C0020Journal Home Page: https://sjes.univsul.edu.iq/

Research Article:

Evaluating the Effect of Crumb Rubber Particle Sizes and Proportions on the Performance of Reclaimed Asphalt Mixture

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Article Information

Article History:
Received : September, 16th 2025
Accepted : October, 30th 2025
Available online: December , 2025

Keywords:
Recycled Asphalt Pavement (RAP), Crumb Rubber (CR), Performance grade (PG), Rutting, Fatigue, Stripping, Indirect Tensile Strength Ratio (ITSR).

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DOI https://doi.org/10.17656/sjes.102002

Abstract

This study investigated the effects of various sizes and proportions of CR into environmentally friendly asphalt mixtures containing 35% RAP. CR particles retained on sieves #30, #50, #100, #200, and the pan were added at 2%, 4%, and 6% by weight of the binder. Mixture performance was evaluated in terms of rutting (Kim test), moisture sensitivity, fatigue (SCB test), and stripping resistance. Both RAP and virgin aggregates met all specification requirements. Although the RAP binder (PG 76-10) was stiffer and more brittle than the virgin binder (PG 70-22), its properties remained within acceptable limits for new asphalt mixtures. Volumetric analysis showed all CR-modified mixtures met Superpave criteria, with coarser CR increasing binder demand and finer CR yielding denser mixtures. CR on sieve #200 provided the highest rutting resistance, with 2% and 4% significantly reducing rut depths, whereas 6% showed no statistically significant improvement. Coarser (#50) and pan-sized CR generally increased rutting, acting primarily as filler. CR had a minor and mostly insignificant effect on ITS, with most mixtures maintaining ITSR values above 80%, except for 4% and 6% of #50 and #200 CR. In SCB tests, only #50 and #200 CR improved fracture resistance, significantly increasing the strain energy release rate (Jc) at 2–6% dosages. Stripping tests indicated that 4–6% #30 CR and 2–4% pan-sized CR improved moisture resistance, while most other sizes slightly exceeded acceptable limits. Overall, the rutting, moisture, fatigue, and stripping resistance of reclaimed asphalt mixtures were significantly affected by CR size and contents.

1. Introduction

Recycled Asphalt Pavement (RAP) was introduced in 1915, but its use gained significant attention during the 1970s Arab oil crisis, when rising asphalt binder costs made incorporating RAP into new mixtures more economically attractive (Shingles, 2014). RAP use has evolved with advancements in materials, updated regulations, and increased emphasis on sustainability. The National Cooperative Highway Research Program (NCHRP) published "Recycling Materials for Highways" in 1978, followed by "Guidelines for Recycling Pavement Materials" in 1980. Meanwhile, the Federal Highway Administration (FHWA) provided further guidance and information on RAP in the 1990s (Copeland, 2011). RAP gained prominence in road design after the Kyoto Protocol (1997) and its 2005 implementation (Reyes-Ortiz et al., 2012). Rising oil prices and material conservation concerns, including landfill reduction- up to 400,000 tons recycled annually in some communities- have further encouraged RAP use (Ebrahim and Karim, 2019). RAP is generated during milling and repair of damaged asphalt layers. Climate change and rising traffic volumes contribute to millions of tons of RAP produced globally each year (Kamal et al., 2023). Approximately 50 million tons of damaged asphalt pavement are milled annually in Europe (Dinis-Almeida et al., 2012), while the US produces about 45 million tons of RAP each year, much of which is disposed of in landfills (Copeland, 2011). Reusing RAP reduces reliance on virgin materials and mitigates the environmental impacts of waste management, while incorporating it into road repair projects can significantly lower carbon dioxide emissions and ecological footprints (Liu et al., 2022). Consequently, RAP is widely recognized as a cost-effective and environmentally sustainable approach for modern road construction (Naser, 2021). Several recycling methods exist, including in situ hot recycling, in situ cold recycling, and plant hot recycling, with hot recycling being particularly popular due to its ability to mix RAP with new materials in various proportions and particle sizes (Reyes-Ortiz et al., 2012). At the same time, public concern about managing discarded tires has grown because of their environmental and health impacts (Moasas et al., 2022). Nearly 1.5 billion tires are produced worldwide each year, with over 17 million tons discarded, and by 2030, the number of waste tires is projected to reach 1.2 billion (Hashamfirooz et al., 2025). Improper tire disposal harms the environment through contamination and rubber manufacturing. Circular economic practices- reducing, reusing, and recycling- can help mitigate these issues, though additional measures, such as redesigning tires and sourcing rubber sustainably, are also essential. Despite these efforts, a significant portion of global waste tires- over 40-75%, or approximately 750,000 annually- still ends up in landfills, emphasizing the importance of treating used tires as valuable resources to reduce environmental impacts across the supply chain (Mowbray, 2023). In the US alone, about 280 million tires are discarded each year, with only 30 million recycled and the remaining 250 million sent to landfills. Car tires dominate the market, representing 85% of the total, with an estimated 2 to 3 billion in stock (Chesner et al., 2002). Recycling waste tires offers clear environmental benefits by reducing landfill volumes and conserving resources. Approximately 86% of waste tires are recycled through various methods, while 16% are still landfilled (Price & Smith, 2006; Fazli & Rodrigue, 2020). In North America, the industrial use of recycled tire rubber has increased significantly. Although recycling rates exceeded 50% in the early 1900s, they declined to around 20% by 1960 due to cheap oil, synthetic rubber production, and widespread adoption of steel-belted radial tires (Reschner, 2008). Grinding used tires into small particles produces CR, which can partially replace bitumen in asphalt mixtures, offering an environmentally friendly solution that reduces paving costs and waste disposal issues (Kilani et al., 2025). CR is primarily incorporated into asphalt mixtures using two methods: the dry process, where CR is mixed with the aggregate, and the wet process, where CR is blended with asphalt cement (Kök & Çolak, 2011). Beyond modifying the binder, CR also increases aggregate voids in Superpave mixtures and enhances rutting resistance in asphalt pavements (Xiao et al., 2009). Highway engineers strive to design safe and cost-effective roads that meet performance standards. Pavement deterioration can result from traffic loads, mixture quality, and weather conditions, manifesting as rutting, moisture damage, and fatigue cracking. Conventional bitumen has limited durability and rheological properties, which can cause fatigue cracking or reduced stiffness under repeated traffic at 10–30 °C (Khodary Moalla Hamed, 2010). Rutting appears as longitudinal surface grooves under repeated loading, becoming noticeable near 20 °C and worsening above 50 °C (Kim et al., 2017; Tan et al., 2025). Moisture-induced damage is a key contributor to pavement degradation, leading to strength loss, stripping, raveling, fatigue, and rutting (Hamzah et al., 2015). In winter, when air temperatures reach -30 °C and pavement surfaces -22 °C, freezing moisture accelerates structural flaws. Freeze-thaw cycles degrade pavements, while stripping occurs when water breaks the bond between asphalt and aggregate (Žiliūtė et al., 2016). Moisture-related distress, particularly stripping, remains a critical concern for pavement performance and sustainability (Khasawneh et al.). Despite the growing interest in CR modification, research examining the comparative influence of CR particle size and proportion on the performance of reclaimed asphalt mixtures remains limited. This study seeks to address this knowledge gap.

