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Review Article

The Feasibility of RCA Treatments Utilised in Asphalt Mixtures to Enhance their Properties and Performance: Narrative Review

Nadheer Albayati [1,*], Mohammed Qadir Ismael [2]

[1] Expressway Directorate, Roads and Bridges Department, Ministry of Construction and Housing, Baghdad, 10071, Iraq

[2] Department of Civil Engineering, College of Engineering, University of Baghdad, Baghdad, 10071, Iraq

* Corresponding Author: Nadheer Albayati, Nazeer.Khaled2101m@coeng.uobaghdad.edu.iq

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Abstract

Recycled concrete aggregates (RCA) can be utilised instead of virgin aggregates to produce hot asphalt mixtures. This contributes to solving the difficulty of construction waste disposal and mitigates the supply-demand dilemma associated with implementing the sustainability strategy. Nevertheless, the presence of cement mortar in the recycled concrete aggregate leads to changes in its mechanical and physical characteristics, posing a major challenge. Therefore, researchers investigated methods to mitigate the harm caused by this cement mortar through various treatments. This paper offers a narrative review of the feasibility of employing several treatments or techniques on recycled concrete aggregates to enhance the susceptibility of asphalt mixtures to fatigue, water damage, permanent deformation, and Marshall properties. Several treatments have been discussed, such as heating, coating, mechanical treatment, immersing RCA in chemical solutions, and the composite method. This review concludes that mechanical treatment is the most practical and effective, making it the most likely to succeed in practical application.

1. Introduction

In all nations, people take pride in their roads because they serve as an interface to civilisation. The development and prosperity of any country can be evaluated by the quality of its constructed road networks. Roads are lifelines for society's ongoing growth because they serve as critical transportation routes for commercial, agricultural, industrial, and other life activities. As a result, a large portion of the funding for major development plans globally is allocated to road construction [1-3]. The roads are built from natural materials and need large quantities of them, which leads to damage to the soil of nature [4, 5].

Additionally, gathering building debris is another major cause of endangering human lives and the environment [6–8]. To lessen the harm that waste materials cause, scientists, engineers, and others interested in the environment have given the concept of sustainability much importance [9]. The primary focus of sustainability is to create innovations that do not endanger the environment or human lives [10, 11]. Waste materials are composed of various materials, but the most important one is Portland cement concrete, which is also present in building scraps along with bricks, wood, and iron [12–15]. Producing eco-friendly aggregates involves transforming concrete waste into recycled concrete aggregate (RCA) by breaking it down into small fragments, providing an alternative to natural aggregates [16–18]. This has the advantage of lowering the quantity of construction waste accumulated; furthermore, it is an alternative source of materials for road construction [19–22]. Without a doubt, the cement mortar's adherence causes RCA to differentiate from natural aggregates; furthermore, the variation between RCA is based on several factors, including the type of aggregate used in concrete production, the age of the concrete, its exposure to sulfates and climate, mortar quality and quantity, and microcracks [23, 24]. Mortar is typically weaker than aggregate, influencing RCA's physical and mechanical properties, such as increased asphalt and water absorption, reduced applied load resistance, and lower density [25].

Consequently, using RCA in asphalt mixtures may alter the properties of these mixtures and negatively affect them as they get subjected to frequent loads and severe outside conditions, affecting performance and durability [26]. Therefore, these poor qualities of the RCA attracted the attention of researchers and urged them to innovate numerous solutions to enhance the characteristics and disposal of cement mortar [27]. Generally, these techniques usually use two approaches: either eliminate cement mortar or enhance its properties [28].

This paper investigates the impact and feasibility of treating recycled concrete aggregates in various ways as a substitute for aggregates in asphalt mixtures, which have been conducted in previous studies, to determine the most practical approach.

2. Treatment Methods

2.1. Immersing in Chemical Solutions

Pre-soaking in acidic solutions to remove remaining mortar has garnered much interest in studies lately. The most common chemical solutions or acids utilised in RCA treatment were HCl, H2SO4, HNO3, and CH3COOH [29]. The essential characteristics of the new RCA after pre-soaking the RCA in HCl, H2SO4, and H3PO4 solutions to remove the deteriorating mortar that was sticking to the RCA surface were looked at by Pandurangan et al. [30].

