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Research Article

Influence of Carbon Fibers on the Rutting Susceptibility of Sustainable HMA Mixtures with Untreated Recycled Concrete Aggregates

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Abstract

This paper focuses on achieving sustainability to reduce the detrimental effect on the environment and the economic aspects by including several ratios of coarse recycled concrete aggregates (RCA) (25, 50, 75, and 100%) in asphalt mixtures. The methodology included testing all raw materials, the wheel tracking test to assess mechanical performance, and the Marshall design approach to determine the appropriate asphalt content. The outcomes demonstrated no discernible difference between the volumetric characteristics of the asphalt mixtures containing RCA and the control mix. Marshall's stability rose by 14.2% when 50% of the mixture contained RCA compared to the control combination. All combinations containing RCA were performed inferiorly to the control mixture regarding rutting. 19.63% was the greatest increase in rut depth for combinations made entirely of recycled concrete aggregate. Several percentages of 0.2, 0.25, and 0.3% carbon fibers(C. F.) were added to the total weight of the asphalt mixture to enhance rutting performance. Marshall's stability and resistance to rutting have significantly increased, attributable to the carbon fibers; nonetheless, the volumetric properties of the asphalt mixture have only slightly altered. The combinations with 0.3% carbon fiber reinforcement and 50% RCA showed the largest gain in Marshall stability, up 34.6% above the control mixture. The same combination had the strongest resistance to rutting, which was —39.08% higher than the control mixture.

1. Introduction

Increased population growth has resulted in a large increase in construction due to its necessity. There is a lot of gathered construction waste, which needs a lot of landfill area because construction waste is disposed of either by landfilling or recycling [1-3]. There are many materials in construction waste, but Portland cement concrete waste is one of the most significant. RCA could be utilized instead of virgin aggregate in asphaltic concrete mixtures to diminish landfill space and prevent soil and plant deterioration from an environmental standpoint [4-6].

On the other hand, as raw materials become more in demand, their prices rise, increasing the expense of producing asphalt concrete and harming the environment [7, 8]. Owing to the availability of ingredients for asphalt mixtures and the simplicity of manufacturing, asphaltic concrete forms most of Iraq's roads [9].

Therefore, from an economic point of view, it is necessary to use RCA in asphalt paving works to apply the sustainability approach. However, it is essential to construct asphalt roads that can withstand heavy traffic volumes and adverse environmental effects [10, 11].

RCA incorporates natural aggregate and mortar adhered to it [12]. The amount of cement mortar influences the qualities of this aggregate. As such, it is imperative to explore the properties of asphalt mixtures containing RCA [13]. Mechanical performance is one of the most essential aspects that should be considered while assessing asphalt mixtures. Rutting is the most significant drawback in asphalt pavement resulting from mechanically underperforming asphalt mixtures. It has been defined as a channel distortion form that develops along truck wheel routes on asphaltic pavements [14]. The components of asphalt mixtures have the biggest influence on rutting brought on by shear failure [15]. Rutting impacts road user safety since it impairs vehicle maneuverability, restricts visibility by scattering water collected in the groove due to the passage of tires, and is considered a contributing factor in accidents [16]. Other factors contributing to the formation of ruts are traffic loads and high temperatures in the summer [17, 18]. In Iraq, the summer season lasts six months and has high temperatures of 50 °C [19, 20]. Therefore, it is necessary to investigate and evaluate this distress.

This paper aimed to assess the influence of RCA on the volumetric properties and the performance of permanent deformation when replaced with different proportions of coarse virgin aggregate to produce an asphalt mixture for wearing coarse according to the Iraqi standard.

The scope of this study was the inspection of all raw materials according to the requirements of the Iraqi Standard for wearing course type IIIA, conducting a Marshal test of hybrid and control mixtures to identify volumetric properties and Optimum Asphalt Content(OAC) and compare them with the requirements of the Iraqi standard. Manufacture slabs with dimensions 300 × 400 × 50 mm to evaluate rutting performance.

This research hypothesis is that utilizing RCA in asphalt mixtures leads to their weakening to perform rutting when these mixtures are subjected to repeated loads at high temperatures because these aggregates are categorized as poor materials because they have high water absorbability and low resistance to abrasion and crushing [3]. These properties make asphalt mixtures perform poorly during their service life when exposed to repeated loads at high temperatures. Therefore, these mixtures need to be strengthened. In this research, carbon fiber was used as a reinforcement element.

The other hypothesis is that RCA absorbs additional quantities of asphalt cement, and this may have no economic feasibility due to the additional costs associated with the high asphalt contents.

