | 0.89 |

The mixtures were prepared with 4.0%, 4.5%, 5.0%, 5.5%, and 6.0% binder. Each RAP proportion and asphalt binder content combination was tested on three replicate specimens to ensure reliability of the results (i.e., 90 specimens), and the average values for stability, flow, bulk specific gravity ($G_{mb}$) according to ASTM D2726M-21, and maximum specific gravity ($G_{mm}$) according to ASTM D2041M-19 were reported.

The bulk specific gravity ($G_{mb}$) was calculated using Equation (4).

[4] $$G_{mb} = \frac{A}{B - C}$$

Where

- $A$: Mass of the specimen in air (g),
- $B$: Saturated surface-dry mass of the specimen (g),
- $C$: Mass of the specimen submerged in water (g).

The maximum density ($G_{mm}$) was calculated using Equation (5).

[5] $$G_{mm} = \frac{A}{A + D - E}$$

Where

- $G_{mm}$: Maximum specific gravity of the asphalt mixture,
- $A$: Mass of dry sample in air (g),
- $D$: Mass of lid and bowl and water (g),
- $E$: Mass of lid, bowl, sample, and water (g).

Figure 8: Marshall Compactor

Figure 9: Specimen Mass in Water

The optimum asphalt content (*OAC*) was determined by averaging the binder contents corresponding to:

- Maximum stability (kN),
- Target air voids ($V_a$) of 4%,
- Maximum bulk specific gravity ($G_{mb}$) of the mixture.

The chosen asphalt content was then validated in accordance with the requirements of SCRB R/9, 2007, as summarized in Table 9.

Table 9: Iraqi Specification for Properties of HMA SCRB R/9, 2007

| Property | Base Course | Binder Course | Surface Course |
|---|---|---|---|
| Resistance to Plastic Flow (ASTM D 1559) 75 Blows / End | | | |
| Marshall Stability (kN) | >5 | >7 | >8 |
| Marshall Flow (mm) | 2-4 | 2-4 | 2-4 |
| Voids in Marshall Specimen ($V_a$) (%) | 3-6 | 3-5 | 3-5 |
| Voids in Mineral Aggregate (*VMA*) (%) | >12 | >13 | >14 |
| Voids Filled with Asphalt (*VFA*) (%) | 65-75 | 65-75 | 65-75 |

### 2.6 Mechanical Performance Tests

After the job mix formula for each RAP proportion was set, specimens were prepared using the OAC, which had already been set for each RAP content. Two sets of specimens were prepared for each RAP level:

- Dried RAP Specimen: RAP was dried in an oven at 110°C until it reached a constant weight (not more than two hours) and then cooled to room temperature before mixing.

- Saturated Surface Dried RAP Specimen: RAP was soaked in water for 24 ± 4 hours. Then it was drained and allowed to dry on the surface, achieving a saturated surface-dried state before the mixing process.

### 2.7 Marshall Stability Test

Samples were prepared according to ASTM D6926, and the Marshall stability test was conducted according to ASTM D6927-22. Each RAP proportion and moisture condition combination was tested on three replicate specimens at their OAC to ensure reliability of the results (i.e., 36 specimens), and the average Marshall stability and flow values were compared between the dried and saturated RAP specimens. The results were examined with varying amounts of RAP to identify patterns and differences in performance.

Figure 10: Specimens for Marshall Test

Figure 11: Conducting the Marshall Test

The stiffness of the mixtures was also checked systematically. This additional analysis helped us understand how the mixtures behave elastically, which is essential for ensuring they perform well over time when subjected to repeated loading. The stiffness (*K*) is determined by dividing Marshall stability by the flow value, as shown in Equation (6).

$$K = \frac{Stability}{Flow} \quad [6]$$

Where

- *K*: Stiffness (kN/mm),
- Stability: Maximum load carried by the specimen (kN),
- Flow: Corresponding deformation at maximum load (mm).