Kanoungo et al. [31] investigated the effect of acid treatment (type not specified) of RCA obtained from demolition waste on Marshall and the moisture effect of asphalt mixtures. According to the study, acid-treated RCA had improved absorption compared to untreated RCA. Regarding Marshall's properties, the study revealed that combinations including treated RCA had less Marshall's stability than mixtures containing untreated RCA. It also revealed a reduction in flow, optimum asphalt content, and air voids in mixtures containing acid-treated RCA compared with mixtures containing untreated RCA. The retained stability test was the assessment index for moisture damage. The study revealed that simple promotions were valued at approximately 5% of mixtures containing acid-treated RCA compared to mixtures containing untreated RCA.

Lei et al. [32] assessed the permeable asphalt concrete's performance containing RCA treated with acetic acid at a concentration of 5% for 0.5 hours to clean the RCA surface from the adherent mortar. Sodium silicate, with a concentration of 3% for 2 hours, is an important material in many industries for its economic cost, flexibility, and versatility. Polyvinyl alcohol with a concentration of 6% for 24 hours is a synthetic polymer dissolved in water to fill the RCA surface's voids and cracks. The efficiency of the asphalt mixture was assessed by Marshall stability, the addition test between asphalt and aggregate (boiling method), the freeze-thaw splitting test to investigate water damage by tensile strength ratio, the wheel tracking test for rutting susceptibility, and a low-temperature crack at -10 ˚C for 6 hours. The study showed a decrease in the optimum asphalt content and density of mixtures, including treated RCA, compared with untreated RCA.

The Marshall stability demonstrated an increase in the mixtures, including treated RCA, compared with untreated RCA. The mixtures containing treated RCA by polyvinyl alcohol showed an effective enhancement of 20% compared with mixtures including untreated RCA, while the mixtures including treated RCA by acetic acid and sodium silicate showed no improvement. Regarding the freeze-thaw splitting test, the study showed that the mixtures including treated RCA had a higher splitting strength ratio than those containing untreated RCA. The maximum rise in the mixtures, including treated RCA by sodium silicate, was 5% greater than in the mixtures including untreated RCA. The permanent deformation resistance was assessed by dynamic stability; the mixtures, including treated RCA, had more dynamic stability than those with untreated RCA. The mixtures containing treated RCA with acetic acid had dynamic stability that was 2.85 times greater than those with untreated RCA. Regarding low-temperature cracks, the study showed an increase in low-temperature splitting strength for mixtures including treated RCA compared with mixtures including untreated RCA. The best enhancement happened in the mixtures including treated RCA with acetic acid, which was 3.33% greater than in the mixtures including untreated RCA.

Eldeen et al. [33] discovered that treatment of RCA with HCL acid at a concentration of 0.1 Molarity for 24 hours has a significant effect. The most important properties of RCA reduced by this treatment are abrasion and absorption; the reduction was 10 and 31%, respectively, compared with untreated RCA. The study concluded that there are adverse effects on the specific gravity of aggregate when RCA is soaked in HCL acid, which is less than that of untreated RCA. The researchers explained that they used hydrochloric acid for two reasons: it effectively removes cement mortar, and the second was the least hazardous robust acid to work with because it is safe.

Abbas & Albayati [34] tested two treatments of RCA utilised in warm asphalt mixtures; the first was soaking RCA in HCL acid with a low concentration of 0.1 Molarity for 24 hours, and the second was soaking RCA in 1.5% hydrated lime slurry for 24 hours. The study findings showed a reduction in optimum asphalt content for mixtures containing treated RCA compared to untreated RCA counterparts. Marshall's stability satisfied the minimum requirements. The durability (investigated by tensile strength ratio) of asphalt mixtures containing treated RCA by acid and the hydrated lime slurry was enhanced by 11.68% and 10.05%, respectively, compared with untreated RCA. The study showed resilient modulus (investigated by uniaxial repetitive compressive stress at 20 ˚C) for mixtures containing treated RCA reduced the decrement of resilient modulus compared with mixtures containing untreated RCA; the decrement dropped from 39.17 to 23.09% for mixtures containing 100% treated RCA by HCL acid and 39.17 to 28.56% for mixtures containing 100% treated RCA by hydrated lime slurry. Regarding permanent deformation (investigated by uniaxial repetitive compressive stress at 40 ˚C), the study showed that the mixtures containing treated RCA reduced the decrement of permanent deformation compared with those with untreated RCA. The decrement dropped from 35.43 to 27.8% for mixtures containing 100% treated RCA by HCL acid and from 35.43 to 30.95% for mixtures containing 100% treated RCA by hydrated lime slurry.

