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Evaluating the Moisture Susceptibility of Asphalt Mixtures Containing RCA and Modified by Waste Alumina

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Abstract

The management of building and demolition waste is an important subject in the government's sustainability efforts. Today, recycling and reusing industrial waste and by-products is a topic of considerable relevance in every industry, but it is especially important in cement and concrete technology. Within the asphalt pavement sector, the necessity for environmentally friendly highway design and construction is at the top of the priority list. Nevertheless, due to the inferior behavior of the resulting recycled concrete aggregate (RCA) mixes, additional enhancement materials are needed. In this study, the effect of using alumina waste in the form of secondary aluminum dross (SAD) in the asphalt compacted specimens that contained RCA as coarse aggregate was discussed. The conventional limestone dust filler is replaced by SAD at rates of 10, 20, and 30% by filler weight in the control mix, and then the best percentage is used in mixtures containing RCA at rates of 25, 50, 75, and 100%. The experimental work includes volumetric properties by employing the Marshall design method, indirect tensile strength (ITS), and compressive strength. All the used percent of SAD enhanced the properties of the asphalt mixture; the tensile strength ratio (TSR) of the control mixture increased by 4.58%, 8.52%, and 7.64% for SAD rates (10, 20, and 30%), respectively. The best dosage of SAD was added to the mixture containing RCA at different specified rates. The maximum TSR (13.92%) was obtained at 25% RCA. The same steps were followed in the compressive strength test; adding SAD increased the index of retained strength (IRS) of the control mixture by 55.11, 13.42, and 9.13% for 10, 20, and 30%, respectively. Thereafter, the best dosage of 20% SAD was added to the hot mix asphalt (HMA) containing different RCA percents. The maximum IRS (17.43%) was also obtained at a 25% RCA.

Keywords: Alumina Waste; Recycled Concrete Aggregate; Tensile Strength Ratio; Index of Retained Strength.

1. Introduction

Moisture has long been acknowledged as a significant factor in the premature deterioration of asphaltic pavements. Numerous studies have collected, described, and measured the moisture susceptibility of asphaltic mixtures [1]. Many variables contribute to the deterioration of asphalt and concrete pavement caused by moisture. When calculating the amount of moisture damage, it is essential to take into account the aggregate type (coarse and fine). When used in asphalt concrete, aggregates like granite, gravel, and other siliceous minerals are easily stripped due to their sensitivity to moisture. Limestone, on the other hand, is more resistant to moisture damage than other aggregates [2]. Natural resources like bitumen and natural aggregates are vital to the production of asphalt paving. The extraction of natural aggregates causes noise, vibrations, and dust emissions into the atmosphere. Additionally, the building industry's rapid expansion results in the depletion of natural aggregates, which may result in the depletion of natural resources [3]. There has been a recent increase in the development of tools to support decision-making in relation to local and national planning in many nations on the subject of solid waste management [4].

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Cost savings can be achieved by using RCA, making its adoption an advantageous move. The decreased cost is explained by the fact that transporting and crushing recycled aggregate is less expensive than transporting natural aggregate in scenarios where RCA is incorporated [5]. Purushothaman et al. [6] report that the building and construction industry generates about 1200 million tons of building and deconstruction trash, mostly concrete. Massive waste handling threatens landfill capacity. Reusing this trash in new construction is sustainable. Recycling structure and destruction waste into asphalt road mixtures (HMA) may improve sustainable construction [3]. However, the lower quality of RCA frequently restricts its use to low-grade applications. The primary factor influencing RCA quality is the substantial amount of cement mortar still attached to the aggregate. As a result, the strength and mechanical performance of RCA are decreased due to greater porosity, higher rates of water adsorption, and a poorer interface area connecting cement mortar and aggregates [7]. It was estimated that 3800 tons of asphalt mixture and about 13,000 tons of normal aggregates are required to construct a 1 kilometer long, 10 meters wide, and 150 mm thick asphalt pavement, so using RCA in the asphalt mixture has great benefits for the sustainable approach [8]. Even though more asphalt cement was needed, replacing virgin aggregate with RCA made it economically feasible, as evidenced by the greatest possible value of $2 per ton of asphalt concrete when using 100% RCA treated mechanically [9].

The rutting resistance, fatigue-cracking, low-temperature cracking, stripping, and effectiveness to moisture performances of asphalt mixtures are all extremely affected by the physical and chemical properties of mineral fillers [10]. In relation to asphalt concrete performance, asphalt mechanical tests were used to examine the impact of converting from limestone filler to aluminum dross filler on asphalt mixture durability. Final conclusions about the usage of aluminum dross waste as a passing sieve (No. 200) in asphalt mixes are offered by Soós et al. [11] after the qualities of fillers and the results of various mechanical tests are analyzed. It was observed that adding dross in place of the limestone filler stiffens the asphalt mixture and raises the phase angle.

2. Literature Review

The design of the HMA by Superpave Mix Design was carried out by Bhusal et al. [12]. The optimum mix was determined by testing five different RCA percentages (100%, 80%, 60%, 40%, and 20%). The laboratory results meet the volumetric and design mix standards for Washington State. Al-Bayati & Ismael [13] examine the impact of carbon fibers on the Marshall properties of HMA containing RCA. Carbon fibers with lengths of 10 and 20 mm were added at three proportions of 0.15, 0.25, and 0.35% of the total weight of the mixture. All mixtures containing RCA met the (SCRB R9/2003) Iraqi standard requirements for wearing coarse, according to the results. When virgin aggregate was replaced with RCA, the optimum asphalt content increased, with the maximum increase reaching 10.78% over the control mixture when 100% coarse recycled concrete aggregate was used.

