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Effect of differently treated recycled concrete aggregates on Marshall properties and cost-benefit of asphalt mixtures

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Abstract

Marshall properties are one of the major requirements for designing hot asphalt mixtures. These properties need to be evaluated to make sure that asphalt pavement performs well over its service life. The evaluation of the Marshall properties of asphalt mixtures containing coarse recycled concrete aggregates (RCA) was the study's main target. RCA properties differ from virgin aggregate in the presence of cement mortar. To improve RCA properties, two methods were adopted. The first, termed pre-soak treatment, consisted of soaking RCA in acetic acid for 24 hours at a concentration of 0.1 M. The second one, termed mechanical treatment, involved placing RCA inside the Los Angeles machine with balls and running it for 500 cycles. RCA was incorporated into asphalt mixtures at percentages 20, 40, 60, 80, and 100% of coarse virgin aggregate. The results of the study showed that replacing virgin aggregate with RCA led to economic feasibility. Despite the amount of asphalt binder increasing as coarse RCA content increased, the characteristics of HMA were not significantly altered except for Marshall stability. The maximum increase in Marshall stability happened in the mixture containing 60% untreated RCA; it was 14.78% greater than the control mixture.

Keywords: Marshall stability, Recycled concrete aggregate, Asphalt mixture, Pre-soaked treatment, Mechanical treatment

1. Introduction

Every nation's road system is crucial for integrating cities and provinces. It is considered a measure of social, cultural, and economic advancement. Asphalt layers play a crucial role in protecting the road's structural integrity by transferring applied traffic loads to the lower or formation layers [1]. Most of Iraq's roads consist of asphalt pavement. Aggregate (coarse, fine, and filler) and asphalt binder are components of an asphalt concrete mixture [2]. The aggregate skeleton is suitable for carrying traffic loads, while the asphalt binder will flow under load. Asphalt pavement durability is related to the characteristics and performance of the asphalt binder [3]. The asphalt binder's primary role is to grip and retain aggregate particles in contact and prevent dislodging these particles by rolling tires. Asphalt cement is a crucial element of asphalt mixtures; there is no other alternative to adhere aggregate together to provide resistance in asphalt mixtures [4].

Air voids are also a basic property of asphalt mixtures, which form a complex composition with aggregate and asphalt binder. The majority of the asphalt mixture is made up of 5% asphalt cement and 95% aggregate [5].

Marshall properties can be divided into two categories: plastic flow resistance and volumetric properties, which are divided into two parts; the primary is directly related to the relative volume of the asphalt mixture ingredients, such as the size of aggregates and binder, as well as air voids. The second part refers to the asphalt mixture volumetric characteristics, which are total volume, volume in mineral aggregate, and voids filled with asphalt [6].

A sustainable activity does not cause any harm to the environment when carried out. It is imperative to evaluate the sustainability of construction projects to ensure that they do not damage the environment or contribute to the reduction of construction costs [7], [8].

As a result of population growth, urban development, and urbanization, many buildings and roads were constructed, which led to an increase in the demand for raw materials, which negatively impacted the environment [9]. However, there is another significant and hazardous factor influencing the environment, and that is the formation of construction waste, which necessitates large land areas for disposal and landfilling [10]. From an environmental perspective, recycled concrete aggregate can be used in asphalt mixtures instead of virgin natural aggregate to minimize landfill areas and protect soil and plants from harm [11].

Many investigations have already been carried out regarding the addition of recycled concrete aggregate to asphalt mixtures.

Al-Bayati et al. [12] studied the impact of treated (by pre-soaking and heating) and untreated RCA on hot mix asphalt's volumetric characteristics. The study showed an increase in RCA led to an increase in asphalt contents and a decrease in bulk density. There were some improvements in properties when treating RCA.

Kareem et al. [13] used a new technique for treating RCA with a double-coated treatment of RCA embedded in HMA. The first layer was cement slag paste, and the second one was sika Tite-BE. It was determined that this treatment resulted in less absorption and more contact between the aggregate and the asphalt binder.