Al-Bayati & Ismael [35] investigated the influence of soaking RCA for 24 hours in acetic acid with a concentration of 0.1 Molarity on the rutting susceptibility of hot mix asphalt. The study's findings did not result in a discernible change in the volumetric properties or rutting performance of asphalt mixes. Hot asphalt mixture containing 25 and 50% treated and untreated coarse RCA has been evaluated for moisture susceptibility by Kavussi et al. [36]. Hydrated lime solutions were employed for RCAs to enhance their quality and lessen their stripping potential. Furthermore, the addition of hydrated lime is beneficial because it has the potential to be applied in HMA mixtures. The treatment process involved impregnating the RCA for 24 hours at room temperature with a 6% hydrated lime solution. Before using these in asphalt mixes, they were allowed to dry at room temperature for 24 hours. The results showed that, despite the production effort required to treat RCAs, there are substantial benefits that lower moisture susceptibility. The RCA's mechanical properties were enhanced, and the treatment decreased water absorption. A slight moisture resistance was observed in mixes with 50% untreated recycled concrete aggregates, while exceptional moisture resistance was observed in mixtures with 50% treated recycled concrete aggregates. Figure 1 shows the treatment procedure. Table 1 shows the summary of the findings of the pre-soaking treatment method.

Figure 1. Treatment procedure [36]

Table1. Summary of pre-soaking treatment findings

Reference	Type of solution	Test	Findings compared with untreated RCA
Kanoungo et al. [31]	Acid (type not specified)	Marshall properties and volumetric characteristics	Reduction in Marshall stability, flow, OAC, and air voids
		Moisture damage resistance	Increase in retained stability index.
Lei et al. [32]	Acetic acid	Marshall properties and volumetric characteristics	increase in Marshall stability and reduction in density, OAC.
		Addition between asphalt and aggregate	no effect
		Freeze-Thaw resistance	Increase
		Wheel tracking test (Dynamic stability)	Increase
		low-temperature crack strength	Increase
	Sodium silicate	Marshall properties and volumetric characteristics	increase in Marshall stability and reduction in density, OAC.
		Addition between asphalt and aggregate	No effect
		Freeze-Thaw resistance	Increase
		Wheel tracking test (Dynamic stability)	Increase
		low-temperature crack strength	Increase
	Polyvinyl alcohol	Marshall properties and volumetric characteristics	increase in Marshall stability and reduction in density, OAC.
		Addition between asphalt and aggregate	Increase
		Freeze-Thaw resistance	Increase
		Wheel tracking test (Dynamic stability)	Increase
		low-temperature crack strength	Increase
Eldeen et al. [33]	HCL	Aggregate properties used in asphalt mixtures	Decrease abrasion and absorption with side effects on bulk density
Abbas & Albayati [34]	HCL, hydrated lime slurry	Moisture damage resistance Permanent deformation	Increase Increase
Al-Bayati & Ismael [35]	Acetic acid	Permanent deformation	No discernible change
Kavussi et al. [36]	Hydrated lime solution	Moisture susceptibility	Increase

2.2. Mechanical Treatment

Adhered mortar on RCA surfaces can often be highly removed in massive quantities by crushing and ball grinding. This is one of the most significant and successful cement mortar disposal methods [37]. Eldeen et al. [33] utilized two mechanical treatments of RCA: the first was using a Los Angeles machine to grind RCA, and the second was RCA particle re-grinding in a jaw-crushing machine. When comparing the mixtures containing treated and untreated RCA, the study findings showed a discernible increase in bulk density and reduced abrasion value. The study concluded that the shape of the RCA produced from the Los Angeles machine was rounder. The most effective way to enhance RCA characteristics was to crush it in a jaw crusher machine.