2. Objective of the Study

This study investigates the optimal CR size and content to enhance the performance of RAP mixtures, highlighting the use of recycled materials in pavement construction. It evaluates the effects of CR on rutting resistance, moisture susceptibility, stripping, and fatigue performance. The objectives include reducing reliance on virgin resources, conserving materials, minimizing energy consumption, and improving waste management strategies.

3. Literature Review

Research on RAP has been ongoing since 1915. Early studies primarily focused on the mechanical performance of high-RAP-content mixtures, while recent investigations have emphasized the integration of CR into RAP mixes and its effects on performance, durability, and sustainability. Shen et al. (2006) reported that RAP mixtures can be successfully reused with CR-modified binders, which enhance both mechanical and rheological properties. Their study demonstrated that incorporating up to 15% RAP did not significantly alter mixture performance compared to virgin asphalt, with rutting resistance, indirect tensile strength (ITS), and resilient modulus remaining consistent. Similarly, Valdés et al. (2011) confirmed that higher RAP contents can be effectively incorporated into bituminous highway repair mixtures, provided that RAP components are properly characterized and managed. Han et al. (2011) evaluated RAP materials from Kansas, USA, using conventional binder and aggregate tests, revealing significant differences between aged and virgin binders. RAP mixtures exhibited unique characteristics distinct from virgin aggregates. Hussain and Yanjun (2013) emphasized the role of residual binder, concluding that RAP increases mixture stiffness but reduces flexibility at elevated temperatures. They also observed that RAP binders age more slowly than conventional binders such as ARL 60/70, which perform better in cold climates. Ortiz et al. (2012) investigated dense-graded hot mix asphalt (HMA) with RAP replacement levels of 15%, 20%, 35%, and 100%, finding that 100% RAP replacement achieved the highest ITS and resilient modulus under both wet and dry conditions. Building on this concept, Zaumanis et al. (2014) explored rejuvenation strategies for 100% RAP mixtures, demonstrating that binder rejuvenation can improve low temperature cracking resistance, rutting resistance, and moisture susceptibility. Noferini et al. (2017) evaluated RAP contents of 10–30%, reporting that aged RAP binders produced stiffer composites with viscosity increases of at least 20% and an extended temperature range of elastic response. Milad et al. (2020) highlighted that well-managed RAP mixtures improve density, moisture resistance, and overall sustainability. Antunes et al. (2021) demonstrated that 75% RAP mixtures rejuvenated with crude tall oil (CTO) - a renewable by-product from paper manufacturing - achieved mechanical properties comparable or superior to virgin mixtures in terms of stiffness, deformation resistance, fatigue life, and moisture sensitivity. Environmental and economic benefits of RAP have also been emphasized. Zhao et al. (2021), through a life-cycle assessment of Maryland projects, found that RAP substantially reduces costs and environmental impacts. Tsakoumaki and Plati (2024) reviewed current best practices, noting regional variability and limited adoption, and highlighted the need for harmonized technical standards to increase RAP utilization in highway construction. The combination of RAP with CR has gained interest due to potential improvements in performance and sustainability. Xiao et al. (2009) reported that CR enhances rutting resistance and reduces air voids in RAP mixtures, while particle size had little effect on ITS and slightly reduced the resilient modulus. Alavi et al. (2016) found that recycled rubberized RAP (R-RAP) improved rutting resistance but reduced fatigue and low-temperature performance. Ebrahim and Karim (2019) investigated RAP mixes modified with SBS, CR, and polypropylene (PP), noting decreased penetration and ductility but increased softening point and elastic recovery. They recommended 3% CR for cold climates and 7% for hot climates, with ITS decreasing as CR content increased, while the indirect tensile strength ratio (ITSR) remained above 80%. Bilema et al. (2021) studied 25% and 40% RAP mixtures containing CR and waste frying oil (WFO), reporting enhanced rutting resistance, binder regeneration, and sustainability, with higher CR and WFO contents yielding superior results. Vigneswaran et al. (2023) demonstrated that larger CR particles (1-2 mm) hinder binder interaction, suggesting the need for improved field processing. Oleiwi and Albayati (2024) confirmed the durability of CR in dry-process asphalt mixes under severe temperatures and its effectiveness in physical modification. Lu et al. (2025) evaluated dense-graded CR-modified mixtures with 15% and 30% CR-RAP, finding that higher CR-RAP content reduced compactability, although satisfactory compaction was still achieved. Overall, the literature indicates that incorporating RAP, particularly when combined with CR and rejuvenators or polymers, can yield asphalt mixtures with properties equal to or exceeding those of virgin materials. Nevertheless, challenges remain in mixture design, binder modification, and compaction, especially at elevated RAP and CR contents. Table 1 summarizes the key findings of studies on RAP mixtures with and without CR.

4. Methodology

Figures 1 to 3 present the flowchart outlining the methodology of the current study. RAP samples were obtained from Sulaimani Municipality stockpiles, which serve as primary storage sites for materials generated from pavement milling operations. Sampling was conducted following established protocols to ensure representativeness and to minimize contamination. According to the Sulaimani Municipality, pavement milling is typically performed every 12–20 years on major highways and every 15–25 years on secondary roads. Initial mixtures were designed with an optimum asphalt content of 5% using a 40/50 penetration-grade binder. The asphalt binder content in RAP was determined using both the ignition and centrifuge extraction methods, with eleven specimens of 2 kg tested per method. The mean value from both methods was adopted as the representative binder content. The standard deviation of binder content, combined with the Performance Grade (PG) of the asphalt binder, was used to establish appropriate blending ratios between RAP and virgin asphalt. The minimum feasible RAP proportion for inclusion in the mixture was defined as the critical blending ratio. Recovered asphalt binder from RAP was obtained using the hot oven method in accordance with EN 12697-3. The solvent-binder solution was poured into flat metal pans and heated in a vented oven at 110°C until complete solvent evaporation. The recovered binder was cooled to room temperature, collected, and preserved for subsequent testing. Physical properties of fine and coarse aggregates from both RAP and virgin materials, as well as those of the filler, were determined according to conventional laboratory methods. Table 2 summarizes the tested material properties alongside corresponding ASTM standards. Three aggregate blends with distinct gradations were initially developed to meet Superpave volumetric requirements (Figure 4). Maximum theoretical specific gravity (Gmm, ASTM D2041) and effective specific gravity (Gse, ASTM D2726) were determined for each blend, followed by volumetric analyses to select the optimal aggregate blend for mixture preparation. Compliance with Superpave design specifications was ensured throughout. The PG of both extracted RAP binder and virgin binder served as one criterion for selecting blending ratios, while the allowable maximum RAP-based on the standard deviation of RAP asphalt content (Figure 5)-served as a second criterion. Classical binder tests were conducted on both aged and virgin binders in accordance with ASTM standards (Table 3). The CR used in this study was sourced from Paiwast Company (Bazian, Iraq). Particle size distribution was determined via sieve analysis, with CR classified into five fractions: retained on sieves No. 30, No. 50, No. 100, No. 200, and the pan. Asphalt mixtures were prepared using 35% RAP and 65% virgin materials, with CR added at 2%, 4%, and 6% by weight. Each combination was prepared with both binders, and average values were used to calculate the effective specific gravity (Gse). Mixtures, both with and without CR, were compacted using the Superpave gyratory compactor to determine the appropriate asphalt content. A total of 64 samples were produced for testing. Four performance tests were conducted on the mixtures: rutting resistance, moisture sensitivity, fatigue resistance, and stripping (Table 4). For rutting tests, 48 specimens were compacted to 4% air voids. Moisture sensitivity tests were performed on 96 specimens compacted to 7% air voids, with 48 specimens conditioned and 48 unconditioned; three replicates per case were tested to determine ITS and ITSR. Fatigue cracking resistance was evaluated using 96 specimens compacted to 4% air voids in the Semi-Circular Bend (SCB) test. Additionally, 16 specimens were used to assess moisture-induced stripping via the boiling water test.

