Assessment of Moisture Susceptibility of Hot Asphalt Mixtures Sustainable by RCA and Waste Polypropylene

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Received: 24 July 2024 | Revised: 8 August 2024 | Accepted: 18 August 2024

ABSTRACT

Sustainability plays an integral role in ensuring the continued existence of life on Earth and the protection of the natural environment. The recycling process is one of the most significant methods through which this strategy can be implemented. The potential environmental benefits of recycled concrete aggregates and polymer waste have attracted considerable interest within the asphalt industry. The present study focuses on the recycling of two materials to create asphalt mixtures. The first of these is polypropylene, which is mixed with asphalt cement at weight rates of 2%, 4%, and 6%. The second is treated and untreated Recycled Concrete Aggregate (RCA), which is substituted with coarse aggregate at weight rates of 20%, 40%, and 60%. The experimental work comprised the identification of the optimum asphalt content through the utilization of the Marshall design approach, the assessment of Marshall and volumetric characteristics, and the evaluation of moisture susceptibility through the measurement of Indirect Tensile Strength (ITS) and compressive strength. The findings indicated that all mixtures containing recycled polypropylene polymers and treated/untreated RCA exhibited a higher Tensile Strength Ratio (TSR) of approximately 6.1-14.7% and compressive strength of approximately 3.1-17.6% compared to control asphalt mixtures. This suggests that the mixture's resilience against moisture damage has been enhanced.

Keywords-recycled polypropylene; Recycled Concrete Aggregate (RCA); Tensile Strength Ratio (TSR); hot mix asphalt

I. INTRODUCTION

It is well established that moisture is a significant factor in the premature deterioration of asphalt pavements. A number of studies have been conducted with the objective of collecting, describing and measuring the moisture susceptibility of asphalt mixtures [1]. The extent of moisture damage in an asphalt mixture is influenced by a number of factors, including the materials used, such as aggregate and bitumen in Hot Mix Asphalt (HMA) [2]. An asphalt mixture is a complex combination of three principal phases: aggregate, binder, and air voids. Furthermore, a variety of additives, including fibers and polymers, are frequently employed to augment its functionality [3]. HMA is primarily composed of natural aggregates, representing approximately 95% of its total weight [4]. The production of asphalt paving materials necessitates the use of natural resources, including bitumen and natural aggregates. The extraction of natural aggregates results in the release of dust emissions, vibrations, and noise into the atmosphere. Furthermore, the exponential expansion of the construction industry is resulting in the depletion of natural aggregate resources, which could ultimately lead to the loss of these natural resources [5]. There has been a recent surge in the development of tools designed to facilitate decision-making in the context of local and national solid waste management planning [6]. The increasing costs of landfill and the reduction in natural resources highlight the necessity of reusing Construction and Demolition (C&D) waste materials as an alternative to Natural Aggregates (NA) in pavement construction [7]. The building and construction industry is responsible for the generation of approximately 1,200 million tons of waste materials, the majority of which is concrete [8]. The negative impact of construction materials on the environment makes recycling a crucial process. It plays a crucial role in the conservation of natural resources and the advancement of sustainable development. Moreover, it contributes to the reduction of waste from the demolition of old concrete structures [9]. The quality of RCA is typically not superior to that of natural aggregates. This is primarily attributable to the presence of two supplementary components: adhered mortar, which is more porous than the NA, rendering it more brittle and more prone to absorbing water. A number of treatment methods have been put forth with the aim of improving the quality of RCA [10]. One such treatment technique is the use of an acid solution, which effectively cleans and refines the surface of the RCA by dissolving the mortar that has adhered to it. The optimal acid concentration is 0.1 mol of hydrochloric acid (HCl) [11].

Despite the necessity for a greater quantity of asphalt cement, the substitution of natural aggregate with RCA rendered the process economically viable. This is indicated by the maximum value of $2 per ton of asphalt concrete when using 100% RCA treated mechanically [12]. The HMA industry frequently employs the use of polymers, including virgin elastomers and plastomers, as modifiers or additives. Recently, researchers have examined the use of polymers derived from plastic waste, which have the potential to enhance asphalt binder properties, improve performance and durability, and offer environmental and economic benefits. It can therefore be concluded that waste plastics can serve as a partial replacement for asphalt [13, 14]. Previous studies have shown that the addition of recycled concrete aggregates to asphalt mixtures results in a weakening of their resistance to moisture, due to the presence of air voids in the cement mortar. This presents a research gap that must be addressed. In order to improve the resistance of asphalt mixtures to moisture damage, the asphalt was modified with polypropylene waste and the mixtures were enhanced with the use of RCA as a partial substitute for aggregate. The objective of this research is to develop a sustainable methodology that employs recycled polypropylene as an asphalt cement modifier and RCA as a partial substitute for aggregate. This will reduce the probability of asphalt mixtures sustaining damage from moisture ingress, while also facilitating the disposal of this waste.