Research by Bhusal et al. in 2011 [14] included replacing RCA ranging from 20 to 100% with a 20% increase from the coarse virgin aggregate. The results of increasing the amount of RCA led to an increase in the amount of asphalt and a decrease in VMA.

In 2020, Abass & Albayati [15] investigated the effect of the usability of treated and untreated RCA in warm mix asphalt. Two types of treatment were adopted: first, hydrated lime slurry. The second one was soaked in hydrochloric acid. They concluded that the treated RCA absorbed less asphalt cement than the untreated RCA.

This study mainly concentrated on the subject of waste disposal and recycling and highlighted the obvious fact that cement mortar affects aggregate properties. Therefore, various treatments of recycled concrete aggregate were applied to examine the accessibility of using this waste in HMA as well as how these treatments affect the volumetric properties of asphalt mixtures and are cost-effective.

The hypothesis that has been adopted was that the recycled concrete aggregate materials are brittle and highly absorbent due to cement mortar. Therefore, these characteristics render them unpreferred for use in asphalt mixtures that are subjected to repeated loads, because it may be crushing or grinding during compaction.

Many previous studies have been concerned with the use of several techniques to treat recycled concrete aggregates by coating or soaking them in different solutions. These treatments did not lead to strengthening the cement mortar but only reduced absorption, and this is considered a research gap. Therefore, in this study, a technique called mechanical treatment was utilized that led to the removal of large quantities of cement mortar adhering to the aggregate and investigating the alterations that have occurred.

2. Materials

The raw materials employed in the current task came from a variety of sources, including virgin aggregate (coarse and fine), recycled concrete aggregate, asphalt cement (40–50 penetration grade), and filler (Portland cement).

2.1. Asphalt cement

A.C. (40–50) penetration grade asphalt, which was provided by an asphalt plant located in the Salman Pak district on the outskirts of Baghdad. The primary supplier of asphalt cement was the Dourah refinery in Baghdad. Table 1 displays the physical properties of the asphalt binder.

Table 1. Test results of the asphalt cement (40-50)

Test	Result	SCRB Requirements
Penetration (25˚C ,100gm, 5 sec), 1/10 mm	43	40-50
Ductility (25 °C, 5 cm/min), cm	167	≥ 100
Flashpoint (Cleveland open cup), ºC	>232	232 Min
Residue from thin film oven test.		
-Retained penetration, % of original, %	77	>55
-Ductility (25˚C, 5 cm/min), cm	92	>25

2.2. Aggregates

Both coarse and fine virgin crushed aggregate were supplied by the Salman Pak asphalt plant. The primary source of the aggregate was the Al-Nebaie quarry.

In the present study, ordinary Portland cement was used as a filler material. It was gained from the main mixing plant in the Saydih neighborhood, south of Baghdad.

According to the SCRB R/9 2003 Iraqi standard, wearing course type IIIA, the mid-range of aggregate gradation was selected. 12.5 mm was the nominal aggregate size allowed. Figure 1 displays the grain size distribution.