Al-Bayati & Ismael [38] investigated the Marshall properties of the asphalt mixtures containing RCA treated by the Los Angeles machine. The process included putting the crushed RCA in the Los Angeles machine with the balls for 500 cycles. The coarse aggregate gradation was retained on the sieve 12.5 and 9.5 mm treated by the Los Angeles machine, while the remaining 4 mm remained untreated. Compared to mixtures containing untreated RCA, the study findings revealed a reduction in optimum asphalt content. Because the aggregate used in Portland cement concrete was rounded in shape, the results showed a decrease in the Marshall stability and the voids in mineral aggregate of asphalt mixtures containing mechanically treated RCA compared with mixtures containing untreated RCA. At the same time, the bulk density and flow demonstrated an increase. However, asphalt mixtures containing mechanically treated RCA demonstrated greater Marshall stability than control mixtures because the mortar firmly adhered to the granule surface, making it rough, which enhanced the adhesion between the aggregate and the asphalt. Figure 2 shows the untreated and mechanically treated RCA.

(a) Untreated RCA (b) Mechanically treated RCA

Figure 2. The untreated and mechanically treated RCA [38]

Bastidas-Martínez et al. [39] investigated the resistance to moisture damage of the asphalt mixtures containing treated RCA by several cycles (50, 100, and 200) in the Los Angeles machine with the ten balls. The study showed that it was advantageous to treat RCA in the Los Angeles machine; adhered mortar was reduced significantly by mechanical treatment. Moisture damage resistance was assessed using the indirect tensile strength parameter and tensile strength ratio, which showed an increase. Table 2 shows the summary of the findings of the mechanical treatment method.

Table 2. Summary of mechanical treatment findings

Reference	Type of mechanical treatment	Test	Findings compared with untreated RCA
Eldeen et al. [33]	Los Angeles machine	Aggregate properties used in asphalt mixtures	Discernible increase in bulk density and a reduction in abrasion value
	Re-grinding in a jaw-crushing machine	Aggregate properties used in asphalt mixtures	Discernible increase in bulk density and a reduction in abrasion value
Albayati & Ismael [38]	Los Angeles machine	Marshall properties and volumetric characteristics	Reduction in optimum asphalt content, Marshall stability, and voids in mineral aggregate Increase in bulk density
Bastidas-Martínez et al. [39]	Several cycles (50, 100, and 200) in the Los Angeles machine with the ten balls	Resistance to moisture damage	Increase

2.3. Treatment by Coating

Because RCA comprises pore-filled cement mortar, it absorbs water greatly and causes stripping that negatively affects durability when combined with asphalt mixtures, resulting in low resistance to water damage [40]. Furthermore, the formation of cracks in RCA due to concrete fragment breaking impairs its structure and strength under substantial loads [41].

Kanoungo et al. [31] investigated the Marshall characteristics and moisture damage of asphalt mixtures containing treated RCA by bitumen emulsion coating. This treatment is intended to reduce the amount of water absorbed by sealing the pores on the RCA surface. The study's findings revealed that Marshall's stability value increased dramatically. Because the pores of RCA are filled with emulsion, the application of bituminous emulsion enhances the connection between the aggregate and the binder, further increasing the compacted density of the mix. The RCA's resistance to moisture damage rose while its water absorption dramatically dropped.

Pasandín & Pérez [42] studied the addition between treated RCA by 5% bitumen emulsion (slow-setting cationic) and binder depending on two test methods: the rolling bottle method and the Texas boiling water test. The study concluded that coating RCA with bitumen emulsion promotes effective adherence. In this instance, the bitumen emulsion may also obstruct pores. Additionally, the bitumen emulsion that covers the RCA's surface can increase the RCA's chemical affinity for bitumen, enhancing its resistance to moisture damage.