II. METHODOLOGY

This section outlines the raw materials employed in the study, compares the results of their examinations to the requisite standards, and provides a detailed account of the research methodology and testing methods used to reach the study's conclusions.

A. Materials

All materials are acquired from local sources, including crushed coarse and fine aggregates from the Al-Nibaai quarry. The aggregates are subjected to testing by SCRB R/9 in order to ensure compliance with Iraqi specifications for road and bridge construction [15]. Table I shows the physical properties of RCA and coarse virgin aggregate. Limestone dust is employed as a conventional filler in the mixture, and its properties are presented in Table II, while asphalt cement with a 40/50 penetration grade was employed, and its properties are presented in Table III. To achieve sustainability, the debris of a building was crushed in order to produce a coarse aggregate of a size ranging from 19 mm to 4.75 mm. The resulting material was immersed 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. Subsequently, the treated RCA was permitted to dry and was finally subjected to a sieving process in order to meet the requisite gradation standards for the wearing course. In addition, the resistance of the asphalt mixture to moisture damage is enhanced by the incorporation of a recycled polypropylene polymer in the bitumen at a weight ratio [16].

TABLE I. PHYSICAL PROPERTIES OF RCA AND COARSE

Test	Bulk specific-gravity	Water absorption (%)	Loss by Los-Angeles (%)	Degree of Crushing, (%)
Virgin	2.54	0.48	14	94
Untreated (RCA)	2.39	3.9	21	100
Treated (RCA)	2.4	3.7	20	100
SCRB-Specification	-	-	30 max	90 min
ASTM	C-127	C-127	C-131	D-5821

TABLE II. PHYSICAL PROPERTIES OF LIMESTONE DUST

Test	Bulk Specific gravity	% Passing Sieve No. 200
Value	2.96	96
SCRB-Specification	-	70 min
ASTM	C-188	-

TABLE III. PHYSICAL PROPERTIES OF ASPHALT CEMENT

Test	Test Method	Result	SCRB Requirements
Penetration, 0.1 mm	AASHTO -T49	47	40-50
Ductility, cm	AASHTO-T51	135	≥ 100
Flashpoint, ºC	AASHTO-T48	248	232 min
Retained penetration after thin film oven test, % of original, %	AASHTO -T49	64	>55
Ductility after thin film oven test, cm	AASHTO-T51	72	>25

The material was subjected to processing at a manufacturing facility, where it was initially reduced to a fine powder through cutting and grinding. Subsequently, the ground polymer was subjected to a sieving process using a No. 50 sieve. The material that passed the sieve was incorporated into the asphalt at varying rates, namely 2%, 4%, and 6% by weight of bitumen, as shown in Figure 1.

Fig. 1. Recycled polypropylene polymer.

An Atomic Force Microscopy (AFM) examination of small particles of recycled polypropylene polymer was performed at the nanoscale prior to milling. Three-dimensional images of the sample's surface topography were produced with nanometer-level resolution, as shown in Figure 2. The surface roughness was determined with high precision during the course of the analysis.

(a)

(b)

(c)

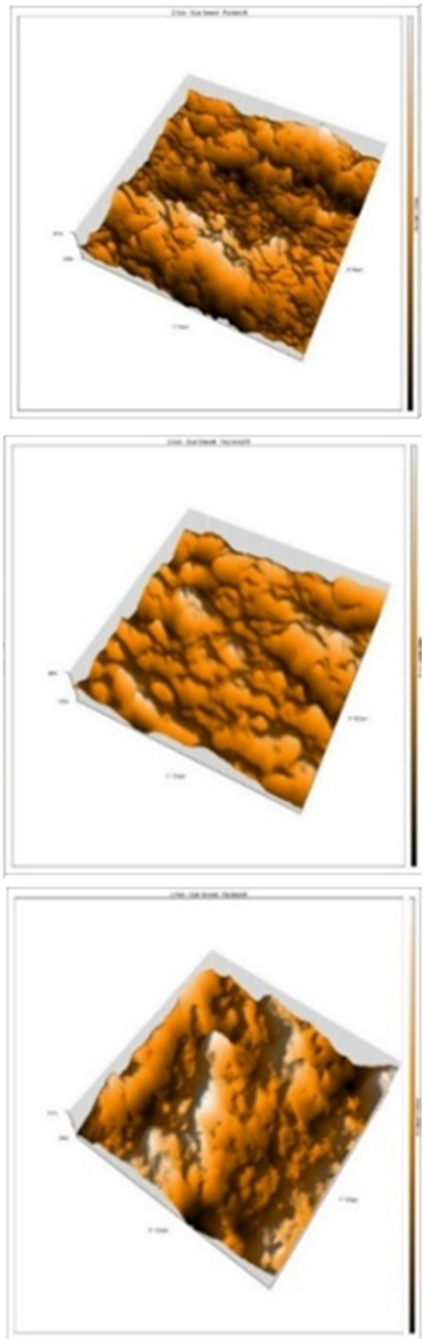

Fig. 2. AFM image of surface topography: (a)x×30 µm, y×30 µm,(b) x×12.8 µm, y×12.8 µm,(c) x×10.5 µm, y×10.5 µm.