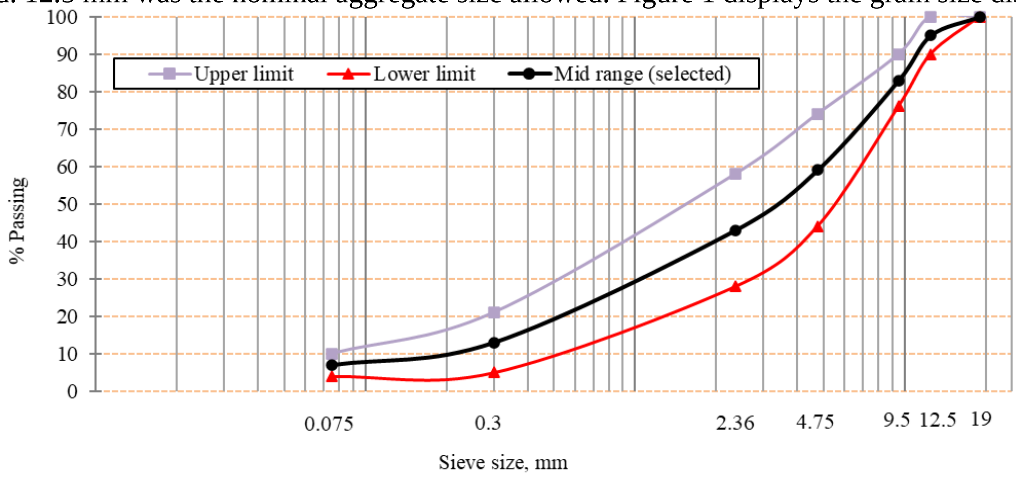

Figure 1. Grain size distribution

2.3. Recycled concrete aggregates

RCA was made by collecting small fragments resulting from crushing the crumbling New Jersey barrier. It was then sieved and separated into the required coarse gradation according to wearing course type IIIA of the SCRB R/9 2003 Iraqi standard. Three operations were performed on RCA after crushing and sieving; the first was termed untreated. The two others were treated to enhance RCA characteristics by removing the improperly attached mortar.

2.3.1. Untreated (URCA)

In this process, the RCA just washed and dried in the oven for 24 hours at a temperature of 110 °C.

2.3.2. Mechanical treatment (MTRCA)

Gradation of coarse aggregate according to wearing course type III of the SCRB R/9 2003 Iraqi standard consists of three sizes, retained on sieve sizes 12.5, 9.5 mm, and No 4. Mechanical treatment (MTRCA) involved placing untreated RCA that was retained on sieves 12.5, and 9.5 mm only in the Los Angeles machine with the balls for 16 minutes, equivalent to 500 cycles, to get rid of mortar adhering to the aggregate. Meanwhile, the retained-on sieve No. 4 has not been treated. After extracting RCA from the device, it was sieved, and the grains outside the gradient limit were neglected.

2.3.3. Pre-soaking treatment (PTRCA)

The second treatment (PTRCA) involved submerging RCA (all sizes) in 0.1 M (concentrated) acetic acid for 24 hours as part of the procedure. The RCA was drained and submerged in distilled water for a whole day, after which it was dried and put in the Los Angeles machine without the balls for 3 minutes (100 cycles) in order to remove the improperly adhered mortar as a result of the soaking. Table 2 displays the physical properties of virgin and recycled aggregate. Figure 2 displays virgin, untreated, and mechanically treated RCA.

Table 2. Physical properties of virgin and recycled aggregate

Test	Untreated	Pre-soaked treated	Mechanically-treated	Virgin coarse agg.	Virgin fine agg.	SCRB requirements
Bulk Specific Gravity, gm/cm^3	2.32	2.333	2.35	2.55	2.58	-
Water absorption, %	2.94	2.89	2.14	0.45	0.83	-
Abrasion by Los – Angeles, % loss	22	21	-	13	-	30 % (Max)

(a) (b) (c)

Figure 2. (a) Virgin coarse aggregate, (b) Untreated RCA, (c) Mechanically treated RCA

3. Experiment methodology

The experiment methodology included the Marshall test for asphalt mix design to identify the optimal asphalt content and volumetric properties.

3.1. Marshall test

The standard Marshall design method, according to ASTM D6926, was carried out for a mixture containing untreated RCA and treated RCA (20, 40, 60, 80, and 100%). Asphalt contents of 4–6% with an increment of 0.5% were adopted according to wearing course type IIIA of the SCRB R/9 2003 Iraqi standard. For each percentage of asphalt cement, three (4×2.5-inch) cylindrical specimens weighing 1200 gm were manufactured and compacted by 75 blows for each face. Following that, the bulk specific gravity was identified according to ASTM D-2726. The theoretical maximum specific gravity and density are identified according to ASTM D-2041. Resistance to plastic flow was determined according to ASTM D-6927. Figure 3 shows the Marshall specimen prepared and tested.

Figure 3. Marshall specimen prepared and tested sequences

4. Results and discussion

4.1. Marshall test results

Table 3 displays the SCRB 2003 specification requirements for the wearing course type IIIA. Marshall test results for mixtures that included different amounts of treated and untreated RCA are shown in Table 4 and Figures 4 to 8. Upon comparing the results summarized in Table 4, all these results met the specifications.