5. Results

The average asphalt content of the RAP samples was 4.95% using the ignition method and 4.78% using the centrifuge method. The ignition method yielded slightly higher values due to partial burning of aggregates, while the centrifuge method gave lower values because some binder remained in aggregate pores. To minimize bias, the average of the two methods (4.865%) was adopted as the representative asphalt binder content of RAP. As presented in Table 5, the standard deviation of asphalt content determined by the ignition method was 0.295, corresponding to an allowable RAP content of 34% according to Figure 5. For the centrifuge method, the standard deviation was 0.32, limiting the allowable RAP content to 30%. PG testing classified the RAP binder as PG 76-10 and the virgin binder as PG 76-28, indicating that incorporation of up to 50% RAP was permissible based on PG compatibility. Considering both PG compatibility and variability, a final RAP content of 35%, blended with 65% virgin binder, was selected for mixture design.

Aggregate gradations obtained from the ignition and centrifuge methods were nearly identical (Figure 6), with both methods producing similar particle size distributions. The ignition method tended to yield slightly finer particles or more complete separation, resulting in marginally higher percent passing values.

Table 6 summarizes the specific gravity properties for both RAP and virgin aggregates. Within the RAP aggregate, specific gravity decreased progressively from coarse to fine fractions, with fine aggregates exhibiting higher water absorption (2.389%) than coarse aggregates (1.9%). In contrast, the virgin aggregates had higher bulk specific gravity (2.598 - 2.688) and apparent specific gravity (2.687-2.709), indicating a dense particle structure and low porosity. These characteristics confirm the stability and suitability of the virgin aggregates for asphalt mixture production. Table 7 presents additional aggregate properties, including particle shape, angularity, and mechanical characteristics. The fraction of flat and elongated particles was low (0.87%), while fractured particles accounted for 92.7%, indicating favorable particle shape. Mechanical properties, including Los Angeles Abrasion (17.74%) and uncompacted void content of fine aggregates (47.49%), complied with specifications, confirming the high quality of the RAP aggregates. Similarly, virgin aggregate characterization met all specification limits, with 95.7% fractured faces, 0.75% elongated particles, fine aggregate angularity of 48.8%, abrasion resistance of 20.5%, and sand equivalent of 75%.

PG testing of asphalt binders is summarized in Table 8. The virgin binder was classified as PG 70-22, providing improved resistance to low-temperature cracking, while the RAP binder was PG 76-10, effective between -10 °C and 76 °C. Both binders exhibited sufficient mechanical properties for rutting, fatigue, and thermal cracking performance. Rotational viscosity (ASTM D4402) indicated that the virgin binder (512 cP) was more workable than the RAP binder (1288 cP). Penetration values further reflected this difference: the RAP binder (27, 20/30 grade) had hardened over time, whereas the virgin binder (52, 50/60 grade) remained softer. Ductility tests showed the RAP binder was brittle (31 cm, below the >110 cm requirement), while the virgin binder exceeded 160 cm, indicating excellent flexibility. The RAP binder also had a higher softening point (59.6 °C vs. 52 °C), consistent with increased stiffness at elevated temperatures. Specific gravity, flash point, and fire point values were comparable for both binders, with all exceeding specification limits.

Volumetric analysis of the experimental mixtures is presented in Tables 10 and 11. Only Blend 3 met all Superpave mixture design criteria for a 12.5 mm nominal maximum aggregate size, whereas Blends 1 and 2 were rejected due to VMA below the 14% minimum. For Blend 3, the optimum asphalt content increased with CR content. The #30 sieve size with 6% CR had the highest asphalt content (16.3%), exceeding the 14% Superpave minimum. VFA values ranged from 73.5% to 75.1%, within the 65-75% specification. The dust-to-binder ratio (D/B) decreased from 0.97 in the control mixture to 0.81 for the #30 sieve at 6% CR. Maximum theoretical specific gravity (Gmm) remained approximately 2.41 across mixtures. Overall, all CR-modified mixtures satisfied Superpave volumetric requirements. Coarser CR particles (#30) required more asphalt and resulted in higher VMA, while finer CR particles (#100, #200, and Pan) required less asphalt and exhibited slightly lower VMA, indicating that coarse CR increases binder demand and void content, whereas finer CR facilitates denser mixtures with reduced asphalt requirements.

Table 12 summarizes the influence of CR particle size and content on the performance characteristics of reclaimed asphalt mixtures. Evaluated properties include rutting (Kim) test converted to Asphalt Pavement Analyzer equivalent), ITS under unconditioned and conditioned states, ITSR, critical strain energy release rate (Jc) from SCB testing, and stripping area percentage. The results indicate that CR retained on sieve #200 exhibited superior rutting resistance compared with other particle sizes. Incorporation of 2%, 4%, and 6% CR reduced rutting depths from 9.849 mm in the control mixture to 6.194, 6.784, and 5.723 mm, respectively, with corresponding p-values of 0.004, 0.009, and 0.088. Among these, the mixture containing 6% CR #200 showed a statistically insignificant improvement ($p > 0.05$), suggesting that 2% and 4% CR produced more consistent reductions in rutting depth. In contrast, coarser CR particles generally decreased rutting resistance; for example, mixtures incorporating #50 CR at 2%, 4%, and 6% exhibited rut depths of 10.794, 13.627, and 14.939 mm, respectively, with p-values of 0.280, 0.455, and 0.245, compared with 9.849 mm for the control mixture. Similarly, CR retained on the Pan sieve reduced rutting resistance, likely because it functioned primarily as a filler rather than contributing effectively to the mixture's structural integrity.

The ITS of unconditioned mixtures was adversely affected by both CR particle size and content. As shown in Table 12, CR incorporation generally reduced ITS values; however, in several cases, these reductions were not statistically significant. For example, adding #30 CR at 2%, 4%, and 6% decreased ITS from 1222.639 kPa in the control mixture to 1006.307, 1113.307, and 1005.028 kPa, respectively, with corresponding p-values of 0.284, 0.480, and 0.153. Since all p-values exceed 0.05, these changes are considered insignificant, indicating that #30 CR had a minor effect on tensile strength. Conditioned ITS values were similarly only slightly influenced by CR incorporation. For instance, adding #30 CR at 2%, 4%, and 6% reduced conditioned ITS from 1047.225 kPa in the control mixture to 831.133, 1006.124, and 954.700 kPa, respectively, with corresponding p-values of 0.052, 0.736, and 0.614. Most mixtures maintained ITSR values above 80%, demonstrating acceptable moisture resistance. However, four specific cases - mixtures containing #50 and #200 CR at 4% and 6% contents - produced ITSR values below 80%, indicating a significant loss in moisture resistance.