Figure 3 shows the aggregate gradation for the surface course (type IIIA), as outlined in SCRB R/9. The coarse aggregate, representing 52% of the aggregate weight, was replaced with RCA at rates of 0%, 20%, 40%, and 60%.

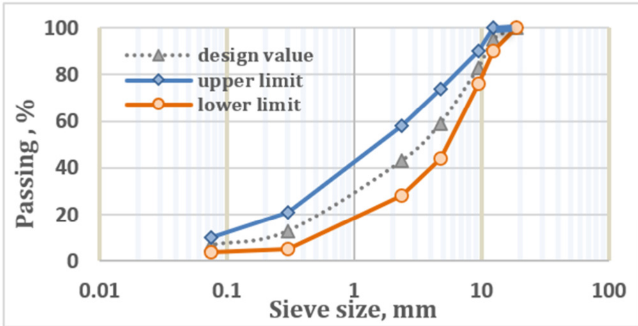

Fig. 3. Aggregate gradation for wearing course (type IIIA).

B. *Mixture Preparation*

The Marshall mix design method was employed to ascertain the ts (OAC) for the specified aggregate gradation [17, 18]. A range of 4-6% asphalt cement content was selected, with a 0.5 increment for the wearing course layer, in accordance with the recommendations set forth in SCRB R/9. The cylindrical specimens, with a diameter of 101.6 mm and a height of 63.5 mm , were prepared in accordance with the procedure described in ASTM D6926 [19]. The compactor, with a mass of 4.54 kilograms, was employed for the purpose of compacting the specimen. The specimens were dropped from a height of 455 mm, with 75 blows applied to each face, in accordance with the specifications for heavy loads road designs. Three samples were taken for each percentage of asphalt, and the average value was used. The OAC was determined in accordance with the guidelines set forth by the Asphalt Institute, which specified an OAC that results in 4% air voids while also meeting the required Marshall stability, flow limits, and density void limits as per local regulations. This air void percentage was selected for its potential resistance to moisture damage [20]. Figure 4 describes the preparation steps for the Marshall specimen.

Fig. 4. Preparation of Marshall specimens.

a) *Marshall Test*

The control specimens and others with varying RCA content were subjected to the test method outlined in ASTM D6927, with the objective of determining the Marshall stability and flow. This was followed by a bulk specific gravity test (ASTM D2726) and a maximum theoretical specific gravity test (ASTM D2041), the objective of which was to obtain the volumetric properties of the asphalt mixture. The apparatus used for the Marshall test is presented in Figure 5. Following the identification of the OAC stages, the recycled polypropylene polymer was incorporated into the asphalt mixture at varying percentages (2%, 4%, and 6%) by the weight of bitumen.

Fig. 5. Marshall test.

b) *Tensile Strength Ratio*

The influence of moisture damage was determined through the utilisation of the test method delineated in the ASTM D4867 standard. The requisite materials are combined to create dry and wet samples of HMA at the optimal asphalt binder percentage. The samples were then subjected to standard testing in a machine. A load of 0.5 mm per minute was applied, and the temperature was maintained at 25 °C. The point of rupture for each specimen was calculated based on the maximum load it was subjected to. Three samples of each mixture were prepared for the test [21-23]. It was essential to maintain the air voids of the compacted samples at a target value of 7 ± 1%. The test method described in ASTM D-6931 is used to determine the ITS of the asphalt cement specimens. For each mixture, six identical samples were prepared. Three were tested in dry conditions, while the remaining sample was tested in wet conditions. The latter was first exposed to a freezer at -18 °C for 24 hours and then to a water bath maintained at 60 °C for an additional 24 hours, as shown in Figure 6.

The ITS and TSR are given as:

$$ITS = \frac{2\times \mathrm{Pu}}{\pi\times \mathrm{t} \times \mathrm{D}} \quad (1)$$

$$TSR\ \% = \frac{ITS\ con}{ITS\ uncon} \times 100 \quad (2)$$

where *ITS* is the indirect tensile strength, *Pu* is the ultimate applied load required to cause failure, *t* is the thickness of the sample, *D* is the diameter of the sample, *TSR* is the tensile strength ratio, *ITS con* is the indirect tensile strength for a conditioned sample, and *ITS uncon* is the indirect tensile strength for an unconditioned sample.

c) *Compressive Strength Test*

This test method is employed to ascertain the compressive strength of compacted bituminous mixtures when subjected to water, as specified in ASTM D1074 [24]. The cylindrical specimens, with a diameter of 101.6 mm and a height of 101.6 mm, were created by subjecting the asphalt mixture to a compressive force until the specified height of 101.6 mm was reached [25]. For each mixture, six specimens were prepared. To ascertain the impact of moisture on compressive strength, three specimens were subjected to dry testing after being stored at 25°C for four hours, and three were tested in a wet environment after being placed in a 60°C water bath for 24 hours and then in a 25°C water bath for two hours. Subsequently, the specimens were subjected to a compressive strength test, the results of which are presented in Figure 7.