### 2.8 Indirect Tensile Strength Test

The test was conducted according to ASTM D6931-24 to determine the indirect tensile (IDT) strength of asphalt mixtures.  Specimens were prepared according to ASTM D6926, using the same method as for Marshall stability testing and the job mix formulas for each RAP proportion (0%, 10%, 20%, 30%, 40%, and 50%). This test needs an air void of 7 ± 0.5 percent (ASTM tolerance of ± 1.0 percent), so some trial and error was required to find the right amount of compaction effort that gets the air voids to the right level by adjusting the number of blows in the Marshall hammer. For conducting the Marshall Stability test, specimens were prepared at OAC and were compacted by 75 Belows/Side, and $V_a$ values were already determined. However, before conducting the IDT test, for each RAP proportion, another set of specimens was prepared at the same OAC, but they were compacted by 50 Belows/Side, and again $V_a$ values were determined. Finally, the proper number of below was determined by interpolation.

After being measured for thickness, the test specimens were kept at 25°C for at least 2 hours in a temperature-controlled water bath. The tensile strength was calculated using Equation (7):

[7] $$S_t = \frac{2000P}{\pi t d}$$

Where

- $S_t$: Indirect Tensile (*IDT*) Strength (kPa),
- *P*: Maximum applied load (N),
- *t*: Specimen thickness (mm),
- *d*: Specimen diameter (mm).

Each RAP proportion and moisture condition combination was tested on three replicate specimens at their OAC to ensure reliability of the results (i.e., 36 specimens), and the average tensile strength values were compared between the dried and saturated RAP specimens. The results were analyzed across RAP proportions to identify trends and deviations in performance. Furthermore, the moisture sensitivity of the mixture is evaluated by calculating the TSR ratio according to Equation (8).

[8] $$TSR = \frac{S_{t2}}{S_{t1}} \times 100$$

Where

- *TSR*: Tensile Strength Ratio (%),
- $S_{t2}$: Indirect Tensile Strength for Saturated-RAP Specimens (kPa),
- $S_{t1}$: Indirect Tensile Strength for Dried-RAP Specimens (kPa).

Figure 12: Conditioning Specimens

Figure 13: Conducting IDT Strength Test

**3. Results and Discussion**

To find the OAC, six Marshall design parameters were plotted against binder content for each RAP proportion (0%, 10%, 20%, 30%, 40%, 50%). This made it possible to look at both the binder and RAP content effects on mixture performance at the same time, as shown in Figure 14.

As shown in Table 10, OAC decreased from 5.22% for the control mix to 4.87% for the 50% RAP mixture, illustrating the contribution of aged RAP binder in lowering virgin binder demand.

Figure 15 shows the Marshall test results for dried and saturated surface-dried RAP samples at each RAP level.

Stability: Stability increased with RAP content in both dried and saturated specimens, due to the stiffening effect of the aged binder. Moisture in RAP gradually reduced load-bearing capacity, especially in high-RAP blends.

Flow: As the amount of RAP increased, the flow values went down. This means that the aged binder was stiffer and less deformable. In high-RAP blends, moisture made the mixture a little more flexible again.

Stiffness: Stiffness increased significantly with RAP content and was highly sensitive to moisture at higher RAP levels. Moisture significantly decreased stiffness in high-RAP mixtures; however, even specimens with saturated RAP surpassed the stiffness threshold of the SCRB R/9 requirement of 1.75–3.50 kN/mm for binder course mixtures.

Table 10: Selecting Optimum Asphalt Content

| Mixture ID | $P_b$ (%) | | | *OAC (%)* |
|---|---|---|---|---|
| | At Max Stability | At Max $G_{mb}$ | At $V_a$ % = 4 | |
| Control | 5.50 | 5.00 | 5.15 | 5.22 |
| 10% RAP | 5.50 | 5.00 | 4.68 | 5.06 |
| 20% RAP | 5.30 | 5.05 | 4.84 | 5.06 |
| 30% RAP | 5.30 | 4.90 | 4.80 | 5.00 |
| 40% RAP | 5.00 | 4.70 | 5.09 | 4.93 |
| 50% RAP | 5.00 | 4.50 | 5.10 | 4.87 |