In the SCB test, only CR particle sizes #50 and #200 improved the fracture resistance of the reclaimed asphalt mixtures. Incorporation of 4% and 6% #50 CR increased the Jc from 0.402 kJ/m² in the control mixture to 0.429 kJ/m² and 0.538 kJ/m², respectively, with corresponding p-values of 0.010 and 0.030, indicating statistically significant improvements ($p < 0.05$). Similarly, the use of #200 CR enhanced fracture resistance, with 2%, 4%, and 6% contents increasing Jc to 0.469, 0.491, and 0.430 kJ/m², respectively, compared with the control mixture. The corresponding p-values of 0.002, 0.003, and 0.018 confirm that these improvements were statistically significant. In contrast, other CR particle sizes and contents reduced Jc, indicating their limited effectiveness in improving cracking resistance at intermediate service temperatures.

The stripping test demonstrated that certain CR particle sizes and contents enhanced moisture resistance. Specifically, mixtures containing 4% and 6% #30 CR exhibited less than 10% stripping, meeting acceptable limits. Similarly, mixtures with pan-sized CR performed satisfactorily, particularly at 2% and 4% contents. In contrast, all other CR sizes and contents produced stripping values exceeding the 10% limit, although most were only slightly above this threshold. The only notable exception was the mixture containing 2% #50 CR, which showed a stripped area of 21.6%, indicating poor moisture resistance.

6. Conclusion

The main findings of this study can be summarized as follows:

• A RAP content of 35%, blended with 65% virgin binder, was selected based on allowable limits determined from the ignition (34%) and centrifuge (30%) methods, as well as PG compatibility, which permitted up to 50% RAP incorporation.

• Both RAP and virgin aggregates satisfied the specified requirements. The RAP aggregates contained 0.87% flat or elongated particles, 92.7% fractured particles, a Los Angeles Abrasion value of 17.74%, and a fine aggregate angularity of 47.49%, indicating high quality. The virgin aggregates exhibited 95.7% fractured faces, 0.75% elongated particles, 48.8% angularity, 20.5% abrasion, and a sand equivalent of 75%, confirming their suitability for use in asphalt mixtures.

• The virgin binder was classified as PG 70-22, providing strong resistance to rutting and low-temperature cracking, whereas the RAP binder was PG 76-10, performing adequately over a temperature range of –10 °C to 76 °C. All CR-modified mixtures satisfied Superpave volumetric specifications. Coarser CR particles increased binder and VMA requirements, while finer CR particles produced denser mixtures with reduced asphalt demand.

• The RAP binder was stiffer and more brittle than the virgin binder, with a penetration of 27 mm, ductility of 31 cm, and a softening point of 59.6 °C. In contrast, the virgin binder exhibited a penetration of 52 mm, ductility exceeding 160 cm, and a softening point of 52 °C. The specific gravities of both binders were comparable, while flash and fire points exceeded the minimum specification limits, with slightly higher values observed for the RAP binder.

• CR #200 showed the highest rutting resistance, with 2% and 4% reducing rut depths from 9.849 mm to 6.194 and 6.784 mm (p-values = 0.004, 0.009); 6% CR was not significant (5.723 mm; p-value = 0.088). Coarser CR (#50) and Pan sieve CR increased rut depths, acting mainly as filler.

• CR slightly reduced ITS, with most changes statistically insignificant. #30 CR at 2%, 4%, and 6% lowered unconditioned ITS from 1222.6 to 1006.3, 1113.3, and 1005 kPa ($p > 0.05$) and conditioned ITS from 1047.2 to 831.133, 1006.124, and 954.7 kPa. Most mixtures maintained ITSR >80%, except #50 and #200 CR at 4% and 6%, which showed reduced moisture resistance.

• In the SCB test, only #50 and #200 CR improved fracture resistance. Adding 4% and 6% #50 CR increased Jc from 0.402 to 0.429 and 0.538 kJ/m² (p-values = 0.010, 0.030), while #200 CR at 2%, 1%, and 6% raised Jc to 0.469, 0.491, and 0.43 kJ/m² (p-value < 0.05). Other CR sizes reduced Jc, showing limited effectiveness in enhancing cracking resistance.

• The stripping test showed that 4% and 6% #30 CR and 2% and 4% pan-sized CR improved moisture resistance (<10% stripping), while most other sizes exceeded the limit, with 2% #50 CR performing the worst (21.6%).

• RAP and CR are recommended for sustainable pavement construction, as their practical use can reduce virgin material demand, lower costs, and support a circular economy while further research ensures long-term performance.

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تقييم تأثير أحجام ونسب جزيئات المطاط المفتت على أداء خليط الأسفلت المستصلح

المستخلص

تتناول هذه الدراسة تأثير دمج أحجام ونسب مختلفة من المطاط المفتت (CR) على أداء الخلطات الأسفلتية الصديقة للبيئة التي تحتوي على 35% من الأسفلت المعاد تدويره .(RAP) تم استخدام جسيمات المطاط المفتت المحجوزة على المناخل رقم 30،50 ،100 ،200 ، وكذلك الباقية في الصينية (pan) بنسب2% ،4% ، و 6%من وزن الرابط الأسفلتي .تم إجراء اختبارات توصيف المواد وفقًا لمعايير ASTM ، بينما تم تصميم الخلطات باستخدام منهجية .Superpave جرى تقييم أداء الخلطات من حيث مقاومة التخدد) اختبار(Kim ، الحساسية للرطوبة، مقاومة التعب) اختبار(SCB ، ومقاومة الانفصال.(stripping)

أظهرت نتائج الفحوصات أن كل من مواد RAP والمواد البكر استوفت متطلبات المواصفات .كما تبيّن أن رابط RAP أكثر صلابة وهشاشة من الرابط البكر (PG 76-10 مقابل PG (70-22، ومع ذلك بقي صالحًا للاستخدام في الخلطات الأسفلتية الجديدة .أظهرت التحليلات الحجمية أن جميع الخلطات المعدلة بالمطاط المفتت استوفت معايير تصميم Superpave، حيث زاد استخدام الجسيمات الخشنة من حاجة الرابط، في حين أدت الجسيمات الدقيقة إلى خلطات أكثر كثافة .وقدمت الخلطات التي تحتوي على المطاط المحجوز على المنخل رقم 200 أعلى مقاومة للتخدد، حيث أدت نسب 2%و 4%إلى تقليل عمق التخدد بشكل ملحوظ، بينما لم تُظهر نسبة 6% أي تحسن معنوي .في المقابل، ساهمت الجسيمات الخشنة) رقم 50 والباقية في الصينية (في زيادة التخدد، إذ عملت بشكل رئيسي كحشوة .كان تأثير المطاط المفتت على مقاومة الشد غير المباشر (ITS) طفيفًا وغير معنوي في الغالب، إذ حافظت معظم الخلطات على نسب قوة شد غير مباشر (ITSR) تفوق80% ، باستثناء نسب 4% و 6%من المطاط رقم 50 ورقم .200 وفي اختباراتSCB ، أظهرت الخلطات التي تحتوي على المطاط رقم 50 ورقم 200 تحسنًا في مقاومة الكسر، مع زيادة ملحوظة في معدل انطلاق طاقة الانفعال (Jc) عند نسب.2–6%

وأشارت نتائج اختبار مقاومة الانفصال إلى أن الخلطات التي تحتوي على 4–6% من المطاط رقم 30 و 2–4%من المطاط الباقي في الصينية أظهرت مقاومة محسّنة للرطوبة، بينما تجاوزت معظم الأحجام الأخرى الحدود المقبولة قليلًا.بشكل عام، أظهرت النتائج أن مقاومة التخدد، والحساسية للرطوبة، وأداء التعب، ومقاومة الانفصال في الخلطات الأسفلتية المعاد تدويرها تتأثر بشكل كبير بكلٍّ من حجم ونسبة المطاط المفتت المضاف.