Fig. 6. Conditioned of the TSR test samples.

Fig. 7. Testing of compressive strength.

III. RESULTS AND DISCUSSION

A. *Marshall Test*

The outcomes of the Marshall test are presented in Table IV for the treated and untreated RCA, in addition to the control mixture. These results comply with the SCRB 2003 specification for the wearing course type IIIA [26]. Figure 8 and Table IV show that all RCA mixtures exhibited a higher OAC in comparison to the control mix. This was due to the fact that the cement mortar adhering to the aggregate absorbed a portion of the asphalt cement through its pores, as evidenced by previous research [26, 27]. The test results demonstrate that mixtures incorporating RCA exhibit enhanced stability and flow characteristics compared to control mixtures. The irregular surface of the recycled aggregate contributed to the enhanced stability of the specimen by facilitating improved adhesion and bonding between the binder and aggregates.

TABLE IV. MARSHALL TEST RESULTS

RCA %	OAC	Gbm, gm/cm³	Stability, kN	Flow, mm	AV, %	VMA, %	VFA, %
Control							
0%	4.9	2.338	11.12	3.46	4.00	15.72	74.13
Untreated RCA							
20%	5.03	2.329	11.54	3.58	4.00	15.57	74.01
40%	5.11	2.317	11.93	3.67	4.00	15.24	73.62
60%	5.2	2.295	12.21	3.79	4.00	15.05	73.18
Treated RCA							
20%	4.99	2.334	11.68	3.51	4.00	15.48	73.84
40%	5.04	2.321	12.22	3.60	4.00	15.20	73.34
60%	5.17	2.298	12.57	3.71	4.00	15.01	72.97

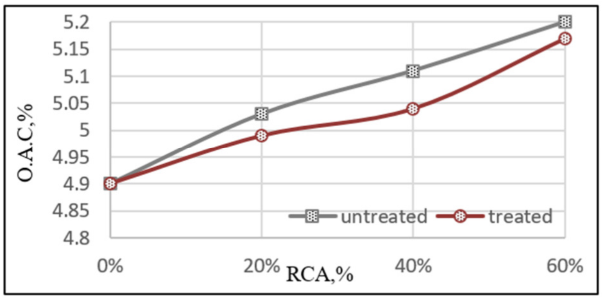

Fig. 8. Effect of RCA on OAC.

As shown in Figure 9, a comparison of the maximum stability values of treated and untreated RCA specimens reveals that acid treatment has the effect of increasing the stability of the 60% RCA mixture by 13.04%, whereas the stability of the untreated specimens is 9.8%. These findings align with those of authors in [28]. The incorporation of RCA into all mixtures resulted in enhanced flow characteristics compared to the reference mixture, potentially attributable to the asphaltene content. The results are consistent with those previously reported by authors in [29, 30]. Figure 10 presents the impact of RCA on the bulk density of asphalt mixtures. The bulk density of compacted specimens was observed to decrease as the percentage of RCA increased. However, the bulk density value of treated RCA appears to be slightly higher than that of the untreated RCA at all RCA percentages. This may be attributed to the removal of the lightweight cement mortar layer. These findings are in accordance with those reported by authors in [31-33]. In comparison to the control mixtures, the mixtures containing RCA exhibited a diminished proportion of Volatile Fatty Acids (VFA). As shown in Figure 11 and Table IV, the specimens comprising 20%, 40%, and 60% untreated RCA as coarse aggregate exhibited a diminished VFA. Subsequently, the control mixture exhibited values of 0.17%, 0.69%, and 1.28%, in that order. The specimens produced with 20%, 40%, and 60% treated RCA exhibited a reduction in voids filled with asphalt compared to the control mix, with a decrease of 0.40%, 1.07%, and 1.57%, respectively. An increase in RCA results in the absorption of asphalt from the mixture due to the presence of surface pores. This absorption results in a reduction in the effective asphalt content of HMA, which in turn leads to a decrease in VMA. As the void in mineral aggregate (VMA) decreased and the air void level in HMA remained relatively constant with increasing RCA, the void filled with asphalt (VFA) also reduced [31, 34, 35].