The impacts of utilizing RCA on HMA volumetric properties were assessed by Al-Bayati et al. [14] RCA was used at several percentages (0%, 15%, 30%, and 60%). The best results for moisture damage resistance were obtained in 30% of RCA. The base course was constructed by Zou et al. [15] using varied rates of RCA (0, 10, 20, 30, 50, 70, and 100%) in place of coarse aggregate. The TSR has a maximum value of 30% RCA content. When compared to control mixtures, the IRS ratio value for this percentage of RCA increased by 10.60%. Wong et al. [16] utilized RCA in HMA at rates of 0, 50, and 100%. The results of the IRS test show that all mixtures satisfy the requirements for the test. The increase in RCA content decreases the IRS for the asphalt mixture. Bushal et al. investigated the possibility of utilizing RCA in the HMA by using 0%, 20%, 40%, 60%, 80%, and 100%. The results of the ITS test approved that increasing RCA decreases moisture damage resistance [12]. Huseen et al. assessed the moisture damage to RCA-containing mixtures reinforced with rock wool fibers. The suggested HAM, according to the findings, is an appropriate option for pavement construction in hot climates [17, 18].

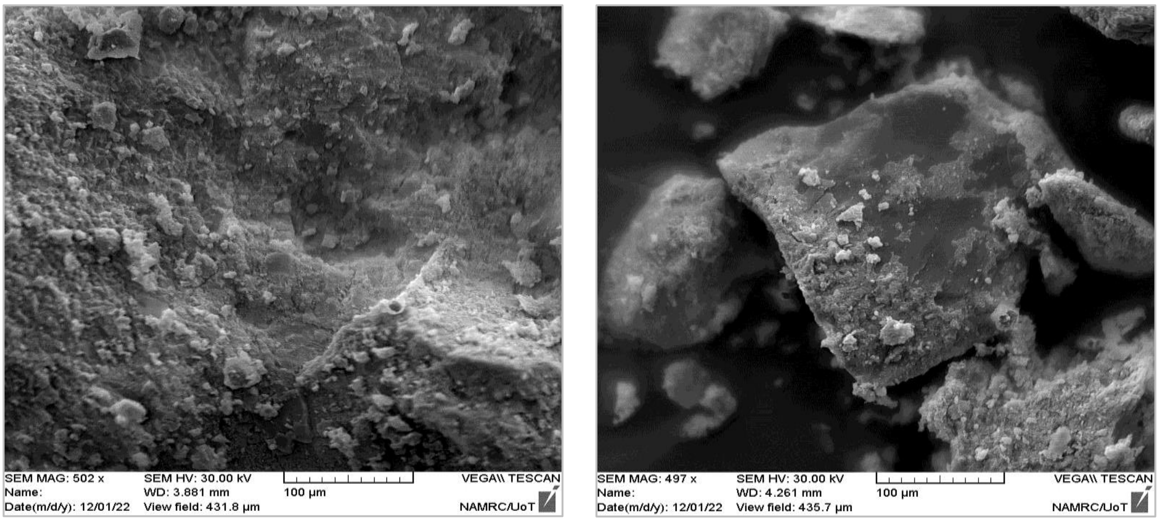
Kavussi et al. [19] examined the way RCA affected the mechanical characteristics of asphalt mixes. Asphalt mixtures made with RCA components exhibited some moisture sensitivity. This was determined to be the outcome of the RCAs utilized in this investigation being siliceous. The findings suggested that treating RCA with HCL acid might enhance the moisture susceptibility of treated RCA. Mills-Beale and You [20] studied the effect of replacing 25%, 35%, 50%, and 75% of virgin aggregate by RCA. Different mechanical tests were adopted to determine the possibility of using demolished waste in HMA. The results of the TSR test show that 25% of RCA has the maximum TSR, so it has the best moisture damage resistance as compared to other percents of RCA. It was examined by Udvardi et al. [21], using aluminum dross as a possible filler for asphalt. According to the test results, these fillers can be used in asphalt mixes. The German Filler Test results showed that aluminum dross has a lesser capacity to absorb oil than limestone; however, this difference is not very large.

3. Materials

All materials are obtained from local sources. Crushed coarse and fine aggregates from the Al-Nibaai quarry are tested in accordance with SCRB R/9 to meet the Iraqi specification for roads and bridges [22]. Table 1 shows the physical properties of coarse virgin and RCA aggregate. Asphalt cement with a 40/50 penetration grade was used. Limestone dust is used as a conventional filler in the mixture. To achieve sustainability, the debris of a building was crushed to obtain a coarse aggregate size ranging from 19 mm to 4.75 mm. The obtained material was socked in a diluted HCL solution with a 0.1 mole concentration for 24 hours to treat the weak cement mortar in RCA and reduce the thickness of this layer. Then, RCA was re-socked in water for 24 hours to discard acidic solution residue. Scanning electron microscope (SEM) technology has been used to detect the treatment effect on RCA. Figure 1 shows SEM images for treated and untreated RCA. From the figure, it’s clear that acid treatment reduces the surface angularity due to the removal of the attached mortar layer. To improve the asphalt mixture's resistance to being damaged by moisture, SAD was used as a partial replacement for the conventional filler to increase the adhesion between aggregate and bitumen. The X-ray Fluorescence (XRF) test was used to indicate the oxides in the SAD, and the XRF test consequences are tabulated in Table 2. Figure 2 shows SAD features and an SEM image. After testing all the materials used in HMA, the aggregate gradation for the surface course (Type ⅢA) described in SCRB R/9 was adopted, as shown in Figure 3. The coarse aggregate, which ranged from 19 mm to 4.75 mm and consisted of 52% aggregate weight, was replaced with RCA at rates of 0%, 25%, 50%, 75%, and 100%. Figure 4 describes the working plan in a flow chart.