Table 3. SCRB Specification limits for wearing course Type IIIA [16]

Property	SCRB Limits for wearing course Type IIIA
Resistance to plastic flow: Marshall Stability, kN Marshall Flow, mm	8 min 2-4
Voids in Marshall specimen (VTM), %	3 - 5
Voids in mineral aggregate (VMA), %	14 min
Asphalt Cement (by total weight of Mix), %	4 - 6

Table 4. Marshall test results

Treatment	RCA, %	O.A.C, %	Stability, kN	Flow, mm	Bulk density, gm/cm^3	VMA, %	VFA, %
Control	0	4.93	11.03	3.3	2.325	14.97	74.46
URCA	20	5	11.8	3.38	2.304	15.09	73.85
URCA	40	5.08	12.43	3.45	2.285	15.2	74.22
URCA	60	5.17	12.66	3.57	2.271	15.11	73.96
URCA	80	5.27	12.27	3.64	2.258	15.07	73.2
URCA	100	5.45	11.95	3.8	2.244	15.06	73.92
PTRCA	20	4.98	11.52	3.43	2.307	15.04	73.64
PTRCA	40	5.02	12.04	3.51	2.289	15.1	73.23
PTRCA	60	5.13	12.3	3.63	2.274	15.09	73.9
PTRCA	80	5.23	11.96	3.74	2.259	15.07	73.85
PTRCA	100	5.4	11.79	3.89	2.246	15.05	73.46
MTRCA	20	4.96	11.27	3.55	2.312	14.88	74.33
MTRCA	40	5	11.6	3.68	2.299	14.78	73.32
MTRCA	60	5.1	11.87	3.77	2.285	14.74	73.64
MTRCA	80	5.19	11.54	3.84	2.273	14.69	73.08
MTRCA	100	5.34	11.3	3.98	2.263	14.6	73.59

Figure 4 displays that the optimal asphalt contents of all the mixtures containing recycled concrete aggregate are higher than the optimal asphalt content of the reference mixture. This may be because the cement mortar adhering to the aggregate had absorbed some of the asphalt cement through its pores. It is also possible to observe that mixtures containing treated RCA have a lower asphalt content than mixtures containing untreated RCA due to the loss of cement mortar after treatment.

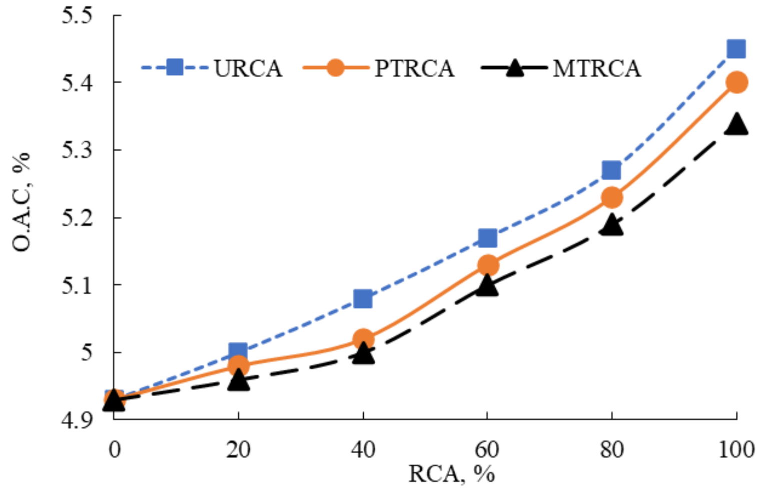

Figure 4. Effect of RCA on O.A.C

Figure 5 displays the impact of RCA on the bulk density of asphalt mixtures. With an increase in the RCA quantities in comparison to the reference mixture, the bulk density dropped for all RCA-containing mixtures. The bulk density of the recycled concrete aggregate was lower than that of virgin aggregate as a result of the cement mortar's adhering to the aggregate, which had a lower density than the aggregate. The outcomes are consistent with Mikhailenko et al., 2020 [17]; Abass & Albayati, 2020 [15]; Motter et al., 2015 [18].