(a)

(b)

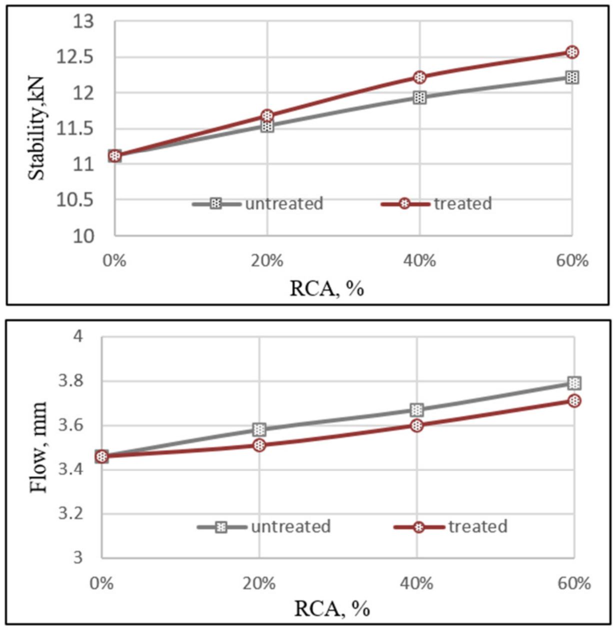

Fig. 9. Marshall test results (a) stability and (b) flow.

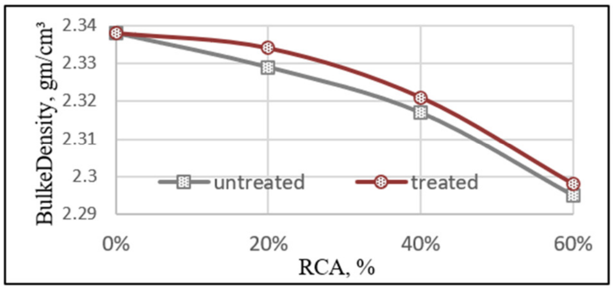

Fig. 10. Effect of RCA on bulk density.

Following the Marshall test, which was conducted to determine the OAC, recycled RPP at rates of 2%, 4%, and 6% by weight was added to the asphalt cement in order to manufacture asphalt mixtures containing different contents of coarse treated and untreated RCA (20%, 40%, and 60%). The Marshall test was conducted on all mixtures for the purpose of evaluating their stability. All mixtures exhibited enhanced Marshall stability relative to the control mixture. The mixtures containing 4% RPP with varying proportions of treated and untreated RCA demonstrated the most noticeable improvement in Marshall stability. The observed increase was 12.05%, 13.85%, and 14.57% for samples containing 20%, 40%, and 60% untreated RCA, respectively. The corresponding increases were 19.16%, 19.79%, and 20.60% for samples containing

20%, 40%, and 60% treated RCA, respectively. This improvement in stability can be attributed to the enhanced adhesion between the binder and aggregate particles, which results in a stronger bond and a more stable asphalt mix. Table V presents the Marshall stability results for mixtures containing RPP and RCA.

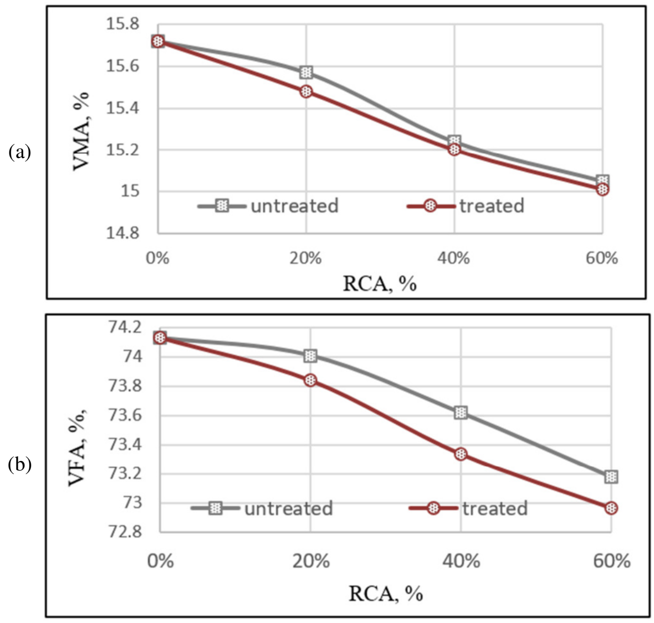

Fig. 11. Effect of RCA on (a) VMA (b) VFA.

TABLE V. MARSHALL STABILITY

RCA, %	RPP, %	Marshall stability, kN	
		Treated RCA	Untreated RCA
20	2	12.56	11.83
	4	13.25	12.46
	6	12.32	11.89
40	2	12.61	11.97
	4	13.32	12.66
	6	12.39	12.03
60	2	12.69	12.32
	4	13.41	12.74
	6	12.46	12.44