Lee et al. [43] investigated the moisture damage and rutting performance of asphalt mixtures containing treated RCA with cement slag paste. The treatment method included several thicknesses of coating: 0.25, 0.45, and 0.65 mm. The outcome demonstrates that the pre-coating RCA with a 0.25 mm coating thickness has the ideal coating paste for the HMA combination. The tensile strength ratio assessed the moisture damage, and the outcomes showed that all mixtures satisfied the minimum requirement of 70%, but the mixtures containing RCA showed a reduction in the tensile strength ratio when the RCA contents increased. The wheel tracking test showed that all RCA mixtures had greater rutting resistance than the control mixture. Figure 3 shows the characteristics of pre-coated RCA with asphalt binder.

Kareem et al. [44] investigated the resistance to water damage of hot mix asphalt containing coated-treated RCA. The treatment methods involved coating the RCA with cement slag paste mixed with the superplasticiser Sikament NN, and the other one, termed double coating, involved coating the RCA with a double layer. The first was to coat the RCA with a thin layer of cement slag paste, and the second was two coats of Sika Tite-BE. The study concluded that the mixtures containing RCA treated by cement slag paste have a higher optimal asphalt content and lower stability than mixtures containing untreated RCA. In contrast, the mixtures containing double coating treatment demonstrated a lower optimal asphalt content and higher stability than mixtures containing untreated RCA, but it was costly. Figure 4 shows the untreated and coating-treated RCA.

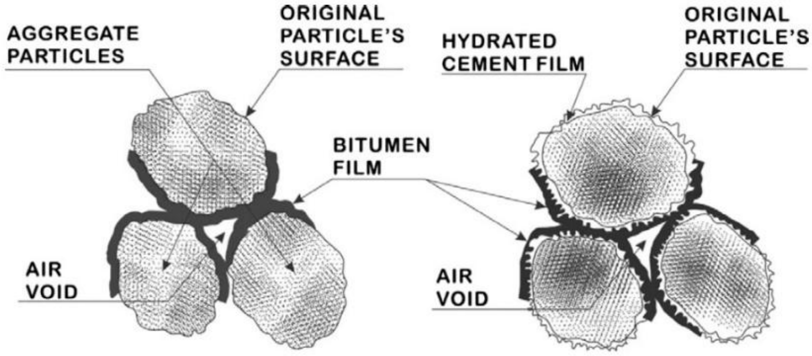
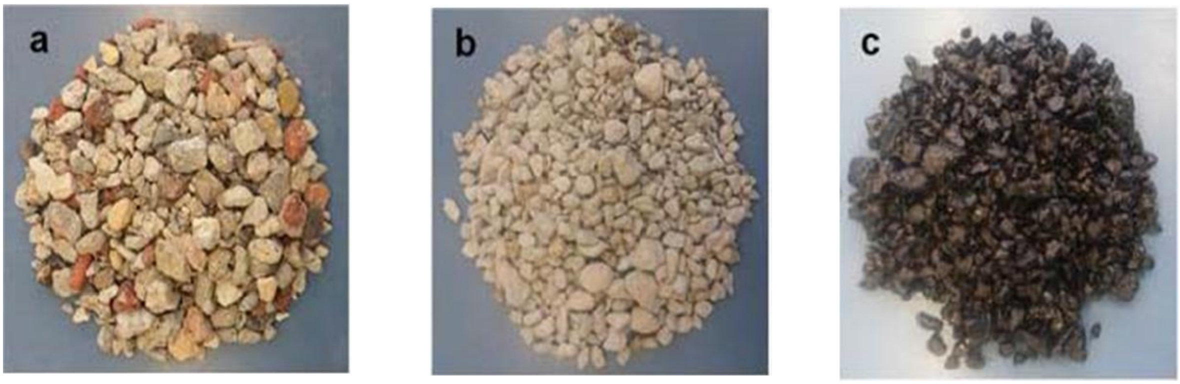


Figure 3. The characteristics of pre-coated RCA with asphalt binder [43]



(a) Untreated RCA (b) RCA coated by cement slag paste (c) Double-coated RCA

Figure 4. Treated and untreated RCA [44]

Ma et al. [45] applied an RCA treatment with waste cooking oil and investigated the permanent deformation, moisture damage, and fatigue cracking of asphalt mixtures containing 40% coarse-treated and untreated RCA. The treatment process was to mix the heated RCA for 1 hour at 160 ˚C with 2% waste cooking oils (by the total mass of the RCA) for 90 seconds inside a mixing pot. The results demonstrated lower resistance to permanent deformation in mixtures containing treated RCA than those with untreated RCA, as assessed by dynamic stability. Regarding moisture damage, the results also showed lower resistance to water damage in mixtures containing treated RCA compared with mixtures containing untreated RCA that were assessed by tensile strength ratio. Fatigue life is the total number of load cycles at which a failure happens. The results showed the three stress ratios of 0.3, 0.4, and 0.5 increase in fatigue life of mixtures containing treated RCA compared with untreated RCA counterparts.