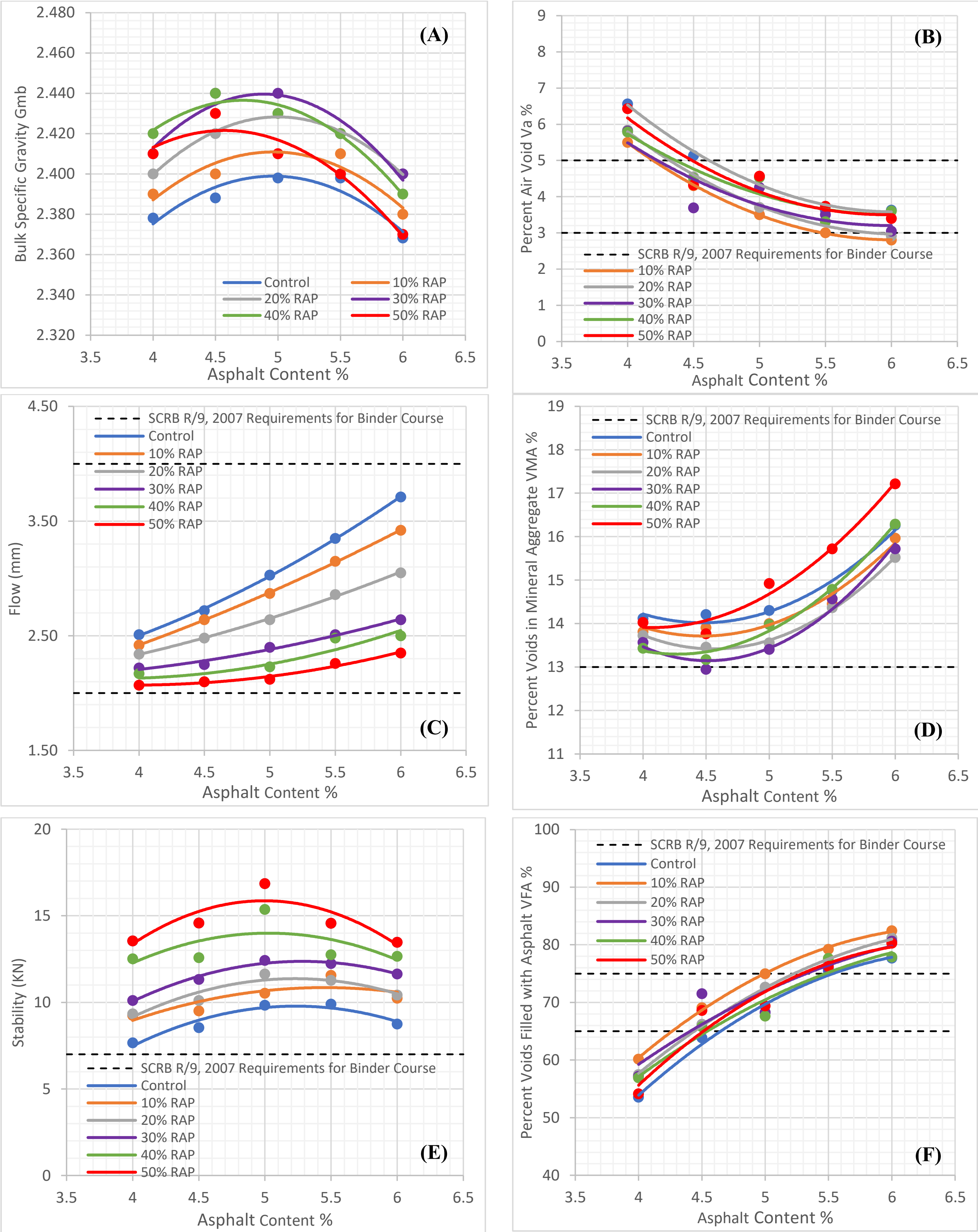


Figure 14: (A-F) Marshall Mix Design Parameters vs Binder Content for Specimens Asphalt Content versus (A) $G_{mb}$, (B) $V_a$, (C) Flow, (D) $VMA$, (E) Stability, (F) $VFA$