B. Tensile Strength Test Results

The ITS test is employed for the purpose of estimating the sensitivity of mixtures to moisture. Subsequently, the TSR is employed to differentiate between mixtures that are susceptible to moisture and those that are resistant, with a minimum recommended threshold of 80%. A high TSR value is indicative of the mixture's enhanced efficacy in preventing moisture-related deterioration. In order to enhance the moisture damage resistance, recycled polypropylene polymer was incorporated into the mixtures comprising both treated and untreated RCA at concentrations of 2%, 4%, and 6%. Figure 12 shows the impact of the specified recycled polypropylene polymer dosage on the change in ITS for unconditional specimens of treated and untreated RCA. It can be concluded that the addition of RPP results in an increase in ITS for the dry specimens of both treated and untreated RCA. The mixtures are composed of 20% untreated RCA and 2%, 4%, and 6% RPP, respectively. The increase in ITS was found to be 18.67%, 24.40%, and 32.90%, respectively. The mixtures consist of 40% untreated RCA and 2, 4, and 6% RPP, resulting in an increase in ITS of 23.38%, 30.66%, and 40.13%, respectively. Mixtures comprising 60% untreated RCA and 2%, 4%, and 6% RPP exhibited an increase in ITS of 37.83%, 44.08%, and 49.32%, respectively. For treated RCA, the increase in ITS was observed to be approximately 22.12%, 30.18%, and 36.13% for mixtures comprising 20% treated RCA and 2%, 4%, and 6% RPP, respectively. The observed increase was 29.24%, 36.99%, and 49.72% for mixtures containing 40% treated RCA and 2, 4, and 6% RPP, respectively. The final increase was 46.72%, 54.29%, and 56.87% for mixtures comprising 60% treated RCA and 2%, 4%, and 6% RPP, respectively.

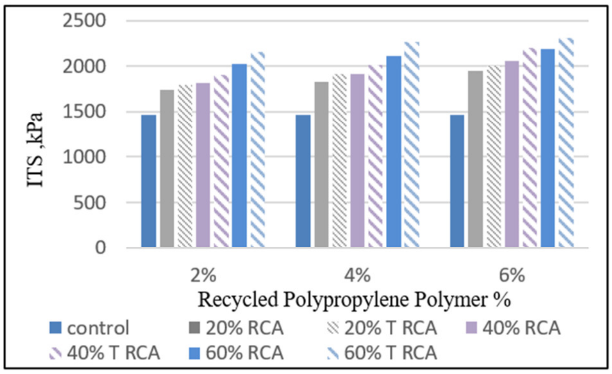

Fig. 12. ITS for unconditional specimens of treated and untreated RCA with RPP.

Figure 13 shows the alteration in ITS for wet specimens of both treated and untreated RCA. The ITS for wet specimens of untreated RCA demonstrates an increase of 34.74%, 39.37%, and 44.20% for mixtures comprising 20% untreated RCA and 2%, 4%, and 6% RPP, respectively. The results for mixtures composed of 40% untreated RCA and 2%, 4%, and 6% RPP, respectively, were 39.17%, 43.48%, and 49.71%, while the results for mixtures composed of 60% untreated RCA and 2%, 4%, and 6% RPP, respectively, were 52.80%, 56.39%, and 58.39%. In contrast, for treated RCA, ITS increased by 40.04%, 46.97%, and 50.27% for mixtures composed of 20% treated RCA and 2%, 4%, and 6% RPP, respectively 46.58%, 52.57%, and 60.61% for mixtures composed of 40% treated RCA and 2%, 4%, and 6% RPP, respectively, and 63.28%, 70.05%, and 68.51% for mixtures composed of 60% treated RCA and 2, 4, and 6% RPP, respectively. Figures 14 and 15 present these results. The TSR obtained can be seen to increase for 2% RPP, then the increase decreases slightly for 4% and 6% RPP, but remains greater than for the control mix. The rough surface of RCA facilitates enhanced bonding with binders, thereby increasing the mixture's resistance to compression and strengthening its ITS. Furthermore, the addition of recycled polypropylene polymer serves to reinforce the bond between the aggregate and asphalt, thereby enhancing the structural integrity of the asphalt mixture. The material in question exhibits favorable mechanical properties, including strength and flexibility. When incorporated into the mixture, these properties are enhanced, resulting in an increased ITS percentage. Furthermore, the addition of this material improves the adhesion between the asphalt binder and the aggregate, thereby maintaining the integrity of the mixture under wet conditions and resulting in an enhanced TSR.

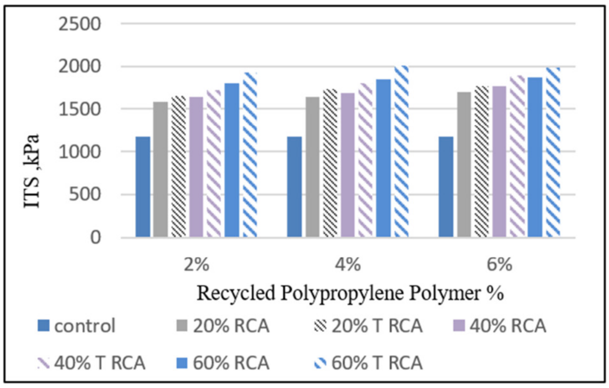

Fig. 13. ITS for conditional specimens of treated and tntreated RCA with RPP.