Table 1. Physical properties of coarse aggregate

Test	Bulk specific-gravity	% Water absorption	% loss by Los-Angeles	% loss by sodium sulphate solution	% Fractured Pieces
ASTM	C-127	C-127	C-131	C-88	D-5821
Virgin	2.63	0.85	19	0.35	98
Untreated-RCA	2.4	4.1%	22%	1.07	100
Treated-RCA	2.41	3.8%	21.5%	0.06	100
SCRB-Specification	-	-	30 max	12 max	90 min



(a) Untreated (b) Treated

Figure 1. Morphological features of RCA

(a) Feature (b) SEM image

Figure 2. Secondary aluminum dross

Table 2. Oxide concentration in secondary aluminum dross

Oxides	MgO	Al_2O_3	SiO_2	SO_3	Cl	K_2O	CaO	MgO	Na_2O	CuO
Concentration, %	7.312	60.250	6.552	3.640	0.709	0.400	8.090	0.390	1.849	0.774

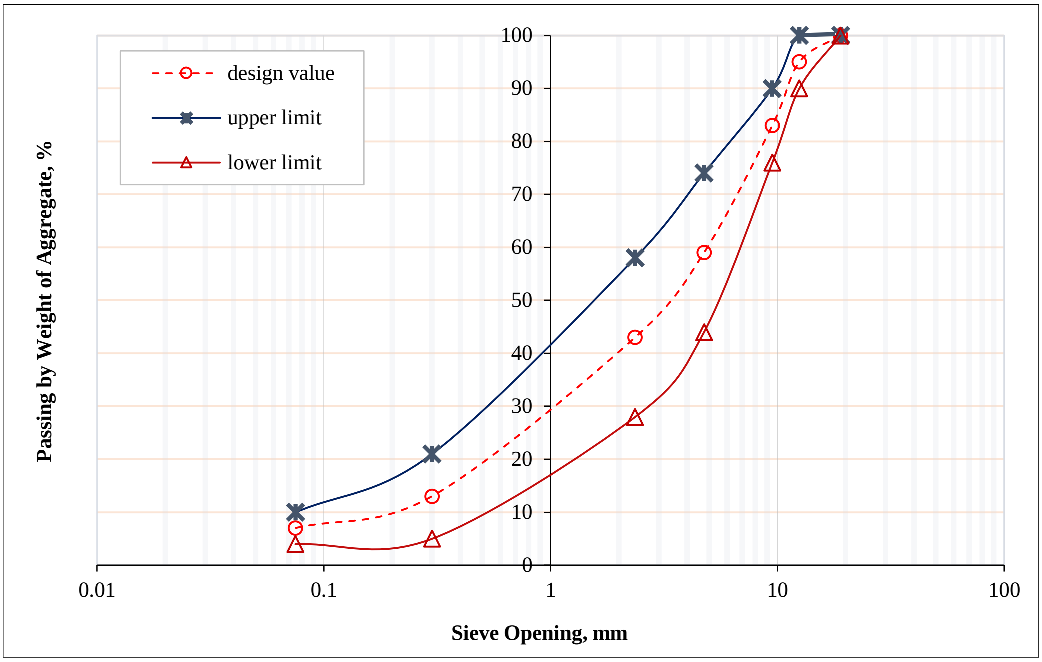


Figure 3. Aggregate gradation in accordance with (SCRB R/9)