Azarhoosh & Moghadas [46] assessed the fatigue life of asphalt mixtures containing untreated and treated RCA from plastic bottle waste in dry and wet conditions. After combining CRCA and WPB at a weight ratio of 5%, the treatment method concluded that the mixture was heated up for two hours at 250–260 °C. The study concluded that adding coarse RCA to hot-mix asphalts reduces their fatigue life, while applying plastic bottle waste enhances their functionality.

Giri et al. [47] investigated the potential usage of RCA, which has been treated with several pretreatment methods by low-viscosity bitumens, asphalt emulsions, and asphalt emulsions combined with oils and water. Several experiments revealed that the most effective RCA pretreatment was an 8% solution of total RCA weight, consisting of 40% medium-setting asphalt emulsion and 60% water. The study concluded that all mixtures containing treated and untreated RCA meet the standard of Marshall characteristics, and there are improvements in Marshall stability, moisture susceptibility resistance, and rutting resistance for mixtures containing treated RCA compared with mixtures containing untreated RCA. Figure 5 shows the treated and untreated RCA. Table 3 shows a summary of the findings of the coating treatment method.

(a) Untreated RCA (b) Treated RCA

Figure 5. Treated and untreated RCA [47]

Table 3. Summary of the coating treatment findings

Reference	Type of coating treatment	Test	Findings compared with untreated RCA
Kanoungo et al. [31]	Coating by bitumen emulsion	Marshall properties and volumetric characteristics	Reduction in Marshall stability, flow, OAC, and air voids
		Moisture damage resistance	Increase in retained stability index.
Pasandín & Pérez [42]	5% bitumen emulsion coating	Moisture damage resistance	increase
Lee et al. [43]	Coating by cement slag paste	Moisture damage	Decrease
		rutting performance	increase
Kareem et al. [44]	Coating cement slag paste	Bitumen absorption	Increase
		Marshall stability	Decrease
	Double coating bu cement slag and Sika Tite-BE	Bitumen absorption	Decrease
		Marshall stability	Increase
Ma et al. [45]	Coating by waste cooking oil	Rutting performance	Decrease
		Moisture damage resistance	Decrease
		Fatigue life	Increase
Azarhoosh & Moghadas [46]	Coating by plastic bottle waste	Fatigue life	increase
Giri et al. [47]	8% by RCA total weight of Medium-setting asphalt emulsion and water	Marshall stability	Increase
		Moisture damage resistance	Increase
		Rutting resistance	Increase

2.4. Composite Method

With the several methods for effectively taking the paste out of the RCA, a combination of two or more improvement techniques was developed [48, 49].

Lei et al. [32] investigated the performance of permeable asphalt concrete containing RCA treated with double treatments. The first was to double-treat the RCA by soaking it in acetic acid to remove unnecessary mortar and sodium silicate to fill the cracks and pores in the RCA. The second double treatment was to create a hydrophobic film on the RCA surface by immersing it in polyvinyl alcohol and strengthening the adhesion between aggregate and asphalt by packaging it in the cement slurry. The third double treatment was to fill the cracks and pores by soaking in a slag powder solution, improving the adhesion between aggregate and asphalt binder, and creating a hydrophobic surface by immersing in a silane coupling agent. The moisture damage was assessed by Marshall residual stability, and the results showed an enhancement in moisture damage resistance for the three methods. Regarding the permanent deformation resistance assessed by dynamic stability, the results showed a significant improvement in permanent deformation resistance for the three methods.