2. Literature review

Researchers have been paying much attention to sustainable asphalt mixtures [21]. The behavior of hot asphalt mixtures containing 25, 35, 50, and 75% aggregate was studied by Mills-Beale [22]. In a summary of the study, rutting depth increased by 8.1, 37.85, and 76% for RCA between 25 and 35%, 35 and 50%, and 50 and 75%, respectively, compared to the control mixture. Nwakaire et al. [23] investigated the efficiency of asphalt mixtures for rutting resistance utilizing RCA. The study included 20, 40, 60, 80, and 100% replacement by coarse aggregate and 100% replacement with fine and coarse virgin aggregate. Study results showed that the mixtures containing 20% RCA demonstrated the highest level of rutting resistance, while the mixtures that included 40% RCA demonstrated the opposite response. The mixtures containing 60, 80, and 100% RCA demonstrated the same behavior as mixtures having 40% RCA. It also showed that the mixtures containing 100% fine and coarse RCA demonstrated the lowest resistance to permanent deformation. Gul & Guler [24] studied the addition of 25, 50, and 75% RCA with two grades: fine (High % passing) and coarse (low % passing). According to the investigation, all combinations were less resistant to persistent deformation than the control mixture.

Additionally, it demonstrated that when fine-grade RCA quantities in the mixes increased, permanent deformation resistance gradually decreased, and the converse happened for coarse-grade RCA. Fatemi & Imaninasab [25] investigated how well rutting performed for mixtures that included different proportions of building and demolition materials. The percentages were 10, 20, 30, and 40% of total aggregates. The study summarized that all combinations included RCA had higher friction properties than the control mix, but RCA was brittle; therefore, all combinations showed greater resistance to rutting than the control mix. The mixtures containing 30% RCA had the highest level of rutting resistance because the friction property overcomes the brittle one.

Radević, et al. [26] study, evaluated the potential application of RCA in asphalt mixes. Coarse, fines, and RCA with 15, 30, and 45% were utilized. The outcomes showed that increasing permanent deformation resistance by adding 30% coarse RCA also produced the same result when adding 30% fine RCA. Meanwhile, fine and coarse aggregate combinations result in a little permanent deformation resistance due to the higher asphalt cement content. Two types of RCA were tested by Bhusal & Wen [27]. The percentages were 20 to 100%, which increased by 20% when coarse RCA was substituted with virgin coarse aggregate. They found that increasing RCA resulted in the absorption of more asphalt binder and reduced the rutting performance of the asphalt mixture. The study's conclusions imply that asphalt cement absorbed at high temperatures may be highly significant. Shaopeng et al. [28] investigated how well asphalt mixtures containing waste demolition performed. Three types of mixes were manufactured. The first mixture involved replacing coarse aggregate with recycled aggregate. The second one involved replacing fine aggregate with recycled aggregate and the control mixture. The findings demonstrated that using coarse RCA can improve rutting resistance, while the opposite happens when using fine RCA.

Motter et al. [29] evaluated asphalt mixtures containing 25, 50, 75, and 100% coarse RCA. The results showed that mixtures that contained RCA had a higher asphalt content than the control mixture due to the higher absorption of RCA. It also showed increases in permanent deformation ranging from 4.4 to 9.3% over the control mixture.

Azarhoosh et al. [30] evaluated asphalt mixtures containing 15, 30, and 50% coarse recycled aggregate at two ambient temperatures of 40 and 60°C. They tried to enhance the recycled aggregate's properties by coating it with plastic bottle waste. The research results showed that using recycled concrete aggregates in asphalt mixtures weakens their resistance to rutting. Mixtures containing recycled concrete aggregates coated with plastic bottle waste material improved rutting resistance compared to their counterparts, which contained uncoated RCA but persisted weaker than the control mixture.

3. Materials

Coarse, fine, and filler obtained from the same source used in the research [3].

3.1. Asphalt cement

A penetration grade of 40–50 was used in this study. It is the common type used in asphalt paving in Iraq. Table 1 exhibits the asphalt cement's physical properties according to the R/9 Iraqi standard [31].

Table 1. Test results of the binder type (40-50)

Test	Test Method	Result	Requirements
Penetration, 0.1 mm	AASHTO -T49 [32]	44	40-50
Ductility, cm	AASHTO-T51 [33]	160	≥ 100
Flashpoint, ºC	AASHTO-T48 [34]	296	232 Min
Residue after thin film oven test	AASHTO-T179 [35]		
-Retained penetration, % of original, %		78	>55
-Ductility, cm		92	>25

3.2. Aggregates

Crushed aggregate was used for both fine and coarse gradients. Tables 2 and 3 exhibit the fine and coarse aggregate physical properties according to the Iraqi standard [31].

The middle range of aggregate gradation was selected according to the Iraqi standard for wearing course type IIIA gradation [31]. Figure 1 shows the particle size distribution.

Table 2. Test results of the fine aggregate [3].

Test	Test Method	Result	Requirements
Specific Gravity.	ASTM C128 [36]	2.58	-
% Water Absorption.	ASTM C128 [36]	0.83	-
Clay Lumps	ASTM C142 [37]	0%	3% Max

Table 3. Test results of the coarse aggregate [3].

Test	Test Method	Result	Requirements
Specific Gravity	ASTM C-127 [38]	2.55	-
% Water Absorption.	ASTM C-127 [38]	0.45	-
Abrasion by Los Angeles Machine	ASTM C-131 [39]	13	30% Max
Degree of Crushing	ASTM D-5821 [40]	92%	90%.