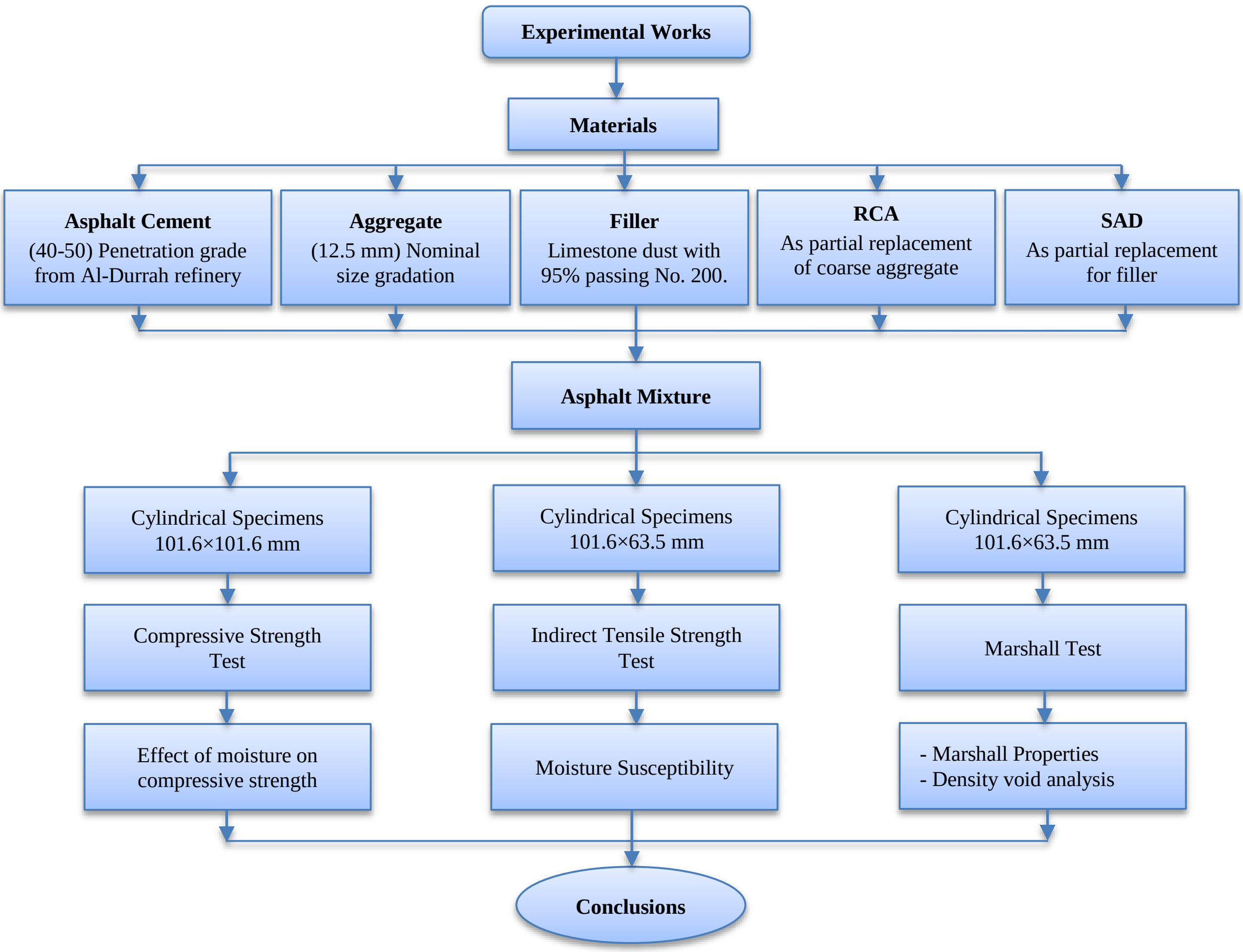


Figure 4. Flow chart of the research methodology

4. Selected Mix

The Marshall mix design method was adopted to find the optimum asphalt content (OAC) for the selected aggregate gradation [23, 24]. The procedure described in ASTM D6926 was followed to prepare cylindrical specimens with a 101.6 mm and 63.5 mm height [25]. The compaction was done in a compactor weighing 4.54 kilograms, falling freely from a height of 455 mm. 75 blows were used for each face. A 4-5% selected range of asphalt cement content was used with a 0.5 increment as recommended in SCRB R/9 for the wearing course layer; three samples were equipped for every asphalt percent, and the average value was adopted. Figure 5 describes the Marshall specimen's preparation steps. To find the OAC, the asphalt institute instructions were followed, which adopted the OAC that produces 4% air voids and at the same time satisfied all other Marshall stability and flow limits and density void limits mentioned in the local requirements. This percentage of air voids was chosen because it gave the best moisture damage resistance [26].

Figure 5. Preparation of Marshall test specimens

4.1. Marshall Test

The test method described in ASTM D6927 was used on the control specimen and specimens with different RCA content to find the Marshall stability and flow, accompanied by a bulk specific gravity test (ASTM D2726) and a maximum theoretical specific gravity test (ASTM D2041) to obtain the volumetric properties of the asphalt mixture. After finding OAC stages, the SAD replaced the limestone dust filler at rates of 10%, 20%, and 30%. These percentages were used based on trial and error. The Marshall test device is shown in Figure 6.

Figure 6. Marshall test

4.2. Tensile Strength Ratio

Following ASTM D-6931, the ITS of the asphalt cement specimens has been determined. Specimens were put in a machine for common testing. A load of 0.5 millimeters per minute was applied during the test, and the test temperature was retained at 25 °C. The specimen's point of rupture was calculated at its maximum load. At least three samples of each mixture were made [27, 28]. The test method mentioned in ASTM D4867 was used to determine the influence of moisture damage. For each mixture, at least six identical samples were prepared; three were tested in dry situations, and the other subset was tested after exposure to a freeze and thaw phase, as shown in Figure 7. The air voids of the compacted samples should be maintained at a range of 6–8% to simulate the field condition [29].

$$\text{I.T.S} = \frac{2 \times Pu}{\pi \times D \times t} \tag{1}$$

$$\text{T.S.R} = \frac{I.T.S\ C}{I.R.S\ U} \times 100 \tag{2}$$

where, I.T.S is indirect tensile strength; Pu is the ultimate load that causes failure; D is the sample diameter; t is the sample thickness; T.S.R is the tensile strength ratio; I.T.S C is the indirect tensile strength for conditioned sample; and I.R.S U is the indirect tensile strength for unconditioned samples.

Figure 7. Conditioned of the TSR test samples

4.3. Compressive Strength Test

Cohesion loss due to water impact on compacted bituminous mixtures can be measured with this test method. Preparations included specimens with a diameter of 4.0 inches (101.6 mm) and a height of 4.0 inches (101.6 mm). The specimens have been prepared in accordance with the procedure described in ASTM D1074 [30]. The mold was wiped and heated to a compaction temperature. Then, place the prepared mixture following ASTM D6926 in two layers and compress the mixture under an initial load of 1 MPa, then raise the load to 20.7 MPa. After that, leave the specimen to warm at ambient temperature for 24 hours. Thereafter, cure the specimens in the kiln at 60 °C for 24 hours. To measure the effect of moisture damage on compressive strength, six specimens are needed for each mixture; the first three specimens were tested dry, and the second group was tested wet. The test specimens were exposed to an axial compression load without lateral supports at a rate of 5.08 millimeters per minute. The ultimate load record and the compressive strength were obtained by dividing this load by the specified specimen section. Figure 8 shows the compaction machine and a sample of compacted specimens.