الكلمات المفتاحية

الرصف الإسفلتي المعاد تدويره(RAP) ، المطاط المفتت (CR)، درجة الأداء(PG) ، التخدد، التعب، التقشر، نسبة مقاومة الشد غير المباشر (ITSR).

Table 1. Summary of the review about the studies of RAP without CR and with CR

Authors	Year	Coincide result
Shen, Amirkhanian, Lee, & Putman	2006	CR-modified binders improve RAP mixtures; ≤15% RAP minimally affects rutting resistance, ITS, and resilient modulus compared to virgin asphalt.
Valdés, Pérez-Jiménez, Miró, Martínez, & Botella	2011	High RAP content can be successfully used in Spanish highway bituminous mixes if properly characterized and managed.
Han, Thakur, Chong, & Parsons	2011	Kansas RAP tests indicate notable differences between aged and recycled binders, with RAP mixtures differing from virgin aggregates.
Reyes-Ortiz, Berardinelli, Alvarez, Carvajal-Muñoz, & Fuentes	2012	Dense-graded HMA with 15%, 20%, and 100% RAP showed 100% RAP yielding the highest ITS and resilient modulus under wet and dry conditions.
Hussain & Yanjun	2013	RAP increases stiffness and reduces high-temperature flexibility, retaining more residual binder and aging slower than virgin ARL 60/70.
Zaumanis, Mallick, Poulikakos, & Frank	2014	Testing 100% RAP mixtures with eleven additives demonstrated that rejuvenation enhances low temperature cracking resistance, rutting resistance, and moisture durability.
Noferini, Simone, Sangiorgi, & Mazzotta	2017	Evaluation of 10%, 20%, and 30% RAP showed aged binders yield stiffer composites with ≥20% higher viscosity and a broader elastic temperature range.
Milad, Taib, Ahmeda, Solla, & Yusoff	2020	Well-managed RAP mixtures improve density, moisture resistance, and overall sustainability.
Antunes, Neves, & Freier	2021	75% RAP mixes rejuvenated with crude tall oil (CTO) matched or surpassed virgin mixtures in stiffness, deformation resistance, fatigue life, and moisture durability, delivering environmental and economic benefits.
Zhao, Goulias, Tefa & Bassani	2021	A life-cycle study of Maryland projects showed that RAP significantly reduces costs and environmental impacts.
Tsakoumaki & Plati	2024	RAP practices vary regionally and are rarely standardized; harmonized guidelines are needed to expand its use in highway construction, with growing interest in RAP–CR blends.
Xiao, Amirkhanian, Shen, & Putman,	2009	CR improved RAP mixtures' resistance to air voids and rutting, while particle size had little effect on ITS and reduced resilient modulus.
Alavi, Hung, Jones, & Harvey	2016	Repaired rubberized RAP (R-RAP) showed improved rutting resistance but reduced fatigue and low-temperature performance
Ebrahim & Karim	2019	RAP mixes with SBS, CR, and PP showed decreasing ITS with higher CR, while ITSR stayed above 80%; recommended CR dosages are 3% for cold and 7% for hot climates.
Bilema, Aman, Hassan, Memon, Omar, Yusoff, & Milad	2021	RAP mixtures containing 25% and 40% RAP, modified with CR and WFO, exhibited improved rutting resistance, binder rejuvenation, and sustainability, with higher CR and WFO levels further enhancing performance.
Vigneswaran, Yun, Jeong, Lee, & Lee	2023	Larger CR particles (1–2 mm) hindered binder performance, highlighting the need to improve field procedures.
Oleiwi & Albayati	2024	CR in dry-process asphalt mixes improved durability at extreme temperatures and served as a physical modifier.
Lu, Balasubramaniam, Enfrin, & Giustozzi	2025	Dense-graded 15–30% CR-RAP mixes had reduced but adequate compactability; recycling with CR and rejuvenators can match virgin performance, though high RAP/CR complicates design, modification, and compaction.