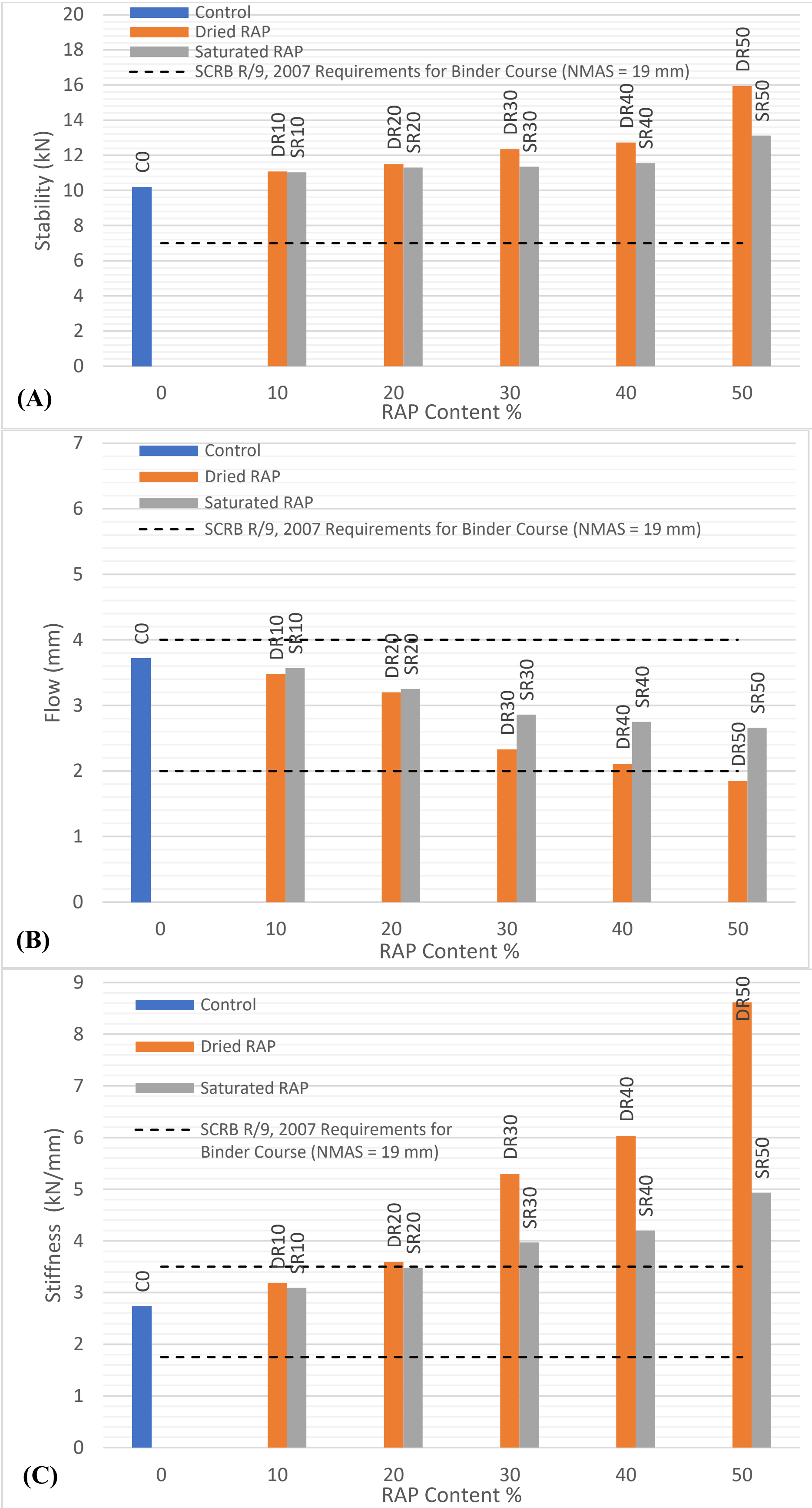


Figure 15: (A-C) Comparing the Effect of RAP Content and Moisture on Marshal Parameters RAP Content versus (A) Stability, (B) Flow, and (C) Stiffness