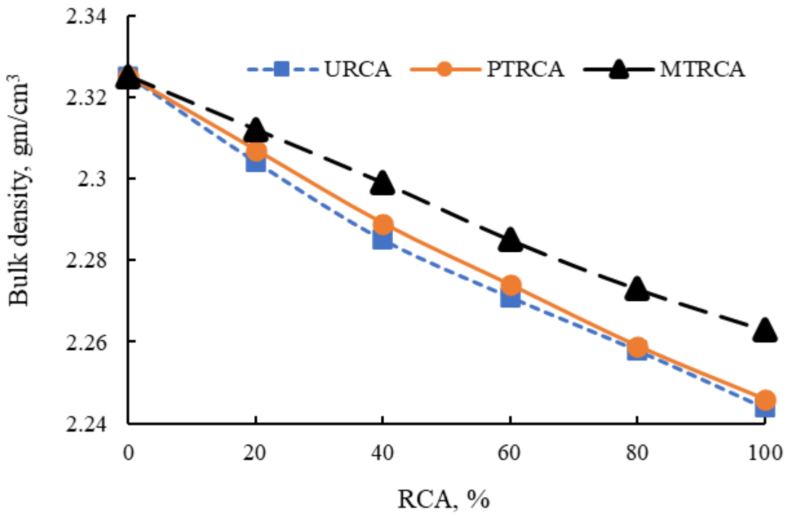

Figure 5. Effect of RCA on Bulk Density

Figure 6 displays the effect of RCA on VMA. All mixtures containing untreated and pre-soaked treated RCA recorded an increase in VMA; this may be due to the roughness of the RCA. The increase started in the mixture containing 20% RCA and reached its maximum in the mixture containing 60% RCA. In the mixtures containing 80 and 100% RCA, the amount of increase decreased, but it remained higher than the reference mixture. It might be a result of some cement mortar of RCA crushing or grinding, which led to the loss of its sharp edges, which makes it simple for the granules to slide and get close to one another during compaction.

While all mixtures containing mechanically treated aggregate recorded a decrease in VMA, it could be due to the gravel used in the cement concrete, which was rounded, and this treatment led to the loss of all or most of the cement mortar, which led to easy sliding of the granules close to one another during compaction. The outcomes are consistent with Daquan et al., 2018 [19]; Cantero-Durango et al., 2023 [20]; Tahmoorian et al., 2022 [21]; Bhusal & Wen, 2011 [14].