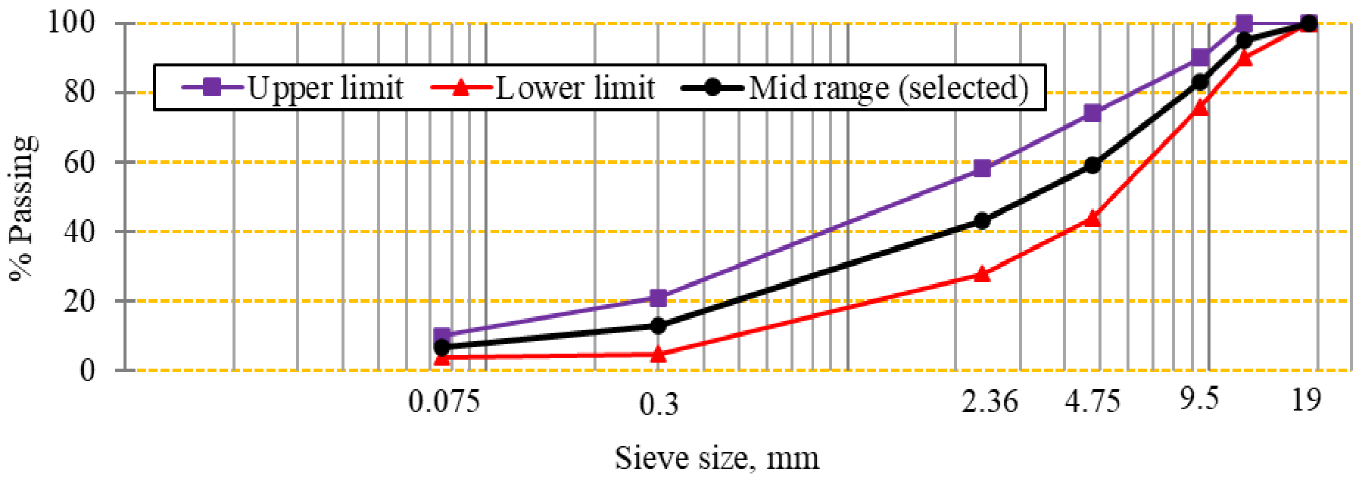

Figure 1. Particle size distribution [3].

3.3. Recycled Concrete Aggregates

It was produced by crushing cement concrete fragments from a minor demolition site. Cement concrete was crushed by a handy crusher (locally manufactured) and sieved and separated according to the Iraqi standard for wearing course type IIIA gradation. Table 4 exhibits the test results of recycled concrete aggregate. Figure 2 shows the crushed recycled concrete aggregates.

Table 4. Test results of the recycled concrete aggregate.

Test	Test Method	Result
Specific Gravity.	ASTM C127 [38]	2.30
% Water absorption.	ASTM C127 [38]	2.89
Abrasion by Los Angeles Machine.	ASTM C-131 [39]	21

Table 4 shows the abrasion value of less than 30% (Iraqi standard limit). Therefore, replacing 100% recycled concrete aggregate with coarse aggregate is possible.

3.4. Filler

Ordinary Portland cement was used as filler materials. Table 5 exhibits the test results of filler.

Figure 2. Recycled concrete aggregates

Table 5. Test results of the filler [3].

Test	Test Method	Result	Standard Requirement
Sieve Analysis. (%Passing)	ASTM C136 [41]		
No 30.		100	100
No 50.		100	95-100
No 200.		98	70-100
Specific gravity	ASTM C188 [42]	3.14	-

3.5. Carbon fibers

In this research, the Sika Wrap 300-C unidirectional woven type was used. The dry tensile strength reached 4000 MPa, and the dry density of 1.82 g/cm3. It works well with asphalt mixtures because of its high melting point and compatibility with asphalt [43, 44]. Figure 3 shows the carbon fibers used.

Figure 3. Carbon fibers

4. Methods

Two basic tests were conducted to complete this task.

4.1. Marshall Test

Following ASTM D6926 [45], the Marshall design approach determined the optimum asphalt contents for the control mixture and other mixes (Hybrid with 25, 50, 75, and 100% of RCA). Three standard specimens (101.6×63.5 mm) in size and weighing 1200gm were manufactured for each asphalt content range of 4 to 6%, with a 0.5% increment, following the Iraqi standard for wearing course type IIIA.

Various quantities (0.2, 0.25, and 0.3% with a constant length of 20 mm by the entire mix weight of carbon fibers) were added to all combinations containing 25, 50, 75, and 100% of RCA that contained optimum asphalt amount. Manually (by hand using a spatula and suitable bowl) blending was done using a dry mixing method, in which aggregates and carbon fibers were blended before the asphalt binder was added.

4.2. Wheel Tracking Test

One slab for each mixture had a size of 300×400×50 mm prepared and tested by the wheel-tracking device under 482 kPa wheel pressure and 55° C ambient temperature for 10000 cycles according to EN 12697-22 standard [46]. Figure 4 demonstrates prepared and tested specimens of Marshall and wheel tracking test.