Al-Bayati & Ismael [38] investigated the Marshall properties of asphalt mixtures manufactured from treated coarse RCA with acetic acid. The process included immersing the coarse RCA in acetic acid at a concentration of 0.1 M for 24 hours, followed by immersion in water for 24 hours. The final part of this process was putting the RCA in the Los Angeles machine for 3 minutes without the balls to remove the acid-affected, weakened cement mortar. After that, the RCA was sieved, washed, and dried to achieve the required gradation and preparation for work. The study concluded no difference in the Marshall properties between the mixtures containing treated and untreated RCA.

Al-Bayati & Tighe [50] investigated the low-temperature thermal crack of asphalt mixtures containing treated RCA by combining methods to improve mechanical properties. The treatment process included placing the RCA in the oven at 300 ˚C for one hour and then applying a short time of mechanical treatment by the Micro-Deval apparatus for 15 minutes with the metal balls. After extracting the RCA sample, it was sieved and prepared for work. The study showed that the average fracture temperature was significantly lowered when a combination of treatments was applied to the RCA.

Al-Bayati et al. [51] investigated the volumetric properties of asphalt mixtures containing treated RCA using three treatment methods. The treatment method included immersing the RCA in a low concentration of acetic acid for twenty-four hours. After that, over an hour later, the CRCA samples were heated in a conventional electric oven at 300 ˚C. Finally, the treated samples from both methods were subjected to the action of steel balls for 15 minutes in the Micro-Deval equipment. The study concluded that utilising the treated RCA in asphalt mixtures that have undergone various treatment techniques was better than those that have not, and there were financial advantages, suggesting that these treatments might be beneficial.

Al-Bayati & Tighe [52] investigated the rutting performance of asphalt mixtures containing treated

RCA obtained from two sources using two combination treatment methods. The first combines pre-soaking in acetic acid 0.1 M for 24 hours and mechanical treatment with a Micro-Deval apparatus for 15 minutes with balls. The second combines the heat inside the oven at 300 ˚C and mechanical treatment by the Micro-Deval apparatus for 15 minutes with balls. The study showed that the mixtures containing treated RCA with the two treatment methods had rutting depths greater than those of their counterparts containing un-treated RCA. Also, the asphalt mixtures containing RCA from two suppliers, which had been treated using the same method, showed differences in their rutting resistance.

The characteristics of an asphalt mixture that includes demolition waste from earthquake-damaged constructions were explored by Zhu et al. [53]. Liquid silicone resin was utilised as a pretreatment for the recycled concrete aggregate. Coarse RCA was submerged in liquid silicone resin for an hour. To complete the pretreatment technique, the RCA was then hardened for 24 hours at 60 °C in an oven. According to the study's findings, pretreatment of coarse RCA improves the material's adherence to asphalt as well as its superior penetrability, hydrophobicity, strength, absorption, and surface morphology. The moisture re-sistance was reduced when untreated RCA was used. These attributes are improved when treated RCA is substituted. At high temperatures, the treatment of RCA material has a negative effect on the asphalt mix-ture's permanent deformation resistance. Table 4 shows a summary of the findings of the composite treat-ment method.

Table 4. Summary of the Composite Treatment Method Findings

Reference	Type of treatment	Test	Findings compared with untreated RCA
Lei et al. [32]	Double by soaking in acetic acid and sodium silicate	Water damage resistance Permanent deformation resistance	Increase Increase
	Double by polyvinyl alcohol and cement slurry	Water damage resistance Permanent deformation resistance	Increase Increase
	Soaking in slag powder solution and silane coupling agent	Water damage resistance Permanent deformation resistance	Increase Increase
Albayati & Ismael [38]	Acetic acid flowed by mechanical (Los Angeles machine without balls)	Marshall properties and volumetric characteristics	No difference
Al-Bayati & Tighe [50]	Combination of heat and mechanical treatment	Low-temperature thermal crack	Lowered in average fracture temperature
Al-Bayati et al. [51]	Combination of pre-soaking and mechanical treatment	Marshall and volumetric properties	The volumetric properties of asphalt mix-tures containing treated RCA are better than those containing untreated RCA.
Al-Bayati & Tighe [52]	Combination of heat and mechanical treatment	Rutting depth	Increase
	Combination of pre-soaking and me-chanical treatment	Rutting depth	Increase
Zhu et al. [53]	Liquid silicone resin followed by heating	Moisture damage resistance Rutting resistance	Increase Decrease

2.5. Treatment by Heating

It is possible to apply either by heating recycled concrete aggregates at high temperatures or by heating the asphalt mixture for a long time at a constant temperature to ensure that the aggregate grains are covered with the asphalt.