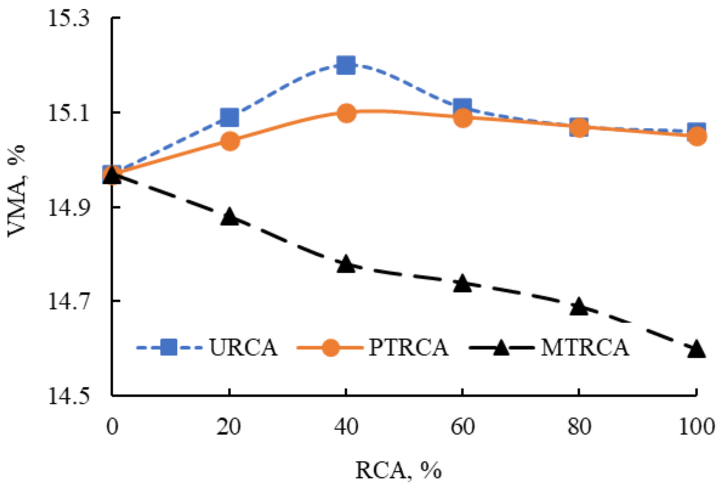

Figure 6. Effect of RCA on VMA

Figure 7 displays the effect of RCA on Marshall stability (maximum load when the specimen fails at a temperature of 60 ˚C). It recorded all mixtures containing untreated and pre-soaked RCA with higher stability than the reference mixture. RCA probably contains more fracture faces than virgin aggregate, which increases the contact area between the aggregate grains, as well as the RCA surface roughness, which leads to more adhesion between aggregate particles. The maximum increase was recorded at 60% RCA, and this increase declined at 80 and 100% RCA. It may be due to the crushing or grinding of some cement mortar, which led to the loss of part of the contact area with the release of some asphalt, which played a negative role in stability. The mixtures containing mechanically treated RCA also recorded higher stability than the control mixture but less than the other two (untreated and pre-soaked treated). It might be due to the roughness of the aggregate surface resulting from the mortar residues, which firmly adhered to the aggregate surface. The maximum increase was reached when 60% of mechanically treated RCA had been added. The increase declined when 80 and 100% of mechanically treated RCA were replaced. It might be due to an increase in the percentage of rounded gravel, which played a negative role in stability. The outcomes are consistent with El-Tahan et al., 2018 [22]; Radević et al., 2020 [23]; Pasandín & Pérez, 2020 [24]; Acosta Alvarez et al., 2019 [25]; Fatemi & Imaninasab, 2016 [26].

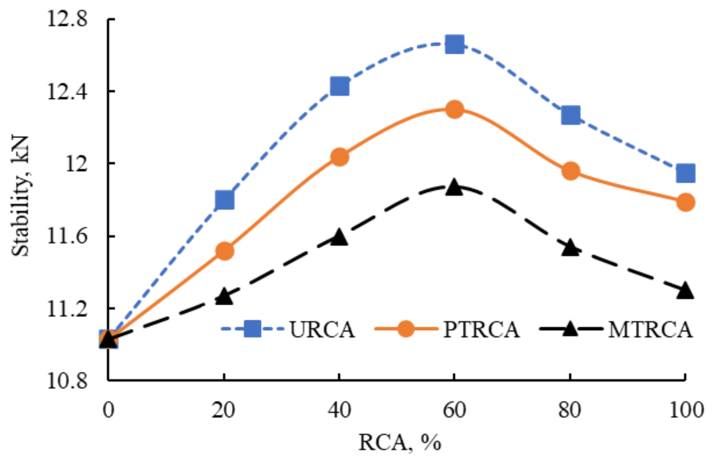

Figure 7. Effect of RCA on Marshall Stability

Figure 8 displays the effect of RCA on flow. All mixtures containing RCA recorded an increase in flow compared to the reference mixture e. It might be because of the asphalt content. The outcomes are consistent with Razzaq, 2016 [27]; Kareem et al., 2020 [28]; Bhusal & Wen, 2013 [29]; Kareem et al., 2019 [30]. The

Marshall quotient is the plastic stiffness index. It is measured by dividing stability by flow [31]. It gives an idea of how resistant a mixture is to permanent deformation [32].

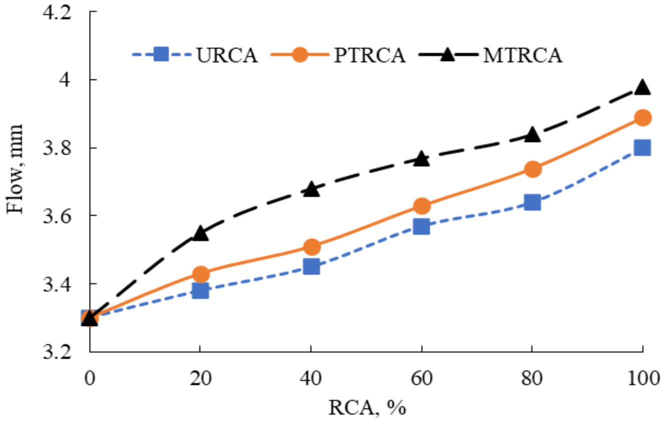

Figure 8. Effect of RCA on Flow

Figure 9 displays the relationship between the RCA and Marshall quotients. The mixtures containing 20–80% untreated and 20–60% pre-soaked treated RCA recorded a higher Marshall quotient than the control mixtures. However, these mixtures had higher asphalt contents than the control mixture. This suggests that at higher temperatures, the absorbed asphalt can have a big impact [29].