Figure 4. Marshall and wheel tracking test

5. Results and Discussion

5.1. Marshall Test Results

The Marshall properties results of the control mixture and hybrid combinations are shown in Table 6 and Figures 5 to 9. All combinations have fulfilled the limits of the Iraqi standard for wearing course type IIIA when comparing the findings with those limits, as indicated in Table 7.

Table 6. Results of the Marshall test.

Mixtures RCA/C. F	O.A.C, %	Stability (kN)	Flow (mm)	Bulk density (g/cm^3)	VMA, %	VTM, %
Control	4.88	10.98	3.21	2.327	14.97	3.83
25/0	5.04	11.94	3.33	2.3	15.1	3.94
25/0.2		13.34	3.13	2.299	15.38	4.2
25/0.25		13.58	3.11	2.296	15.43	4.26
25/0.3		13.74	3.10	2.293	15.49	4.32
50/0	5.14	12.54	3.43	2.278	15.18	3.92
50/0.2		14.04	3.26	2.274	15.45	4.19
50/0.25		14.49	3.22	2.27	15.51	4.21
50/0.3		14.78	3.12	2.267	15.57	4.25
75/0	5.27	12.31	3.61	2.26	15.12	3.93
75/0.2		14.01	3.12	2.256	15.41	4.2
75/0.25		14.42	3.38	2.253	15.47	4.23
75/0.3		14.71	3.32	2.249	15.52	4.26
100/0	5.49	11.94	3.79	2.242	15.04	3.93
100/0.2		13.3	3.39	2.239	15.31	4.22
100/0.25		13.74	3.36	2.236	15.36	4.25
100/0.3		14.12	3.36	2.233	15.43	4.28

Table 7. Iraqi Specification limits for wearing course Type IIIA [31].

Property	Requirements
Marshall Stability, kN	Min 8
Marshall Flow, mm	2-4
(VTM), %	3 - 5
(VMA), %	Min 14
Asphalt Cement Content, %	4 - 6

Figure 5 demonstrates that the optimal asphalt contents of all combinations comprising RCA are greater than the optimal asphalt content of the control mixture. This could result from some of the cement mortar's pores absorbing some of the asphalt cement. The mixture containing 100% RCA showed the highest rise, measuring 12.5% higher than the control. The average bulk density, 4% air voids, and asphalt cement at maximum stability were used to determine the optimum asphalt content for each composition. The results obtained correspond with El-Tahan et al. [47], Acosta Alvarez et al. [48], Pasandín & Pérez [49].

As RCA has more crushed faces than virgin aggregates, Figure 6 shows that all RCA combinations had more stability than the control mixture. In mixes with 50% RCA, the maximum increase has been achieved. It was 14.2% higher than the control mixture. Although they were still greater than the control mixture, the mixtures containing 75 and 100% RCA showed less stability than those containing 50% RCA. This could be because some of the cement mortar was ground or crushed during compaction due to the brittleness of the cement mortar, which resulted in the loss of some particle contact areas. The results obtained correspond with those of Fatemi & Imaninasab [25], El-Tahan et al. [47], Acosta Alvarez et al. [48], Pasandín & Pérez [49], Radević et al. [50], Giri et al. [51]. They reported a growth event in the value of Marshall stability when adding RCA to the asphalt mixtures.

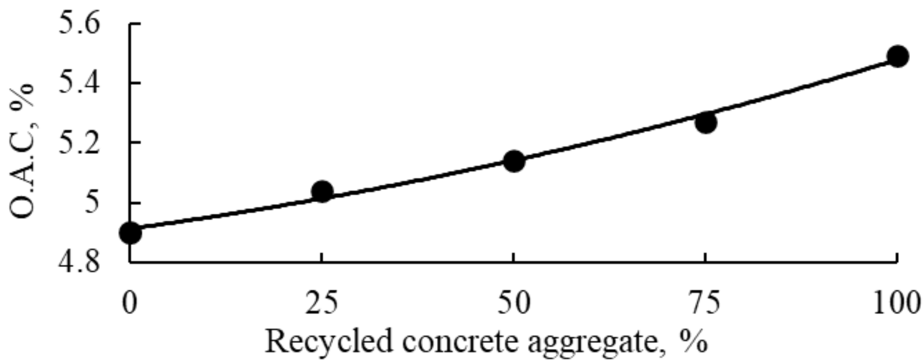

Figure 5. Relationship between RCA & OAC

An increase in Marshall stability was witnessed, as well as an increase in the carbon fiber contents of all mixtures. The mixture with 0.3% carbon fibers and 50% RCA satisfied the highest rise, outperforming the control mixture by 34.6%.