Figure 8. Preparation and testing of compressive strength test specimens

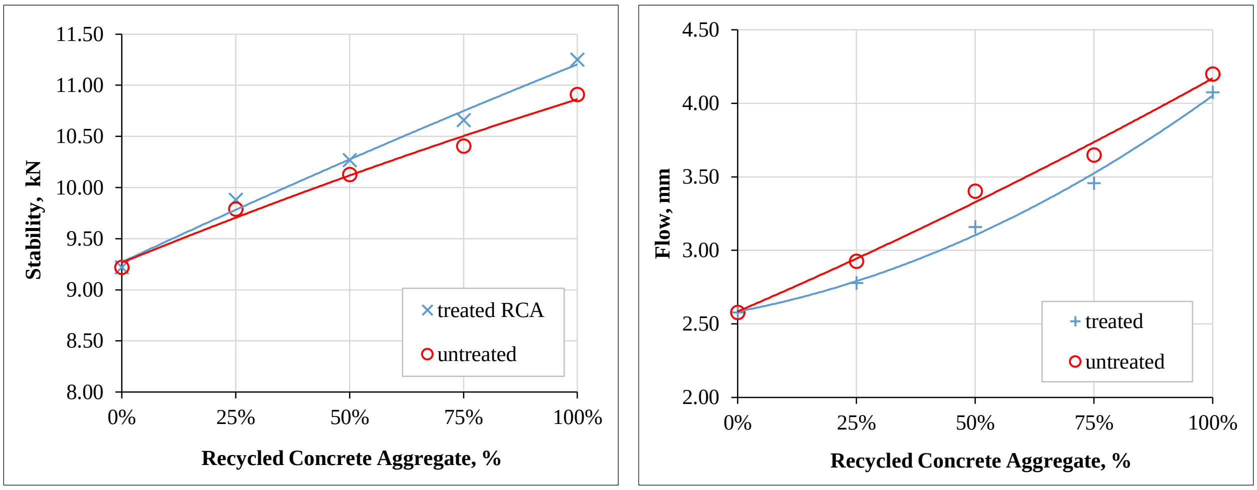
5. Results

5.1. Marshall Test

The results of the Marshall test are tabulated in Table 3 for the treated and untreated RCA in addition to the control mix. From Figure 9 and Table 3, it’s clear how changes in RCA percent affect the specimens' plastic flow and Marshall stability. The test results revealed that RCA mixtures have more stability and flow values than the control mixtures. All treated and untreated RCA samples met the SCRB's lower limit of stability requirement. According to earlier research [31-34], the uneven exterior layer of the recycled aggregate contributed to the greater stability of the specimen due to the enhancement of adhesion and bonding between the binder and aggregates.

Table 3. Marshall test and density void analysis results

RCA, %	OAC, %	Stability, kN	Flow, mm	Gbm, gm/cm³	AV, %	VMA, %	VFA, %
Control							
0	4.9	9.23	2.58	2.323	4.01	15.59	74.27
Untreated RCA							
25	5.10	9.81	2.91	2.305	4.00	15.51	73.55
50	5.30	10.15	3.38	2.294	4.00	15.18	72.44
75	5.40	10.46	3.63	2.286	4.00	14.58	72.13
100	5.65	10.87	4.23	2.272	4.00	14.50	71.57
Treated RCA							
25	5.00	9.92	2.76	2.313	4.00	15.06	73.20
50	5.20	10.38	3.20	2.307	4.00	14.68	72.48
75	5.30	10.69	3.43	2.300	4.00	13.97	71.52
100	5.50	11.27	4.06	2.279	4.00	13.93	70.65



(a) Stability (b) Flow

Figure 9. Marshall test results

When comparing the maximum stability values of treated and untreated RCA specimens, acid treatment was found to increase the stability of the 100% RCA mixture by 3.68%. The treated 100% RCA specimens had a 4.01% lower flow value compared to the untreated RCA specimens. All plastic flow values increase; however, they do meet the SCRB's standard except 100% RCA, which has a higher flow value than the specified limits.

Figure 10 displays the obtained specimen bulk densities. It can be understood that the bulk density of compacted specimens declines with an increment in RCA percent. Nevertheless, the bulk density value of treated RCA is detected to be little more than the untreated RCA at all RCA percent, which may be due to the removal of the lightweight cement mortar layer. These results are consistent with Daquan et al. [33] and Sanchez-Cotte et al. [35]. Less dense asphalt mixtures are associated with a higher asphalt content of RCA, which is the lowest density ingredient in the asphaltic mixture, and an increase in RCA content, which has less density than natural aggregates.

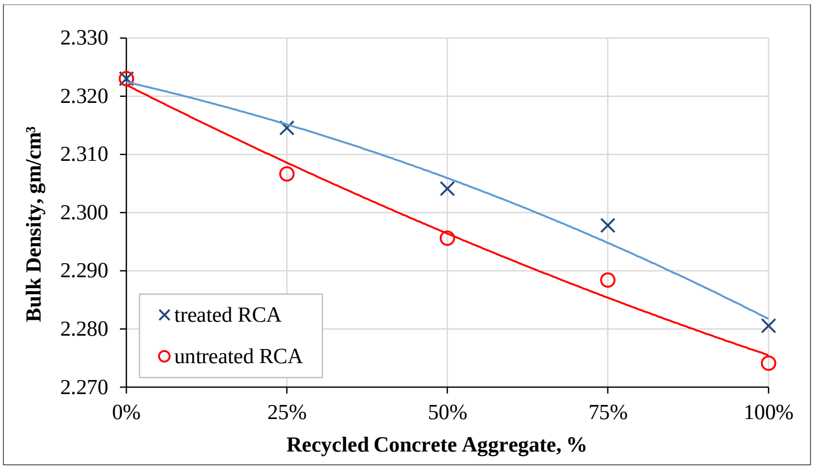
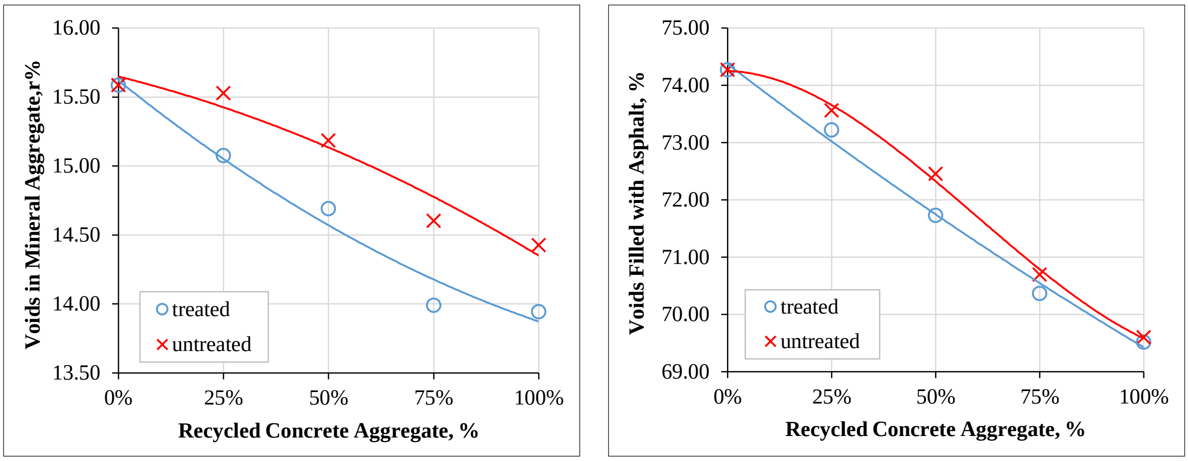