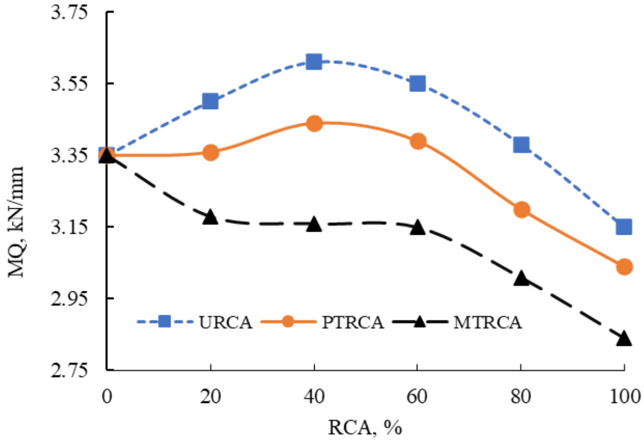

Figure 9. Relationship between RCA & Marshall quotient

5. Statistical analysis

One of the most common computer applications that can be adopted in the field of statistical analysis is the SPSS program. The main objective of the statistical analysis of Marshall's stability is to investigate whether treatments have an impact on test results and whether statistically significant differences occur. To determine the sources of the difference, post hoc or multiple comparisons must be conducted with a sig value of 0.05. By using SPSS V27, the results are summarized in Table 5. It showed there are differences between the control and the other mixtures containing different amounts of treated or untreated RCA. The difference is not statistically significant between untreated and pre-soaked treated RCA. The difference is statistically significant between untreated and mechanically treated RCA, whereas the difference is not statistically significant between pre-soaked and mechanically treated RCA.

Table 5. Multiple comparison test results

Treatment (I)	Treatment (J)	Mean Difference (I-J)	Sig.
Control	URCA	-1.738	< 0.001
Control	PTRCA	-1.377	< 0.001
Control	MTRCA	-1.056	0.011

Treatment (I)	Treatment (J)	Mean Difference (I-J)	Sig.
URCA	PTRCA	0.360	0.254
URCA	MTRCA	0.682	0.003
PTRCA	MTRCA	0.321	0.354

6. Cost analysis

A cost analysis is performed to determine whether it can be implemented practically or not by calculating and evaluating benefits and revenues with economic costs. The benefits were determined based on the cost difference between virgin aggregate and recycled aggregate, which adopted a value of 8.3 $ per ton of RCA. The costs were calculated based on the difference in the additional asphalt cement that was determined according to the Marshall method.

Equations (1) and (2) illustrate the benefits and costs of 1-ton asphalt concrete.

Benefit = % Agg.× 0.42(% C.Agg in Mix)× % RCA × $8.3 (benefit of 1 ton RCA) (1)

Where:

%Agg = % of total aggregates (100 - O.A.C)

Cost= % of the difference in O.A.C × $315 (cost of 1-ton asphalt cement in Iraq) (2)

Table 6 displays the result of the benefit-cost analysis. All values of the benefit-cost analysis are greater than zero. Thus, there is economic feasibility in using recycled concrete aggregate instead of virgin aggregate.

Table 6. Benefit-cost analysis results

Treatment	RCA, %	O.A.C, %	Difference in O.A.C	Aggregate, %	Benefit, $/ton	Cost, $/ton	Benefit-cost, per 1 ton asphalt concrete
Control	0	4.93	-	95.07	-	-	-
URCA	20	5	0.07	95	0.67	0.23	0.44
URCA	40	5.08	0.15	94.92	1.33	0.48	0.85
URCA	60	5.17	0.24	94.83	1.99	0.76	1.23
URCA	80	5.27	0.34	94.73	2.65	1.08	1.57
URCA	100	5.45	0.52	94.55	3.3	1.64	1.66
PTRCA	20	4.98	0.05	95.02	0.67	0.16	0.51
PTRCA	40	5.02	0.09	94.98	1.33	0.29	1.04
PTRCA	60	5.13	0.2	94.87	1.99	0.64	1.35
PTRCA	80	5.23	0.3	94.77	2.65	0.95	1.7
PTRCA	100	5.4	0.47	94.6	3.3	1.49	1.81
MTRCA	20	4.96	0.03	95.04	0.67	0.1	0.57
MTRCA	40	5	0.07	95	1.33	0.23	1.1
MTRCA	60	5.1	0.17	94.9	1.99	0.54	1.45
MTRCA	80	5.19	0.26	94.81	2.65	0.82	1.83
MTRCA	100	5.34	0.41	94.66	3.3	1.3	2

7. Conclusions

The following crucial aspects can be added as a summary of this research based on the tests carried out, as well as the properties of the materials utilized that have been highlighted:

1. The investigation demonstrated the feasibility of utilizing recycled concrete aggregate in HMA due to its insignificant impact on the volumetric characteristics of these combinations.