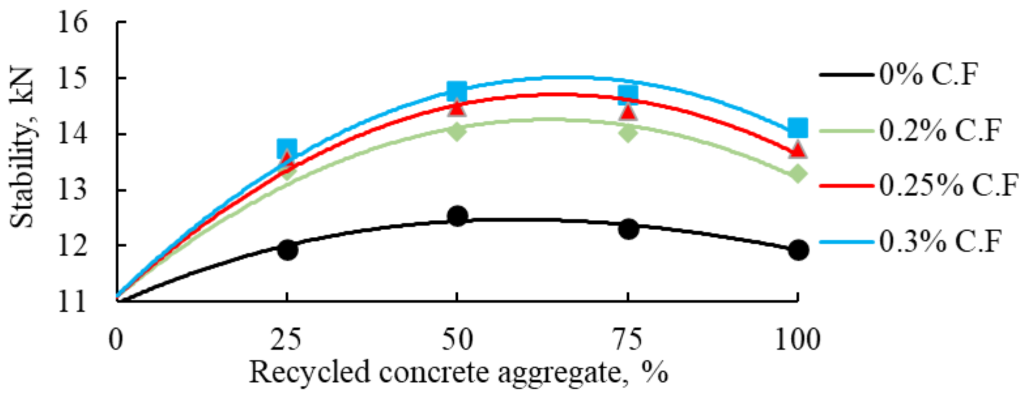

Figure 6. Influence of RCA & Carbon Fibers on Stability.

Figure 7 demonstrates that the gradual increase in the flow of all RCA mixtures might be due to the asphalt cement content. The results obtained correspond with Nwakaire et al. [23], Bhusal & Wen [27], Razzaq [52], Kareem et al. [53], and Kareem et al. [54]. They reported increased Marshall flow when adding RCA to the asphalt mixtures.

Adding carbon fibers decreased all mixtures' flow, which the mixtures' increased stiffness may have caused.

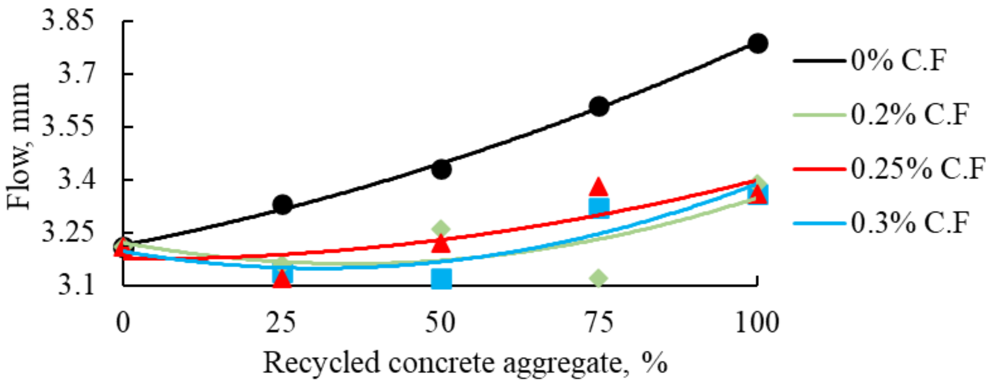

Figure 7. Influence of RCA & Carbon Fibers on Flow.

Figure 8 demonstrates a gradual decrease in the bulk density due to the increase in the percentage of mortar adhering to RCA. The results obtained correspond with Motter et al. [29], Giri et al. [49], Abass and Albayati [55], Mikhailenko et al. [56], and Hussein et al. [57]. They reported decreased bulk density when adding RCA to the asphalt mixtures.

The addition of carbon fibers caused a decrease in bulk density since carbon fibers occupied gaps inside the asphalt mixture between the aggregate grains. Carbon fibers filled these gaps with a lower weight than total aggregates in the same volume, which led to this decrease.

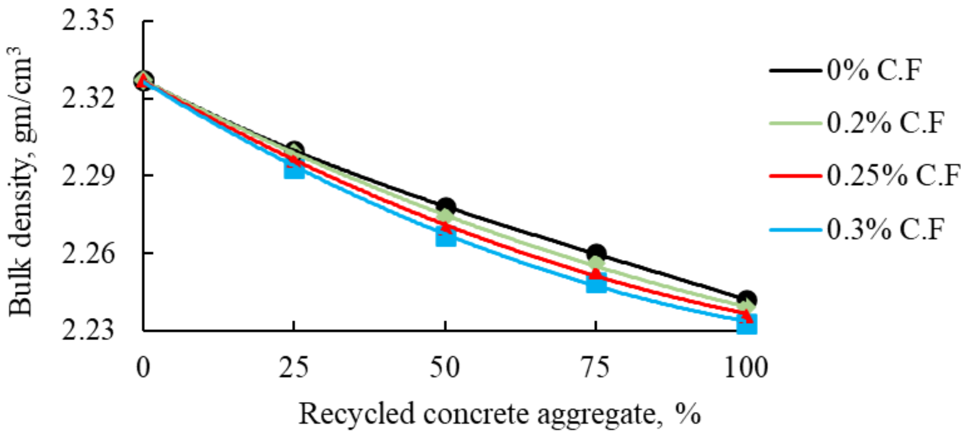

Figure 8. Influence of RCA & Carbon Fibers on Bulk Density.