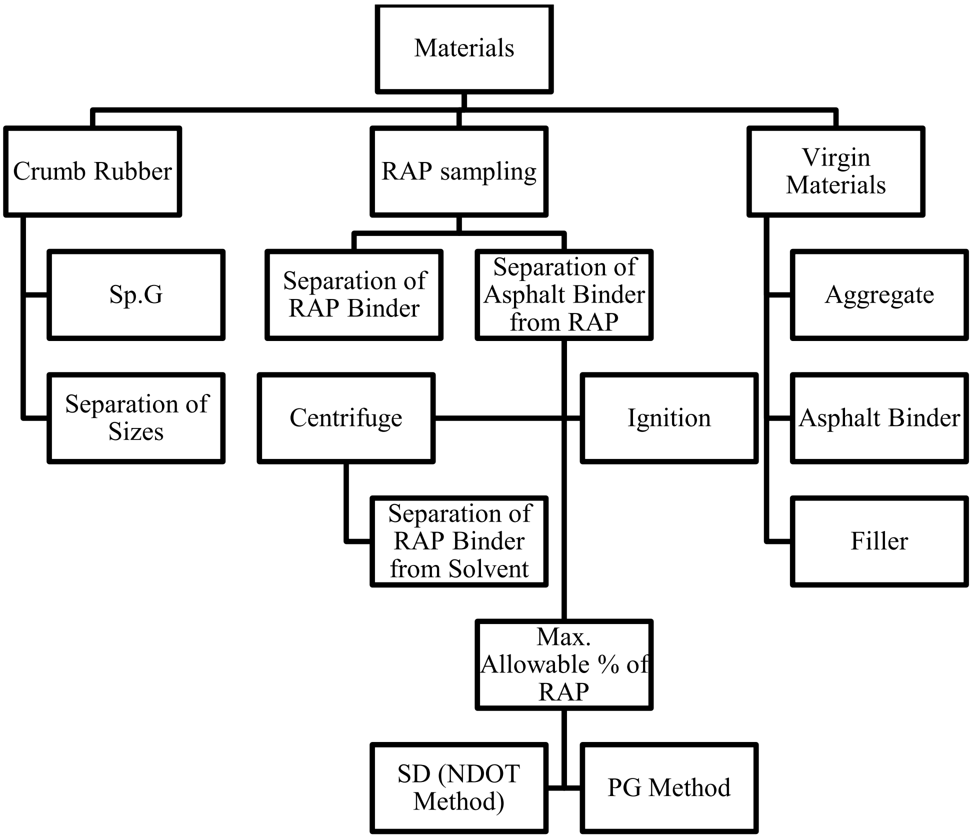

Figure 1. Step one flowchart of the methodology

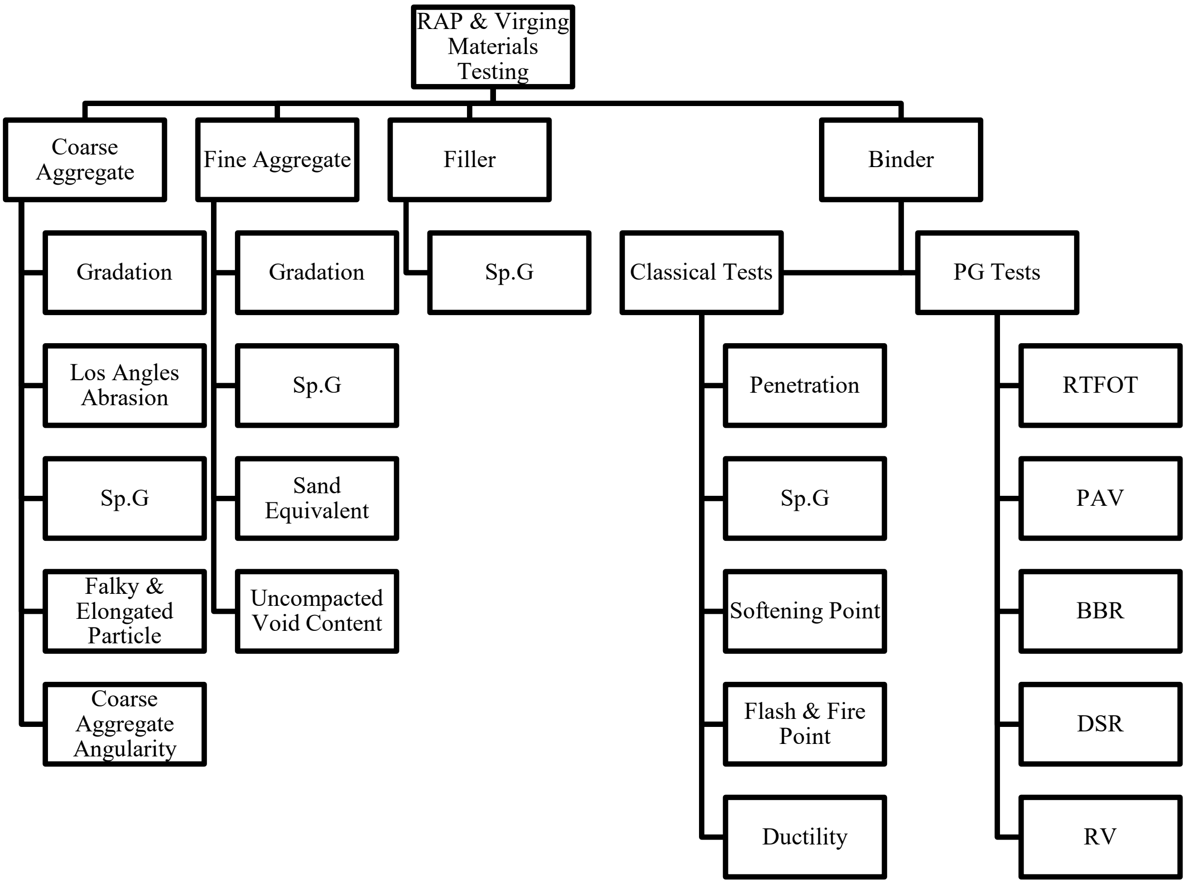

Figure 2. Step two flowchart of the methodology

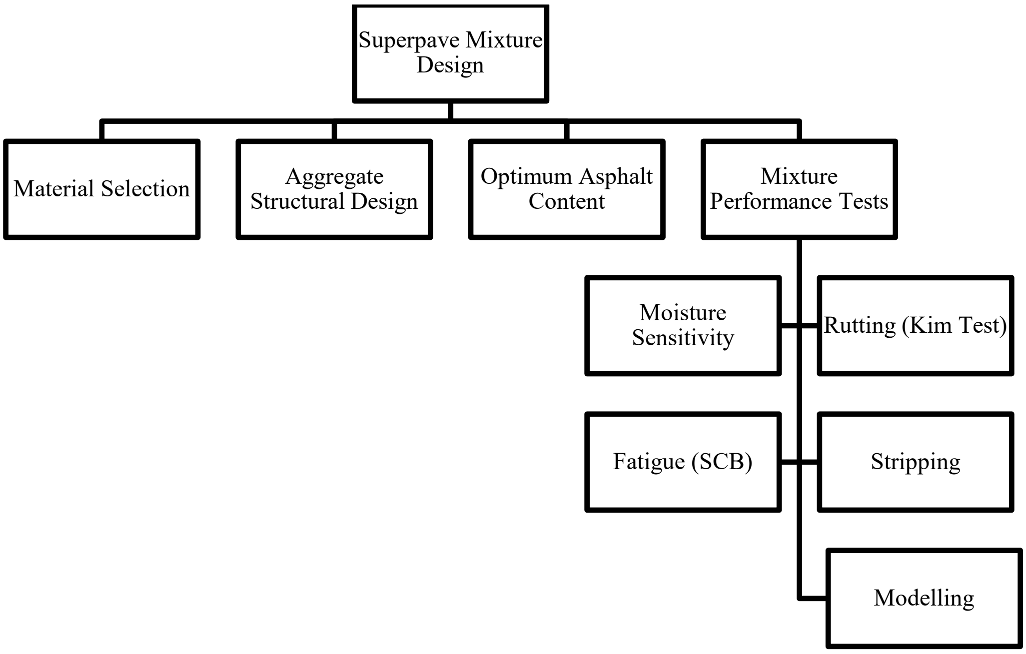

Figure 3. Step three flowchart of the methodology

Table 2. ASTM specifications for aggregate and filler testing

Material Type	Test	Method
	Gradation	ASTM C131
Coarse Aggregate	Los Angeles Abrasion (LAA)	ASTM C131, C535
	Specific Gravity (Sp. G)	ASTM C127
	Flaky and elongated	ASTM D4791
	Coarse Aggregate Angularity	ASTM D5821
Fine Aggregate	Gradation	ASTM C131
	Specific Gravity (Sp. G)	ASTM C128
	Fine Aggregate Angularity	ASTM C1252
	Sand Equivalent	ASTM D2419
Dust (Filler)	Specific Gravity	ASTM D854