2. The asphalt cement content was raised when RCA was replaced with virgin aggregate. The maximum rise was 10.55% over the reference mixture when 100% utilized untreated RCA instead of virgin aggregate.
3. Marshall stability increased with the continued addition of RCA to mixtures. The biggest increase occurred when 60% of untreated recycled concrete aggregate was replaced, which was 14.78% over the reference mixture.
4. The mixture containing 40% untreated RCA demonstrated the highest Marshall quotient and could have potential rut resistance.
5. The bulk density gradually declines as the RCA percentage in the asphalt mixture rises; the lowest value was seen when untreated RCA constituted 100% of the asphalt mixture; at that point, the bulk density was 3.5% lower than the reference mixture. This aspect adds another economic feasibility to the use of recycled concrete aggregates, as it is possible to use more quantity with less weight because the asphalt mixture is purchased by weight.
6. The process of replacing recycled concrete aggregate with virgin aggregate led to economic feasibility despite the increase in the quantities of asphalt cement required, as the maximum benefit value of $2 per ton of asphalt concrete when using 100% RCA treated by mechanical method.
7. The treatment process led to a reduction in the asphalt content compared to mixtures containing untreated RCA due to the diminished amount of mortar that attaches to the aggregate, which decreased absorption.
8. The mechanical treatment method led to a significant difference from the untreated process due to the loss of a large amount of adhering mortar. However, this treatment led to a slight increase in Marshall stability compared to the control mixture because the aggregates used in Portland cement concrete were rounded in shape which plays a negative role in Marshall stability. Therefore, this slight increase is due to the roughness of the surface of the recycled concrete aggregate resulting from the strong adhesion of cement mortar residues.
9. After using recycled concrete aggregates treated by the mechanical method, it can be concluded that the type and shape of aggregates used in Portland cement concrete play a major role in the properties and performance of asphalt mixtures when embedded as recycled concrete aggregate in asphalt mixtures.

8. Recommendations

In addition to the current work, it is necessary to examine the following topics:

1. Performing additional asphalt mixture tests such as rutting, moisture, fatigue, and low-temperature crack and wear tests if the mixture is utilized as a wearing course.
2. The properties of RCA vary depending on the amount of mortar adhering to the aggregate granules. As a result, it must be taken into account to simulate the reality of the asphalt concrete plant, where the aggregate is passed through the dryer with stirring and heat, resulting in the loss of a significant amount of adhering mortar and a change in the properties. Furthermore, the crushed cement mortar will blend with fine aggregate (sand) inside the dryer and cannot be separated. Therefore, mechanical processing is highly effective because of the loss of large quantities of cement mortar.
3. The mechanical method is expected to be very effective with asphalt layers that the standard does not require to be created with crushed aggregate because it is very likely that the aggregates used in Portland cement concrete will be round-shaped.
4. It should be noted that the mechanical method is very effective in producing recycled concrete aggregates resulting from dilapidated Portland cement concrete that has been attacked by sulfates during its service life.
5. It is essential to use caution when employing mixtures including 80 and 100% of untreated and pre-soaked treated recycled concrete aggregates since some recycled aggregate grains were ground on the specimen's surface when subjected to direct compaction.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author contribution

Nadheer Khaled Al-Bayati collected the data and wrote the article. Mohammed Qadir Ismael designed and observed the article.

Abbreviations

HMA	Hot mix asphalt
MQ	Marshall quotient
MTRCA	Mechanically treated recycled concrete aggregates
O.A.C	Optimum asphalt content
PTRCA	Pre-soaked recycled concrete aggregates
RCA	Recycled concrete aggregates
SCRB	State Corporation for Roads and Bridges
URCA	Untreated recycled concrete aggregates
VFA	Voids filled with asphalt
VMA	Voids in mineral aggregates

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