Figure 9 demonstrates that all combinations had a larger VMA than the control mixture due to the roughness of RCA and its sharp edges. The greatest growth was recorded in the mixture containing 50% RCA; it was 1.4% over the control mixture. A decrease in the increase of VMA was recorded in mixtures containing 75, and 100% RCA but persisted higher than the mixture used as a control. This might be due to grinding or crushing some cement mortar during compaction or rounded aggregate present, making aggregates move easily together during compaction. The results obtained correspond with those of Bhusal & Wen [58], Daquan et al. [59], Tahmoorian et al. [60], and Cantero-Durango et al. [61]. They reported increased VMA when adding the RCA to the asphalt mixtures. The inclusion of carbon fibers led to a clear rise in the voids in mineral aggregates due to the decrease in bulk density.

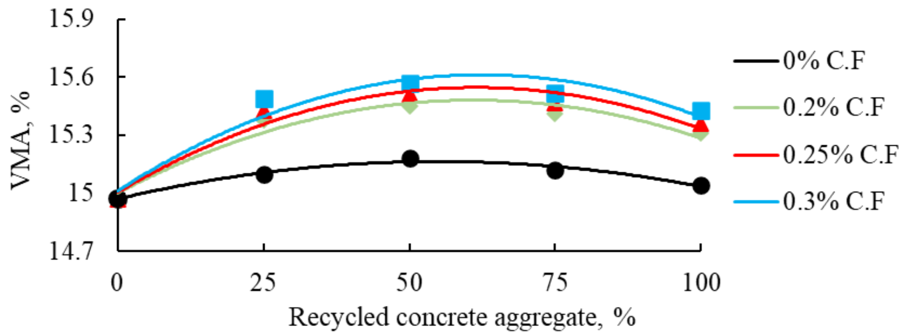

Figure 9. Influence of RCA & Carbon Fibers on VMA.

5.2. Wheel Tracking Test Results

Table 8 and Figures 10 to 13 illustrate the wheel tracking test results at 10000 cycles for the control and other mixtures. All RCA combinations reported a deeper rut than the control mixture due to the asphalt content, which adversely affected rutting resistance at high temperatures despite the increasing roughness of the aggregate. The greatest rutting depth happened in the mixture containing 100% RCA, which was 19.62% over the control mixture. The results correspond with Mills-Beale [22], Azarhoosh et al. [30].

Carbon fibers have significantly improved resistance to permanent deformation. The mixture containing 50% RCA and 0.3% carbon fibers found that their resistance to permanent deformation was 39.08% higher than that of the control combination.

Table 8. Rutting depth @ 10000 cycles.

Mixtures RCA/C. F	Rut depth (mm)
Control	12.28
25/0	13.30
25/0.2	9.71
25/0.25	8.65
25/0.3	7.72
50/0	13.53
50/0.2	9.62
50/0.25	8.69
50/0.3	7.48
75/0	13.89
75/0.2	10.12
75/0.25	8.63
75/0.3	7.63
100/0	14.69
100/0.2	11.02
100/0.25	9.55
100/0.3	7.79

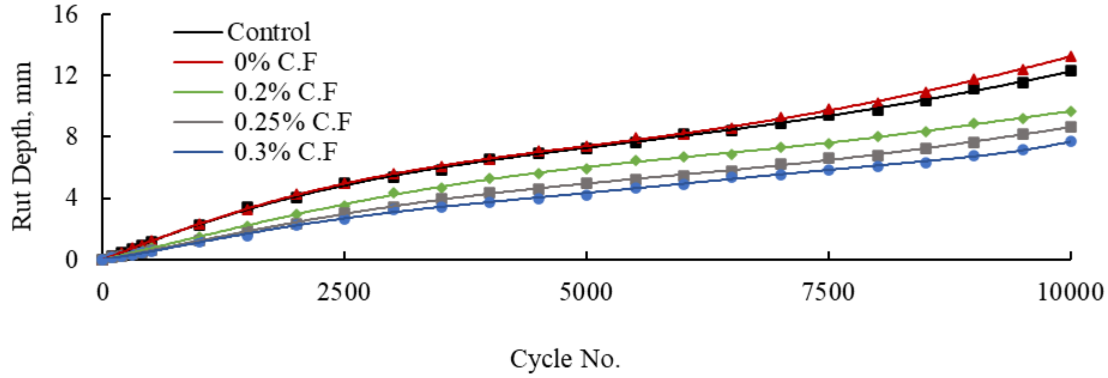

Figure 10. Wheel tracking test results @10000 cycles for 25% RCA.