Figure 10. The bulk density of compacted specimens

Compared to the control mixtures, the RCA-containing mixtures had a reduced percentage of V.F.A. As it is shown in Figure 11 and Table 3, the specimens with (25, 50, 75, and 100%) untreated RCA by coarse aggregate weight had a lower V.F.A. than the control mixture by 0.94, 2.43, 2.85, and 3.61%, respectively. When the specimens made with (25, 50, 75, and 100%) treated RCA had lower voids filled with asphalt than the control mix by 1.41, 2.38, 3.68, and 4.84%. Increased RCA absorbs some asphalt from the mix due to its surface pores. This absorption lowers HMA's effective asphalt content. When effective asphalt content decreases, VMA decreases. As VMA decreased and HMA air void level did not vary much with increasing RCA, VFA also decreased. Pourtahmasb and Karim [32], Daquan et al. [33], and Hou et al. [36] also find that increasing RCA percent causes a decrease in the bulk density of asphalt mixtures.



(a) Voids in mineral aggregate (b) Voids filled with asphalt

Figure 11. Effect of RCA on (A) VMA (B) VFA

After completing the Marshall test to find the OAC, aluminum dross was added to the control mixture and each RCA content at rates of 10%, 20%, and 30%. To find the best dosage, the Marshall stability test was applied. The best dosage of SAD was found to be 20%, which increases the Marshall stability by 24.16%, 30.34%, 34.68%, 36.42%, and 39.01% for 0%, 25%, 50%, 75%, and 100% RCA, respectively. Stability increases as the RCA percent increases. That’s caused by the increase in adhesion between the asphalt and the aggregate, which further increases the bond between aggregate particles. SAD also caused an average decrease in the flow of 5.1%, 6.33, 9.32%, 12.25%, and 16.4% for 0%, 25%, 50%, 75%, and 100%, respectively. This decrease is caused by the SAD absorption of the asphalt cement in the mixture.

5.2. Tensile Strength Test Results

Mixtures' sensitivity to moisture has been predicted using the ITS test. TSR is employed to differentiate between mixtures that are sensitive to moisture and those that are resistant to it, with a recommended minimum limit of 80%. High TSR values imply that the mixture is supposed to work more effectively at eliminating moisture damage. To improve the moisture damage resistance, SAD was first added to the control mixture at 10%, 20%, and 30%. Figure 12 shows the change in ITS with the specified SAD dosage. It can be understood that adding SAD with conventional filler increases both wet and dry ITS for the dry specimens by 5.09%, 6.62%, and 10.5% for 10%, 20%, and 30% SAD, respectively. The ITS for wet specimens is increased by 9.9%, 15.7%, and 18.95% for 10%, 20%, and 30%, respectively. Thereafter, the TSR was obtained to evaluate the SAD effect on moisture damage resistance. Figure 13 Clarifying the results of the TSR, it can be seen that TSR increased for both 10% and 20% SAD, then a slight decrease in 30% that may be affected by the high absorption of SAD to the asphalt cement, which decreases the bond of the mixture and, as a result, decreases the TSR. 20% SAD showed the best improvement. The increase in the ITS may be caused by increasing the adhesion of the asphalt mixture because SAD is a complex material that consists of different oxides that increase adhesion. The maximum increase in the TSR was calculated to be 8.52% at a 20% SAD dosage. Then, the best dosage was selected to enhance the resistance of the mixture to moisture damage for each percent of RCA in the treated and untreated samples. The ITS was tested for all mixtures incorporating RCA, and the results are described as a graph in Figure 14. From Figure 15, it's clear that 25% RCA replacement increases TSR, and any more replacement causes a decrease in TSR. The increase in TSR was attributed to the increase in adhesion, while the decrease was due to the increase in RCA percent, which is a porous material that has more voids, absorbs more water, causes more stress during the freezing cycle, and weakens the condition specimen as a result, causing a reduction in TSR and making the mixture more sensitive to moisture.