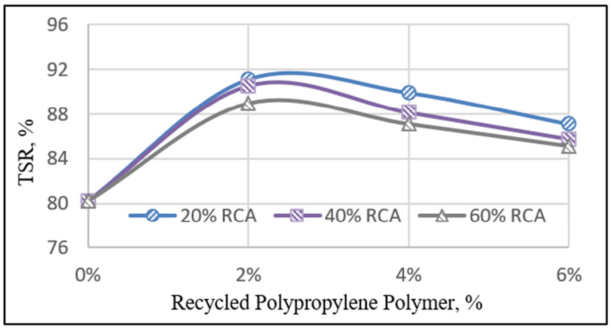

Fig. 14. TSR of recycled PPR percentages and untreated RCA.

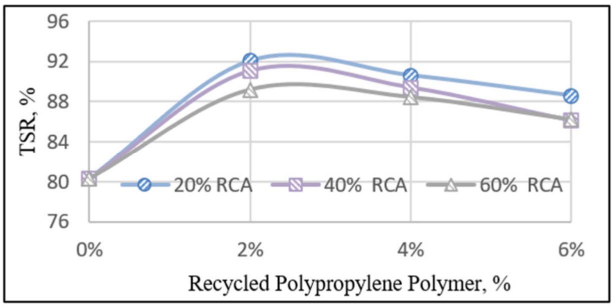

Fig. 15. TSR of recycled PPR percentages and treated RCA.

C. Compressive Strength Test Results

The Iraqi specification uses IRS parameter to estimate damage from moisture in asphaltic mixtures. The IRS is limited to a minimum value of 70%, as indicated in SCRB R/9. Figure 16 shows that adding recycled polypropylene polymer to mixtures containing RCA increased dry compressive strength for both treated and untreated RCA. Mixtures with untreated RCA had 14.48%, 18.18%, and 20.63% more strength when they had 20% untreated RCA and 2%, 4%, and 6% of RPP. The increase was 20.74%, 24.88% and 29.37% for mixtures containing 40% untreated RCA and 2%, 4% and 6% of RPP. The increase was 24.52%, 26.58%, and 41.01% for mixtures containing 60% untreated RCA and 2%, 4%, and 6% of RPP. Mixtures with treated RCA had an increase in strength of about 19.20%, 22.60%, and 24.46% for mixtures with 20% treated RCA and 2%, 4%, and 6% of RPP, respectively. The increase was 23.29%, 26.92% and 31.25% for mixtures containing 40% treated RCA and 2, 4 and 6% of RPP. Additionally, the increase was 24.80%, 29.91%, and 43.49% for mixtures containing 60% treated RCA and 2%, 4%, and 6% of RPP. Figure 17 shows the change in wet compressive strength of treated and untreated RCA. Mixtures containing 20% untreated RCA and 2%, 4%, and 6% RPP had a strength increase of 32.36%, 34.68%, and 36.18%, respectively.

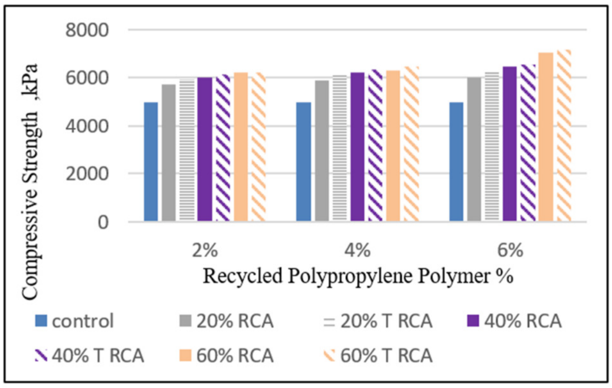

Fig. 16. Compressive strength for dry specimens of treated and untreated RCA with RPP.

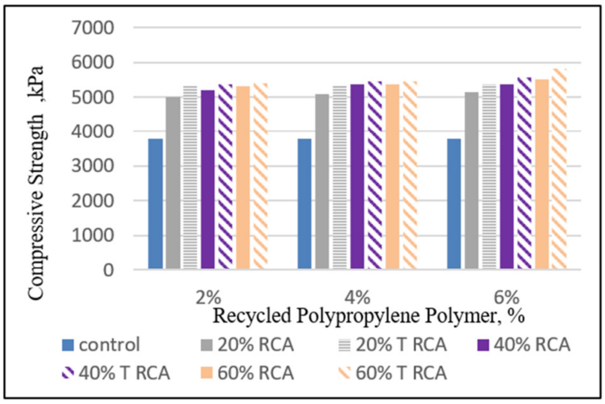

Fig. 17. Compressive strength for wet specimens of treated and untreated RCA with RPP.