Kanoungo et al. [31] investigated the Marshall properties and moisture damage of asphalt mixtures containing thermal-treated RCA. To produce the thermally treated RCA, it was heated to 350 °C for two hours in a muffle furnace, and then the RCAs were rubbed together. In mixtures containing thermal-treated RCA, the results showed a decrease in Marshall stability, flow, air voids, and voids filled with asphalt compared to mixtures containing untreated RCA. Regarding moisture damage, it was noted that there was an insignificant increase in retained stability (factor-dependent in moisture damage assessment).

Other researchers have taken a different approach to the heat-up treatment process, heating the asphalt mixture for an extended time prior to compaction to finish the RCA covering process by asphalt.

Pasandín et al. [54] left asphalt mixtures containing RCA inside the oven for four hours at mixing temperature before compaction to strengthen the resistance against water damage. The study demonstrated that the mixtures displayed excellent water damage resistance, higher than those made without curing time in the oven. Furthermore, the cured mixtures were stiffer than the uncured mixtures, indicating they were more resistant to permanent deformation. Table 5 shows a summary of the findings regarding heating treatment.

Table 5. Summary of the heating treatment findings

Reference	Type of treatment	Test	Findings compared with untreated RCA
Kanoungo et al. [31]	Heating RCA at 350 ˚C for 2 hours	Marshall and volumetric characteristics	Lowering in Marshall stability, flow, air voids, and voids filled with asphalt
		Moisture damage resistance	Increase
Pasandín et al. [54]	Heating of asphalt mixture for 4 hours	Moisture damage resistance	Increase
		Permanent deformation resistance	Increase

3. Conclusions

This review extensively discusses the treatment of recycled concrete aggregate (RCA) and its effects on asphalt mixture performance. The efficiency of asphalt mixtures is significantly influenced by the removal of cement mortar that remains attached to the aggregate particles. Additionally, the source and quality of concrete blocks used as substituted aggregates can impact the performance of these mixtures compared to virgin aggregates. Pre-soaking treatment is often deemed economically unfeasible due to the RCA's tendency to absorb large quantities of chemical solutions, which can be costly and time-consuming. Furthermore, treatment methods that involve coating the RCA with various materials depend heavily on the quality of the coating and its ability to adhere properly. One challenge is that during the high-temperature of processes in hot asphalt production plants, the coating materials can be scraped off due to stirring. Composite processing, which combines multiple treatment methods, is another option but tends to be costly and time-consuming. While sometimes effective, heating treatments can also increase production costs and contribute to environmental pollution by releasing more pollutants.

In contrast, mechanical treatment is often considered one of the most effective and feasible approaches, as it significantly reduces the amount of weak cement mortar. This treatment enhances the roughness of the aggregate surface—promoting better adhesion with asphalt—and allows the aggregate to regain its original shape, whether rounded or crushed. This property is advantageous because rounded aggregates can be effectively used in asphalt mixtures for applications that do not require crushed aggregates, such as thicker asphalt-stabilised layers. Consequently, this approach allows for substantially incorporating RCA, supporting sustainability in asphalt production.

4. Recommendations

Implementing mechanical treatment to improve the mechanical and physical characteristics of recycled concrete aggregates can potentially allow for the substantial replacement of virgin aggregates. This approach enhances the performance of the asphalt mixtures and enables the reuse of ground cement mortar as a filler, significantly contributing to sustainability efforts. Conducting thorough tests on asphalt mixtures containing mechanically treated recycled concrete aggregates, ideally sourced from various origins, is essential to validate these benefits further. This comprehensive testing will provide valuable insights into the effectiveness and reliability of these aggregates in practical applications.

Declaration of Competing Interest The authors declare that they have no known competing of interest.

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