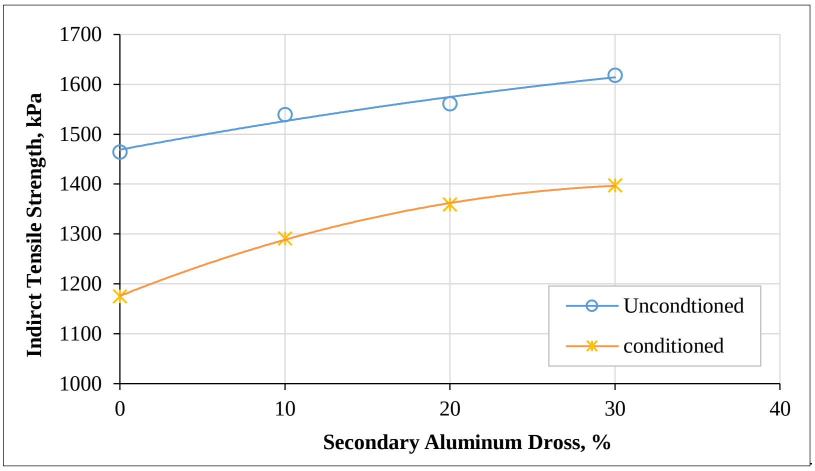


Figure 12. Effect of SAD on ITS

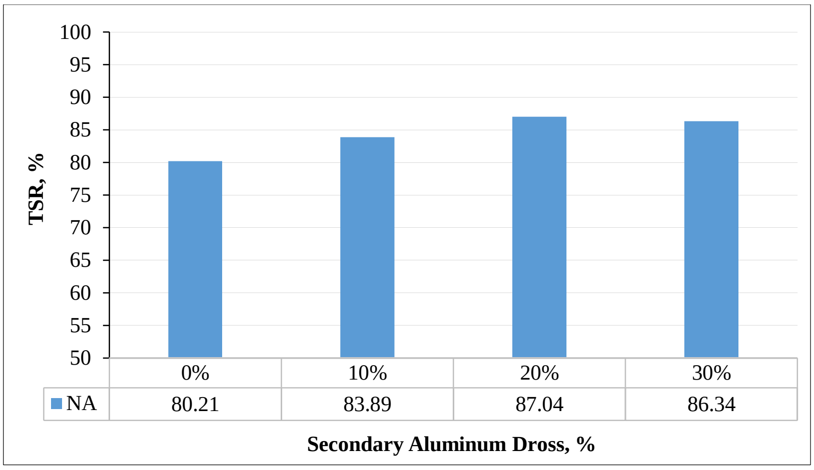


Figure 13. The effect of SAD on TSR

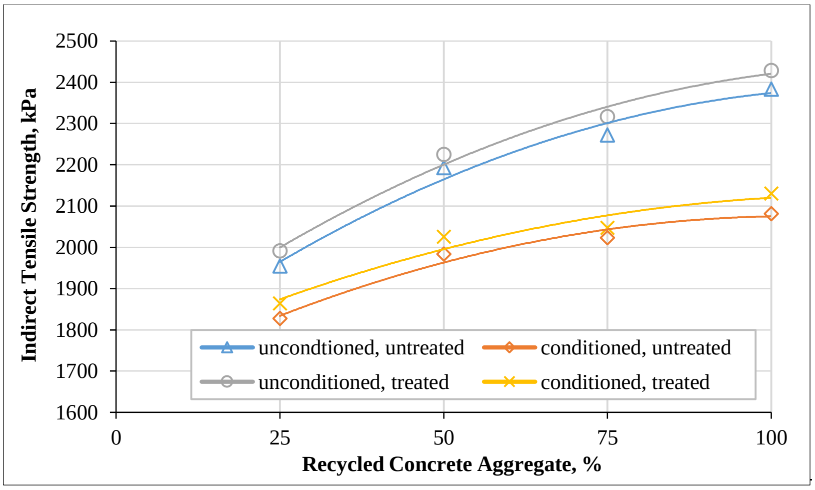


Figure 14. Effect of RCA on ITS

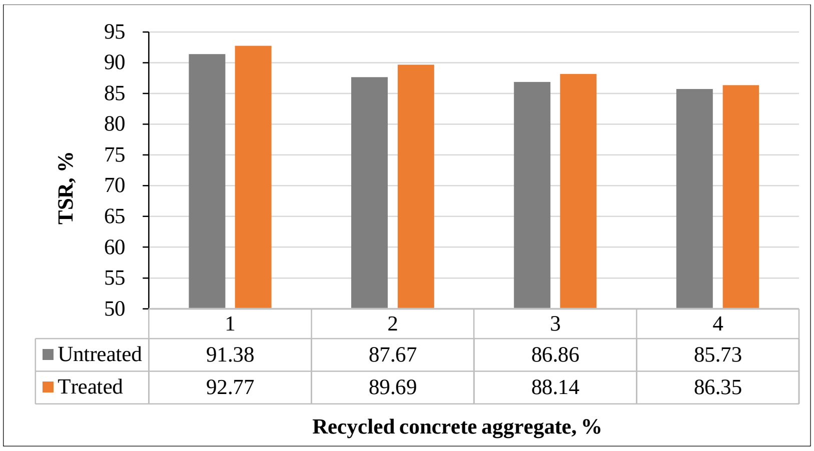


Figure 15. The effect of RCA+20% SAD on TSR

5.3. Compressive Strength Test Results

The Iraqi specification adopted the IRS parameter to estimate the damage due to moisture in the asphaltic mixture and limited the IRS to a minimum value of 70%, as mentioned in SCRB R/9. The samples were tested by applying the (ASTM D1075) test method, as shown in Figure 13. The results shown in Figure 16 indicate that adding SAD to the control mixture caused an increase in dry compressive strength for both wet and dry compressive strengths. The increase in compressive strength is also explained by the increase in adhesion because SAD improves the bond between asphalt mixture component particles. Figure 17 shows the IRS results: replacing 10%, 20%, and 30% limestone dust by SAD causes an increase in TSR by 5.11%, 13.42%, and 9.13%. Then, the best dosage of SAD (20%) was added to the mixtures containing different percentages of RCA. As shown in Figure 18, the dry and wet compressive strengths increased for both treated and untreated RCA specimens. The combined effect of replacing RCA with coarse aggregate and replacing SAD with conventional filler caused an increase in IRS (17.44%, 13.2%, 10.7%, and 6.97%) for untreated RCA (25%, 50%, 75%, and 100%) + 20% SAD, respectively, and (18.26%, 14.25%, 11.62%, and 7.86%) for treated RCA (25%, 50%, 75%, and 100%) + 20% SAD, respectively, as shown in Figure 19.