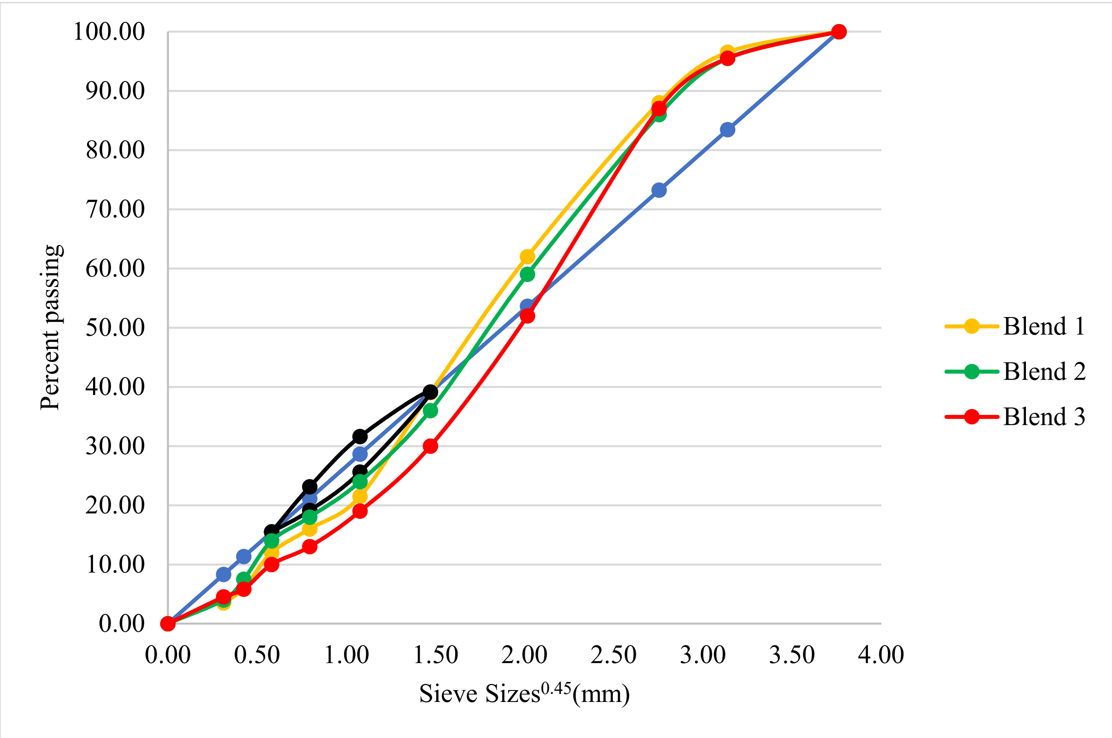

Figure 4. Aggregate gradation of the designed blend mixtures

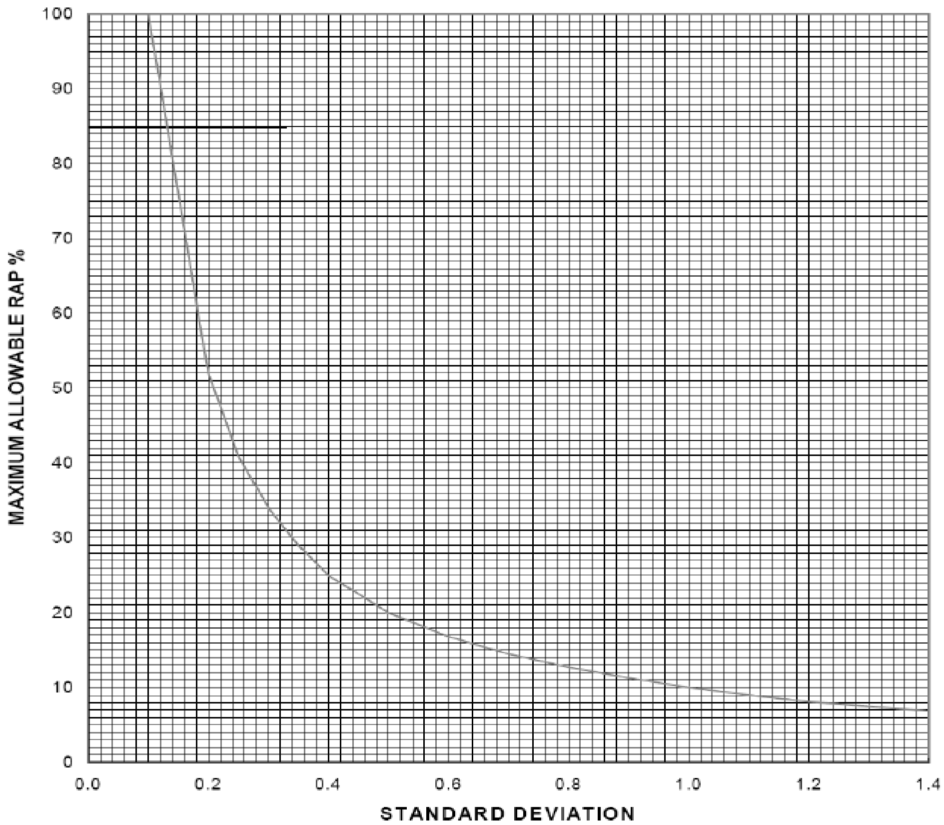

Figure 5. Maximum allowable RAP vs. standard deviation of asphalt content (MDOT 1999, Mehta, (NJDOT),2009)

Table 3. Classical and Superpave tests for asphalt binder

Type of Tests	Test	Method
Classical Tests	Penetration	ASTM D5
	Softening Point	ASTM D36
	Ductility	ASTM D113
	Viscosity	ASTM D2196, ASTMD4402
	Specific Gravity	ASTM D2726
	Flash and Fire Point	AASHTO T79
Superpave Tests	Rolling Thin-Flim Oven (RTFO)	ASTM D2872
	Pressure Aging Vessel (PAV)	ASTM D6521
	Dynamic Shear Rheometer (DSR)	ASTM D7175
	Bending Beam Rheometer (BBR)	ASTM D6648

Table 4. Superpave tests for asphalt binder

Test	Method
Rutting	Kim Test Procedure
Indirect Tensile Strength Ratio (ITSR)	ASTM D6931
Semi-Circular Bend (SCB)	ASTM D8044
Stripping	ASTM D3625

Table 5. Average value of asphalt contents in RAP Samples

Sample No	% Asphalt Content Ignition Method	% Asphalt Content Centrifugal Method
Mean	4.95	4.78
Avg	4.865	
SD	0.295	0.32

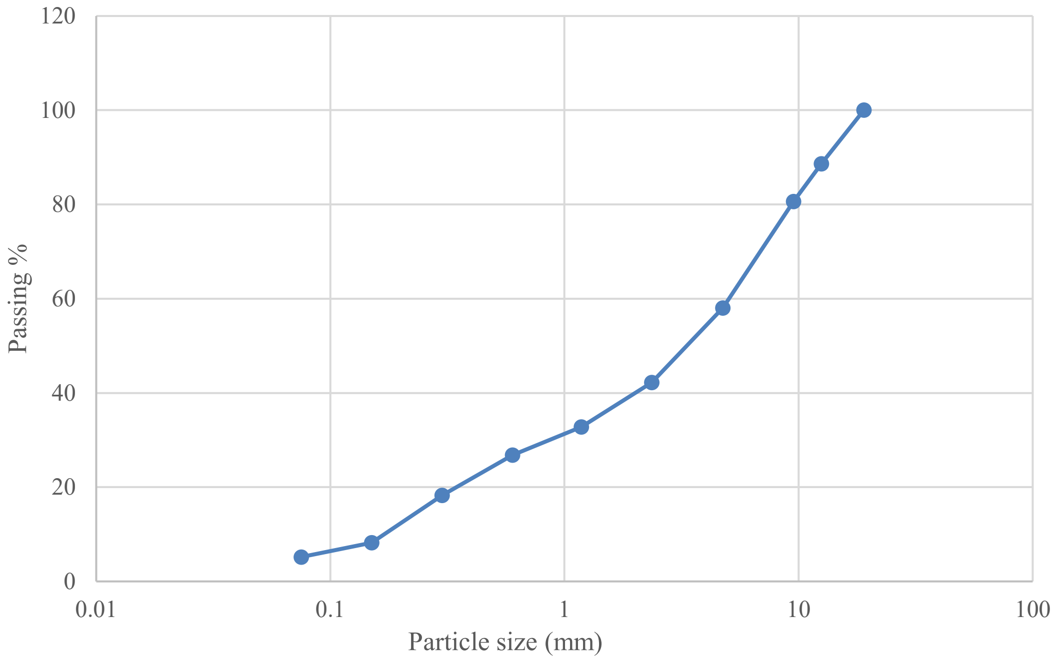

Figure 6. RAP aggregate gradations using centrifuge and ignition extraction methods