Mixtures with 40% untreated RCA and 2%, 4%, and 6% RPP showed strength increases of 37.46%, 41.55%, and 41.87%. Mixtures with 60% untreated RCA and 2%, 4%, and 6% RPP had strength increases of 40.18%, 42.11%, and 45.33% respectively. Mixtures with 20% treated RCA and 2%, 4%, or 6% RPP had strength increases of 40.19%, 40.76%, and 41.61%, respectively. Mixtures containing 40% treated RCA and 2%, 4%, and 6% RPP had strength increases of 42.02%, 44.09%, and 47.08% respectively. Mixtures containing 60% treated RCA and 2%, 4%, and 6% RPP had strength increases of 42.47%, 43.78%, and 53.54% respectively. The increase in strength is also due to better adhesion. Recycled polypropylene enhances the bond between particles in the asphalt mixture. Replacing RCA with coarse aggregate and adding recycled polypropylene caused an increase in IRS, as shown in Figures 18 and 19. The mixtures containing 20% treated or untreated RCA with 2% RPP demonstrate the greatest IRS.

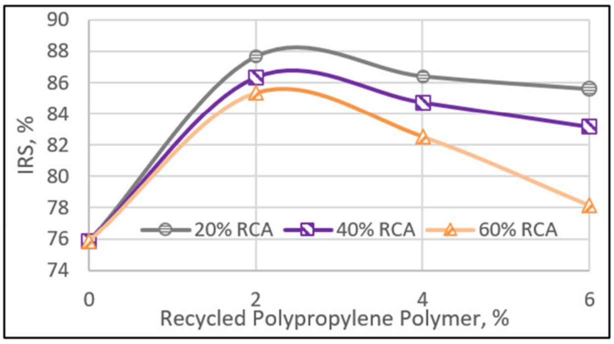

Fig. 18. Index of retained strength of recycled PPR percentages and untreated RCA.

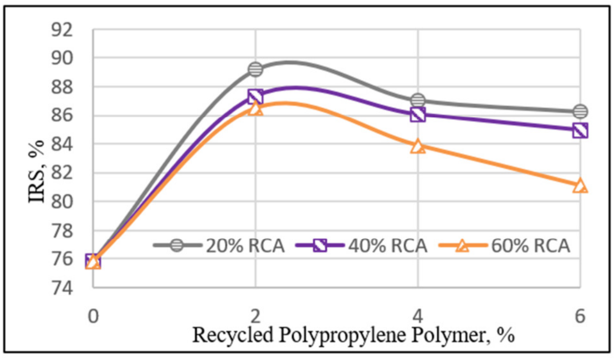

Fig. 19. Index of retained strength of recycled PPR percentages and treated RCA.

IV. CONCLUSIONS

This study employed the Marshall mix design and conducted moisture damage resistance tests to evaluate the resilience of Hot Mix Asphalt (HMA) to moisture damage through the assessment of Indirect Tensile Strength (ITS) and compressive strength. In accordance with the findings of the experimental investigation:

- The replacement of virgin coarse aggregate with Recycled Coarse Aggregate (RCA) has been observed to enhance the Marshall stability of the asphalt mix associated with the reference mixture. The asphaltic mixture exhibited a reduction in bulk density due to the lightweight nature of the RCA.
- The Optimal Asphalt Content (OAC) of the mixes incorporating RCA increased by 2.65%, 4.29%, and 6.12% for untreated RCA content of 20%, 40%, and 60%, respectively, and by 1.83%, 2.86%, and 5.51% for treated RCA.
- The application of acid treatment to the RCA resulted in an average increase in stability of 2.2% and a corresponding decrease in Marshall flow of 2%. Concurrently, the density of the mixtures prepared with treated RCA exhibited a minimal increase, with an average value of less than 1%.
- The incorporation of Recycled Polypropylene Polymer (RPP) into mixtures containing RCA led to enhanced resistance to moisture damage, as evidenced by the elevated Tensile Strength Ratio (TSR) and IRS values.
- The use of recycled polypropylene polymer at all dose levels resulted in enhanced stability, with the most notable improvement observed at 4% in the RCA mixture for both treated and untreated samples.
- The greatest increase in the TSR and IRS values is observed when 2% of recycled polypropylene polymer is added to the asphalt mixture, irrespective of the RCA ratio.
- The specimens demonstrate the highest values of the tensile strength ratio in comparison to the control specimens. In the case of the untreated RCA, the values observed ranged from 6.1% at a ratio of 60% RCA and 6% recycled polypropylene polymer to 13.5% at a ratio of 20% RCA and 2% recycled polypropylene polymer. In the case of treated RCA, the values range from 7.42% at 60% RCA and 6% recycled polypropylene polymer to 14.7% at 20% RCA and 2% recycled polypropylene polymer.
- The highest value of compressive strength was observed when compared with the control specimens. The value is approximately 3.1 to 17.6 times higher than that of the control asphalt mixtures.
- Based on the findings of this research, recommendations can be made for future studies, including the usage of higher percentages of recycled concrete aggregates, up to 100% of coarse aggregates. An alternative method of treating concrete aggregates may prove to be a more effective means of improving moisture resistance.

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