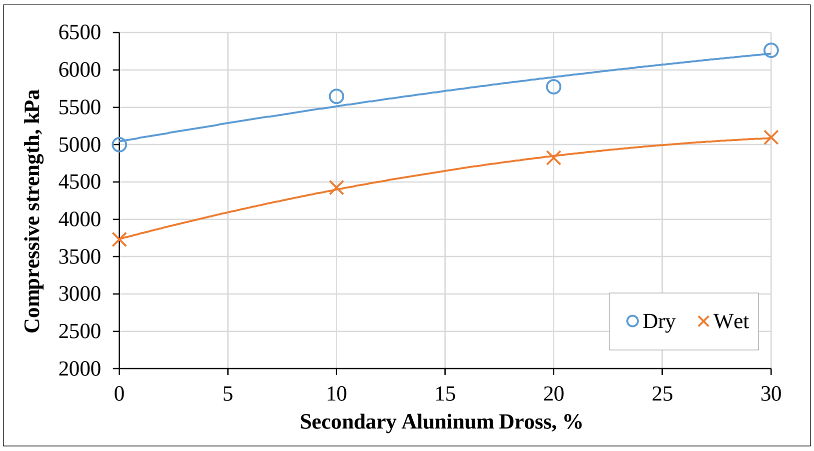


Figure 16. Effect of SAD on compressive strength

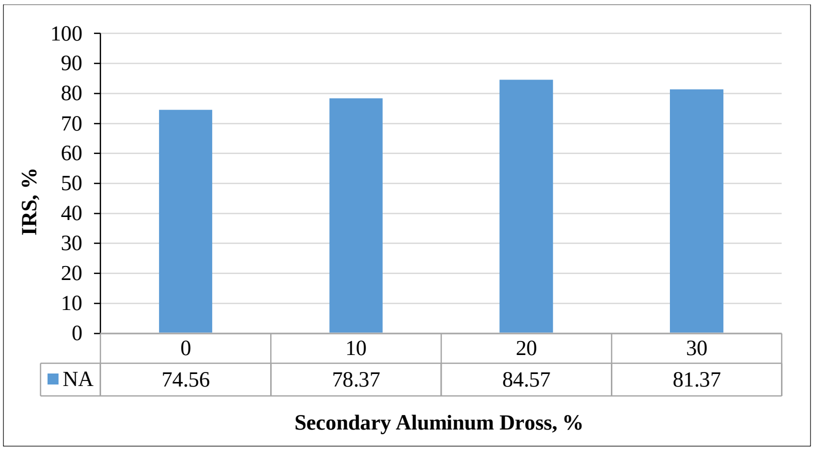


Figure 17. The effect of SAD on IRS

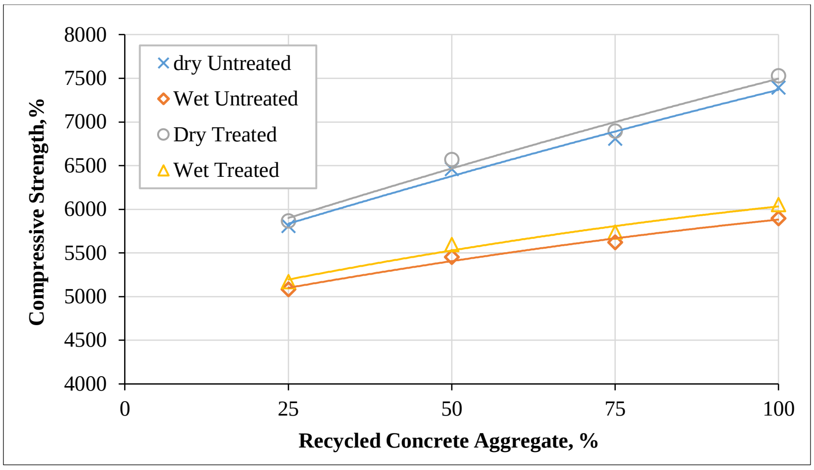


Figure 18. Effect of RCA + 20% SAD on compressive strength

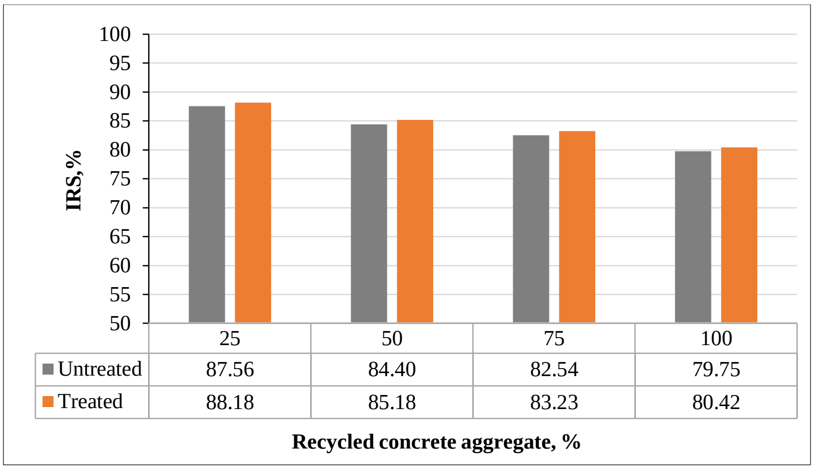


Figure 19. The effect of RCA + 20% SAD on IRS

6. Conclusions

- Replacing virgin coarse aggregate with RCA increases the Marshall stability of the asphalt mix associated with the reference mixture. The bulk density of the asphaltic mixture decreased due to the light weight of RCA.
- The OAC of the mixes incorporating RCA increased by 4.08%, 8.16%, 10.20%, and 15.31% for untreated RCA content of 25%, 50%, 75%, and 100%, respectively, and by 2.04%, 6.12%, 8.16%, and 12.24% for treated RCA.
- Using acid treatment for the RCA increases the stability by 5.8% as an average value and decreases the Marshall flow by 3%. At the same time, the density of the mixtures made with treated RCA had a very slight increment, with an average of less than 1%.
- Using aluminum dross in the control mixture enhances the Marshall stability, flow properties, and density void properties. In addition, it has been approved that mixtures containing SAD as a filler have better moisture damage resistance based on the increase in TSR of 4.58%, 8.52%, and 7.64% for 10%, 20%, and 30% SAD, respectively. And the increases in IRS of 5.11%, 13.42%, and 9.13% for 10%, 20%, and 30% SAD, respectively, gave the same indication.
- Based on the Marshall test, the TSR, and the IRS, 20% SAD is the best dosage that gives desirable Marshall properties and satisfies the best moisture damage resistance.
- Replacing 20% of conventional filler with SAD in the mixture containing RCA at different rates satisfies the requirements of TSR and IRS. The best moisture damage resistance was obtained at 25% RCA.

7. Declarations

7.1. Author Contributions

Conceptualization, S.K.U. and M.Q.I.; methodology, S.K.U. and M.Q.I.; investigation, S.K.U. and M.Q.I.; data curation, S.K.U.; writing—original draft preparation, S.K.U. and M.Q.I.; writing—review and editing, S.K.U. and M.Q.I. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available in the article.

7.3. Funding

This research was funded by the Department of Civil Engineering, College of Engineering, University of Baghdad, and Ibn-Rushed Company.

7.4. Conflicts of Interest

The authors declare no conflict of interest.

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