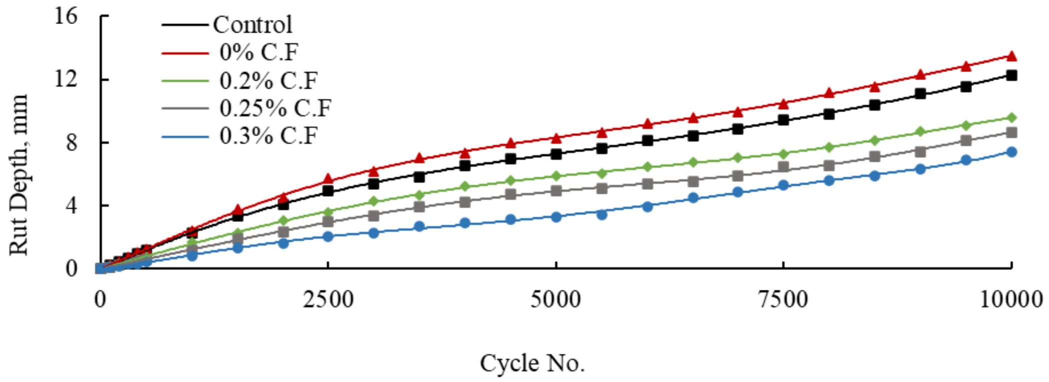

Figure 11. Wheel tracking test results @10000 cycles for 50% RCA.

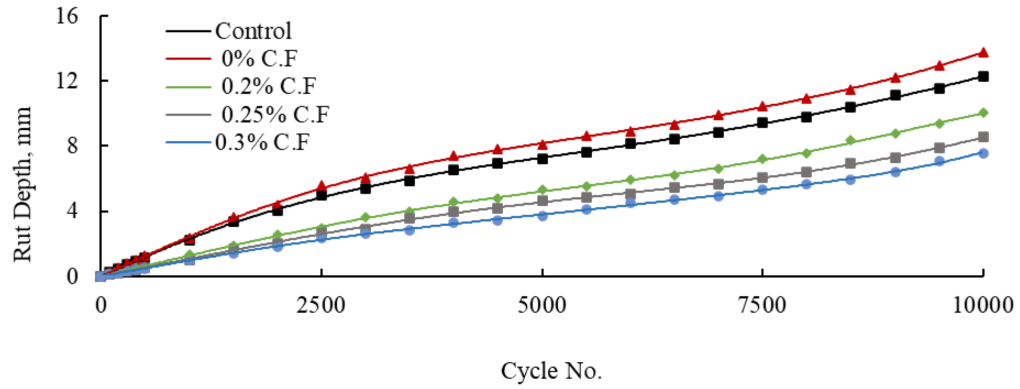

Figure 12. Wheel tracking test results @10000 cycles for 75% RCA.

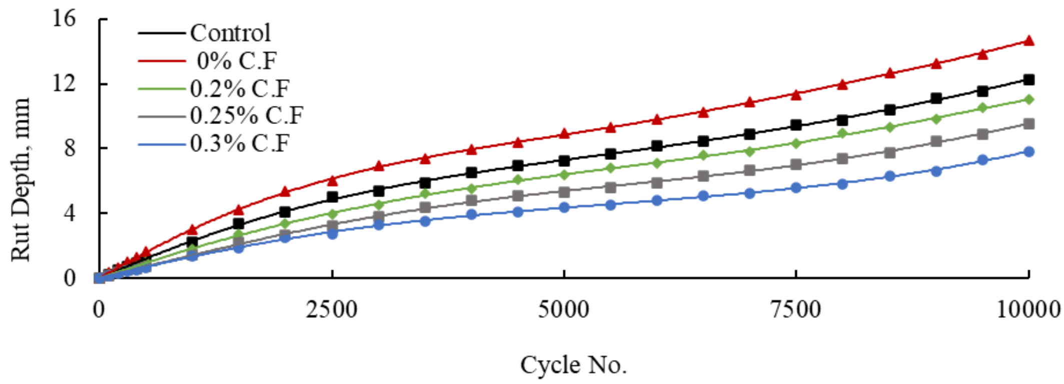

Figure 13. Wheel tracking test results @10000 cycles for 100% RCA.

6. Statistical Analysis

Regression analysis is a statistical technique for estimating the functional relationship between two or more variables, which allows one variable's change to be known or expected based on how it affects other variables. In practical use, the linear regression model is one of the most common and prominent models of the regression function. In this study, the proportion of RCA and the cycle period were regarded as two independent variables that impacted the dependent variable, the rutting depth, which was predicted according to Equation 1 using SPSS software. Table 9 illustrates the ANOVA test results based on rut depth; the sig—value of the test < 0.05 means rejecting the null hypothesis that provides a non-significant linear relationship. Where R2 (coefficient of determination) equals 0.943, it indicates a strong relationship between variables in the estimation model.

$$RD = 2.735 + 0.001 \times C + 0.008 \times RCA - 11.414 \times C.F \quad (1)$$

Where:

RD= Rutting depth in mm

C= Cycle length (500 to 10000)

RCA= percentage of recycled concrete aggregate (25, 50, 75, and 100)

CF = Percentage of Carbon fibers (0, 0.2, 0.25, and 0.3)

Table 9. ANOVA test results.

Model		Sum of Squares	df	Mean Square	F	Sig.
	Regression	3745.520	3	1248.507	2500.377	< 0.01
1	Residual	227.297	416	0.546		
	Total	3972.818	416			

7. Cost-Effective

A cost study was conducted to determine whether employing RCA rather than virgin aggregate is economically feasible, comparing and evaluating revenues and benefits.