Table 6. Specific gravity of aggregate

Description	RAP Aggregate			Virgin Aggregate		
	Coarse Aggregate	Fine Aggregate	Filler	Coarse Aggregate	Fine Aggregate	Filler
Apparent Sp.G	2.696	2.674	2.48	2.702	2.687	2.709
Bulk Sp.G	2.564	2.513	2.41	2.598	2.604	2.688
Effective Sp.G	2.63	2.594	2.45	2.650	2.645	2.699
Water Absorption	1.9	2.389	-	1.478	1.187	-

Table 7. Aggregate quality test

Test Type	Result		Specification/ Limit	Evaluation
	RAP %	Virgin %		
Flat and Elongated Coarse Aggregate	0.87	0.75	≤ 10% (Iraqi Specifications)	Pass
Fractured Particles of Coarse Aggregate	92.70	95.7	≥ 90% (Iraqi Specifications)	Pass
Los Angeles Abrasion Test (LA)	17.74	20.5	≤ 30% (ASTM/AASHTO limit)	Pass
Uncompacted Void % of Fine Aggregate	47.49	48.48	≥ 45% (Superpave Specifications)	Pass
Sand Equivalent	-	75	≥ 45% (Iraqi Specifications)	Pass

Table 8. Performance grade of virgin and RAP asphalt binder

Properties	Specification	Virgin Binder		RAP Binder	
		PG (T) °C	Measured Value	PG (T) °C	Measured Value
Original DSR, G*/sin δ	≥ 1.0 KPa	70	0.89	76	3.16
RTFO DSR, G*/sin δ	≥ 2.2 KPa	70	-	76	6.95
S @ 60 sec Mpa	Max. 300 MPa	-22	284	-10	122
m-Value @ 60 sec	Min. 0.3	-22	0.302	-10	0.316
PG		76-22		76-10	
RV (CP)		512		1288	

Table 9. Classical test results of RAP and virgin asphalt binders

Test	Binder Type	
	Virgin	RAP
Penetration	27	52
Ductility	31	more than 160
Softening Point	59.60	52
Sp. G	1.033	1.035
Flash Point	325	327
Fire Point	334	339

Table 10. Volumetric analysis of three blends

Data	Blend 1	Blend 2	Blend 3	
Gmb	2.370	2.339	2.283	
Gmm	2.450	2.453	2.457	
Gb	1.0343	1.0343	1.0343	
Pb %	5	5	4.8	
Ps %	95	95	95.2	
Pd%	3.75	4	4.5	
Gsb	2.579	2.579	2.58	
Hini (mm)	75.41	75.95	77.19	
Hdes (mm)	68.01	69.15	69.79	
Computed Values				Criteria
Gse	2.640	2.644	2.640	
VTM %	3.265	4.65	7.08	
VMA %	12.70	13.84	15.76	
VFA %	74.29	66.42	55.06	
% Gmm, ini	87.24	86.82	84.01	< 89
Pba %	0.93	0.98	0.91	
Pbe %	4.117	4.07	3.93	
D\B	0.911	0.98	1.14	
Adjusted Values				
Pb, est%	4.71	5.26	6.03	
C	0.1	0.2	0.2	
VMA, est%	12.77	13.71	15.14	>14
VFA, est%	68.68	70.83	73.58	65-75
%Gmm, Nini, est	86.51	87.46	87.09	
Pbe, est, %	3.82	4.32	5.16	
D\Best	0.98	0.93	0.87	0.8-1.6

Table 11. Volumetric parameters of the reclaimed asphalt mixtures for blend 3 with and without using different crumb rubber sizes and ratios

Size		Optimum AC%	VMA %	VFA %	Gmm ini.	D\B	Gmm
Base (Control Mixture)		5.6	14.52	72	86.1	0.97	2.4288
#30	2% CR	6.3	16.15	74.8	86	0.83	2.405
	4% CR	6.35	16.2	75	85.6	0.82	2.404
	6% CR	6.4	16.3	74.8	86.4	0.81	2.404
#50	2% CR	6.2	15.81	74.8	87.3	0.846	2.409
	4% CR	6.25	16.1	75	87.4	0.838	2.408
	6% CR	6.32	16.08	75.1	87.55	0.826	2.406
#100	2% CR	6.02	15.42	74.8	85.6	0.88	2.415
	4% CR	6.1	15.68	74.6	86.95	0.862	2.412
	6% CR	6.18	15.82	74.5	87.2	0.85	2.409
#200	2% CR	5.95	15.32	74	86.4	0.89	2.417
	4% CR	6.05	15.58	74	86.7	0.87	2.415
	6% CR	6.1	15.64	74	86.52	0.86	2.414
#Pan	2% CR	5.83	15.07	73.5	86.75	0.91	2.421
	4% CR	5.9	15.27	73.8	87.62	0.9	2.42
	6% CR	6	15.44	74.5	87.51	0.88	2.417

Table 12. Influence of crumb rubber sizes and proportions on rutting, fatigue, moisture sensitivity, and stripping of asphalt mixtures

Size		Rutting APA (mm)	ITS Unconditioned (KPa)	ITS Wet (KPa)	ITSR %	Jc (Kj/m2)	Stripping Area %
Control	CR%	9.849	1222.639	1047.225	85.653	0.402	5.777
#30	2	10.678	1006.307	831.133	82.592	0.182	14.693
	4	13.576	1113.866	1006.124	90.327	0.142	6.029
	6	7.185	1005.028	954.720	94.994	0.255	3.846
#50	2	10.794	932.536	905.299	97.079	0.281	21.576
	4	13.627	1223.075	953.954	77.996	0.429	4.380
	6	14.939	1020.758	786.661	77.066	0.538	14.800
#100	2	12.077	1049.369	976.490	93.055	0.181	10.238
	4	13.605	1040.294	854.135	82.105	0.265	14.470
	6	15.860	1076.332	893.906	83.051	0.142	14.810
#200	2	6.194	953.762	785.350	82.342	0.469	11.569
	4	6.784	1066.839	804.248	75.386	0.491	11.894
	6	5.723	1190.833	840.102	70.547	0.430	12.221
#Pan	2	17.848	1087.479	880.570	80.974	0.367	4.718
	4	16.545	1102.015	945.626	85.809	0.283	7.832
	6	18.066	900.167	809.842	89.966	0.335	10.558