Figure 16 shows the relationship between tensile strength and RAP content for both moisture conditions. It makes two critical points: the graph shows that the tensile strength of the dried-RAP mixes increases almost linearly up to 20% RAP, indicating that the addition of more recycled binder makes the mix stronger. The two curves, on the other hand, start to separate after 20% RAP. The dried-RAP line levels off and then declines, while the saturated-RAP line drops more sharply. As the RAP content increases, the difference in tensile strength between the dried and saturated mixtures becomes more pronounced. This widening gap indicates that the detrimental effects of moisture increase as the RAP content rises. This is because water weakens the bond between the aggregate and the binder, preventing the full benefit of the aged binder from developing.

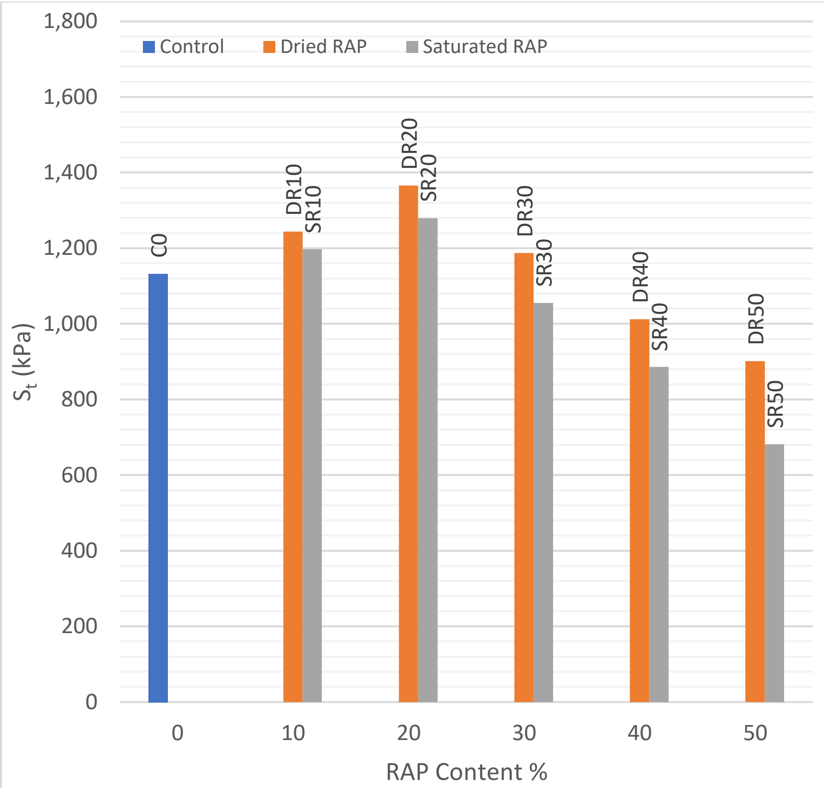


Figure 16: Comparing the Effect of RAP Content and Moisture on Tensile Strength

The observed behavior can be explained by the influence of the aged binder in RAP and moisture interactions. Reclaimed asphalt binder is stiff and oxidized from previous use, so adding more RAP usually results in a stiffer, stronger mixture. This explains why ITS initially increased: the old binder collaborates with the new binder to create a more cohesive and stiff mixture. However, excessive RAP makes the mixture too stiff, which can cause the binder film to become thinner and the mix more brittle. Additionally, when RAP is saturated, the extra water hampers the adhesion between asphalt and aggregate. Moisture weakens the bond and cohesion, which is why saturated-RAP samples perform worse than dry ones. Essentially, as more RAP (and its associated moisture) is incorporated, the mixture becomes increasingly sensitive to moisture, leading to the significant strength losses observed beyond 20% RAP.