The benefits are calculated by the price difference between RCA and virgin aggregate in addition to the cost of the landfilling process (rent machine costs), where an amount of 15.71 $ per 1 ton of RCA was adopted [21], taking into account that the percentage of coarse aggregate is 42% of the total aggregate. The benefit value in Table 10 of each 1-ton of asphalt concrete produced was identified according to Eq. (2).

$$Benefit\ value\ (\$/ton) = 42\% \times \%\,Agg. \times \%\,RCA \times 15.71 \quad (2)$$

The additional costs of using RCA are only the cost of the additional asphalt cement required when adding the recycled concrete aggregate. 315 $ per 1 ton of asphalt cement was adopted as the prevailing price. Another cost is adding amounts of carbon fiber to the asphalt mixture to strengthen it (The prevailing price of the material in local suppliers).

The cost value in Table 10 of each 1-ton of asphalt concrete produced was identified according to Equation 3.

$$\text{Cost value(\$/ton)} = \text{\% of add. asphalt cement} \times 315 + \text{\% of carbon fibers} \times 10 \times 1000 \quad (3)$$

$$\text{\% of add. Asphalt cement} = \text{O.A.C of any \%RCA} - \text{O.A.C of control mixture (4.88)} \quad (4)$$

Table 10. Benefit-Cost values.

Mixtures RCA/C. F	% Agg. in the total mix	% of additional asphalt cement	Benefit value ($/ton)	Cost value($/ton)	Benefit-Cost, $ per 1 ton asphalt concrete
25/0	94.96	0.16	1.57	0.51	1.06
25/0.2				20.51	-18.94
25/0.25				25.51	-23.94
25/0.3				30.51	-28.94
50/0	94.86	0.26	3.13	0.82	2.31
50/0.2				20.82	-17.69
50/0.25				25.82	-22.69
50/0.3				30.82	-27.69
75/0	94.73	0.39	4.69	1.23	3.46
75/0.2				21.23	-16.54
75/0.25				26.23	-21.54
75/0.3				31.23	-26.54
100/0	94.51	0.61	6.24	1.93	4.31
100/0.2				21.93	-17.69
100/0.25				26.93	-20.69
100/0.3				31.93	-25.69

8. Conclusions

In light of the test results and the materials' characteristics, several key components should be included in the research report on asphalt mixtures. Firstly, when recycled concrete aggregates (RCA) replaced virgin aggregate, the optimal asphalt content increased notably; for mixtures with 100% RCA, this increase was 12.5% higher than in the control mixture. This diminishes the benefits of using RCA as a substitute for virgin aggregate.

Secondly, the Marshall stability of the mixtures improved when RCA was used. The most significant increase, 14.2% over the control mixture, was observed in a mixture containing 50% RCA. This stability was further enhanced by incorporating carbon fibers; a mixture with 0.3% carbon fiber and 50% RCA showed a substantial rise in stability, up 34.6% compared to the control mixture.

Furthermore, the addition of RCA and carbon fibers did not significantly alter the volumetric properties of the asphalt mixtures, as all combinations met the Iraqi standard requirements of 2003. In terms of permanent deformation resistance, however, mixtures with 100% RCA exhibited the deepest rutting, 19.62% deeper than the control mixture. This effect was mitigated by adding carbon fibers, which improved rutting resistance in the mixture containing 50% RCA and 0.3% carbon fibers by 39.08% compared to the control mixture.

Economically, using RCA instead of coarse virgin aggregate offers some benefits despite the increased asphalt content. However, the addition of carbon fibers renders the mixtures uneconomical due to the high cost of the fibers, although there are other savings from the lower bulk density of the mixtures, which means less weight is required to pave the same volume.

Lastly, including carbon fibers and the rough surface of the RCA necessitates maintaining temperatures at least 160 °C during mixing and prolonging the mixing duration to ensure adequate coating. This increases the cost of producing asphalt concrete and exacerbates environmental impact by releasing additional pollutants into the atmosphere.

Apart from the ongoing research, it is important to investigate several additional subjects. First, conducting supplementary asphalt mixture testing, such as fatigue, moisture, and low-temperature cracking and wear tests, is crucial, especially if the mixture is used as a wearing course. Exploring different types of fibers or asphalt cement additives could also enhance economic feasibility. Additionally, tests must be performed to identify the resilient modulus of asphalt mixtures. This helps assess their economic viability since increasing stiffness can extend the service life of roads, potentially avoiding future maintenance work or allowing for a reduction in the thickness of the asphalt layer, which in turn can reduce production and implementation costs. Lastly, a study of rutting performance with base-layer mixtures should be considered. Utilizing greater quantities of recycled concrete aggregates can contribute to improved environmental sustainability. Moreover, recycled concrete aggregates (RCA) can be very useful for developing resistance to permanent deformation without the need for additives, particularly in cases where specifications do not mandate the use of crushed aggregates.

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