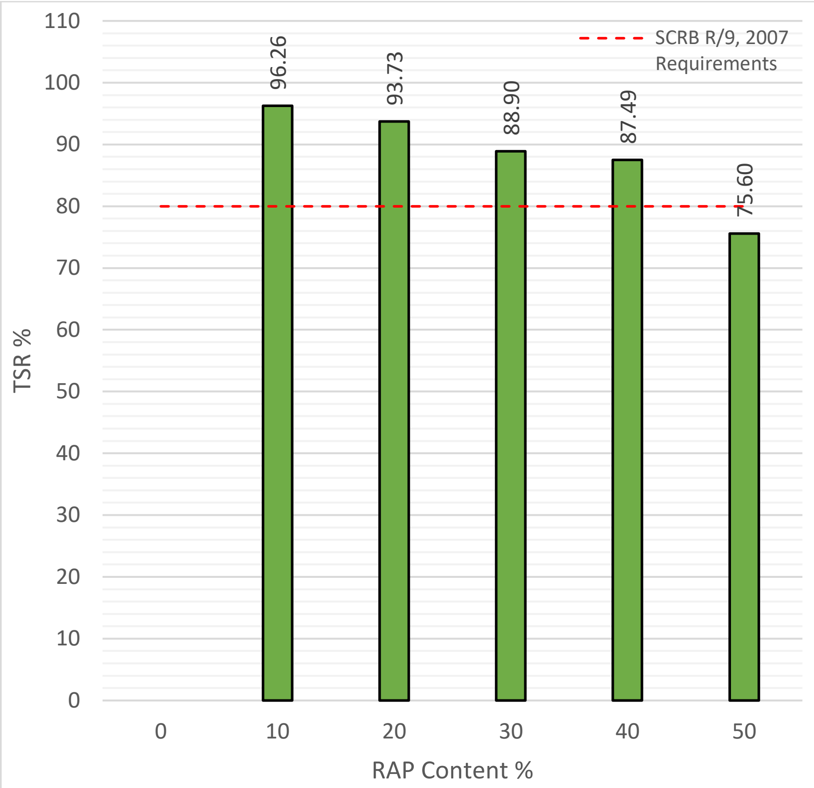


Figure 17: Variation of TSR versus RAP Content

## 4. Recommendations

- Covering the stockpiles can help keep moisture from rain out. Using conical-shaped stockpiles that naturally shed rain and snow is another good option. Putting stockpiles on paved slopes also helps get rid of extra water. Limiting the height of stockpiles reduces the risk of self-consolidation, and keeping heavy equipment off the top prevents compaction.
- Explore bio-based or waste-oil rejuvenators that can restore the properties of old binders, allowing RAP contents to exceed 20% while maintaining stiffness and minimizing cracking risk.
- Assess the addition of polymers to asphalt binders, which can strengthen HMA, increase elasticity, and improve moisture resistance.
- Conduct Wheel-Tracking (AASHTO T 324) and Fatigue Beam Testing (AASHTO T 321) on high-RAP mixtures to evaluate their resistance to rutting and fatigue over extended periods.

**Author's Contribution:**

We confirm that all named authors have read and approved the manuscript. We also confirm that each author has the same contribution to the paper. We further confirm that all authors have approved the order of authors listed in the manuscript.

Saman K. Ibrahim was in charge of the research work. He came up with the idea, designed the study, collected and analyzed the data, interpreted the results, and wrote the manuscript as part of the requirements for his Master's degree. Assistant Professor Faris M. Jasim oversaw and guided the study, providing helpful feedback, technical assistance, and critical reviews throughout the process.

**Use of AI tool Declaration:**

The authors declare that any AI tools used in the preparation of this manuscript were limited to language and readability improvement only, and were not used to generate scientific content, data, analyses, or conclusions, with full responsibility retained by the authors.

**Conflict of Interest:**

There is no conflict of interest for this paper.

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