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Research Article

Moisture Susceptibility of Sustainable Warm Mix Asphalt

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Sustainable pavements are pavements that meet the requirements of present generation without influencing the capability of the future generation to meet their needs. One of the problems of the warm mix asphalt is that it has low resistance to moisture damage; therefore, the aim of this research paper is to study the possibility of producing more durable warm mixes against the moisture damage with the use of recycled concrete aggregate (RCA) which has not been studied before. Six replacement rates (0, 20, 40, 60, 80, and 100%) for the coarse version aggregate (VA) with RCA were studied. The Marshall mix design method was used to determine the optimum asphalt cement content for each replacement rate. Thereafter, specimens with the optimum asphalt cement content were prepared and tested in the indirect tension test to evaluate their moisture susceptibility. The results revealed that the mixes with higher percentage of RCA possess higher optimum asphalt content. Moreover, an improvement of 13 and 28% in Marshall stability and tensile strength ratio (TSR), respectively, was obtained in case that the VA was entirely replaced by the RCA.

1. Introduction and Background

Recently, the increase of construction prices coupled with the increase of the environmental regulations and awareness has driven a strong movement toward the adoption of sustainable technology in various construction projects including the asphalt concrete pavement. The sustainable pavement is the pavements that meet the requirements of the present generation without influencing the capability of the future generation to meet their needs. Examples of sustainable pavement include warm mix asphalt mixtures, mixes containing recycled products, and mixes containing waste products. The warm mix asphalt mixes are mixtures which could be produced and compacted approximately 15–40°C lower than that of hot mix asphalt (HMA) mixtures depending on the type of additives adopted to produce the warm mix [1].

Globally, the amount of construction and demolition waste generated each year has been estimated to be 1183 million tonnes [2]. In Iraq, annually, the generated waste solid is approximately 144 thousand tonnes and 68% of them is the construction and demolition waste. The concrete is the most significant component in the construction and demolition waste. The management of these huge waste quantities is considered as a serious challenge due to the landfill shortage and transport costs. This leads to the introduction of the RCA concrete aggregate as an alternative sustainable material for asphalt mixes. Many research studies have performed to examine and evaluate the use of RCA in hot mix asphalt.

Wong et al. [3] studied the substitution of the granite filler/fines by the RCA in hot mix asphalt (HMA), and the mixes with percent of RCA satisfied the Marshal mix design criteria. They found that the higher percent of replaced RCA revealed a greater stiffness and rutting resistance. Mills-Beale and You [4] studied the behavior of hot mix asphalt (HMA) containing RCA based on the superpave mix design method. They concluded that the voids in mineral aggregates (VMA) and voids filled in asphalt (VFA) were decreased as the percent of RCA was increased in the mix.

A study has been performed to evaluate RCA as a hot mix aggregate by Bhusal and Wen [5] as a sustainable material in which six different percentages of RCA were used. Test results indicated that the optimum asphalt ratio increases due to the high absorption of RCA and a reduction in other properties of

Table 1: Physical properties of asphalt cement based on performance grade.

Binder	Parameters	Temperature measured	Measured parameters	Specification requirements, AASHTO M320-05
Original	Flash point (°C)	—	298	230°C, min
	Viscosity at 135°C (Pa s)	—	0.487	3 Pa s, max
	DSR, $G/\sin\delta$ at 10 rad/s (kPa)	58	3.3522	1.00 kPa, min
		64	2.020	
		70	0.889	
RTFO aged	Mass loss (%)	—	0.654	1%, max
	DSR, $G/\sin\delta$ at 10 rad/s (kPa)	58	4.1596	2.2 kPa, min
		64	3.1483	
		70	1.9809	
PAV aged	DSR, $G/\sin\delta$ at 10 rad/s (kPa)	28	4684	5000 kPa, max
		25	6477	
	BBR, creep stiffness (MPa)	−6	134.0	300 MPa, max

hot mixes (modulus, resistance to rutting, fatigue, thermal cracking, and resistance to moisture damage).

Rafi et al. [6] conducted a study to evaluate the results obtained from the use of RCA aggregate in hot asphalt mixtures as compared with reference mixtures made with RCA using the Marshall method. Their test results showed that the specific gravity, air voids, and voids in mixes made by adding RCA were less than the reference mixes, and the ratio of stability/flow remained similar for all the mixes.

Motter et al. [7] evaluated the use of fractions of RCA that were obtained from 30 MPa compressive strength concrete in hot mix asphalt instead of natural aggregate coarse with different ratios of replacement (0, 25, 50, 75, and 100%). Test results for permanent deformation and durability by the moisture-induced damage test were studied according to the Marshall mix design method. Test results indicated that it is possible to use RCA as an asphalt concrete surface layer on low-volume roads in spite of high absorption, higher Los Angeles abrasion, and lower density for RCA rather than the crushed stone aggregates.

Al-Bayati et al. [8] studied the effect of RCA on the volumetric properties of HMA in which different mix designs of the HMA mixture was performed for RCA with different percentage ratios of replacing and treatment methods. Test results showed that the treatment method is more successful for developing the physical properties of RCA. The replacement of natural aggregate by RCA concrete aggregate increases the optimum asphalt content for the mixtures, and the voids in mineral aggregates (VMA) is decreased. The use of treated RCA with 30% leads to an improvement in VMA and a little increase in void filled with asphalt VFA as compared with the same percent of untreated RCA. It was seen in general the treated RCA seems to have better performance than untreated RCA properties.

Perez et al. [9] studied the availability of using RCA in HMA. Two asphalt mixes of 50% containing RCA with additional two reference mixtures without recycled aggregate were prepared. It was observed that the mixtures with RCA had high water absorption level which results in open graded and had considerable potential for stripping, a characteristic and higher dynamic modulus. Also, a deterioration of the fatigue law was indicated as compared with the reference mixtures. They concluded that it was possible to use RCA in the design of flexible pavements for roads with medium to low volume of traffic, and more research is required to cover the use of asphalt mixtures with different types of RCA. The aim of this paper is to establish the use and study the performance of RCA in warm mix asphalt aiming at more sustainable paving products.

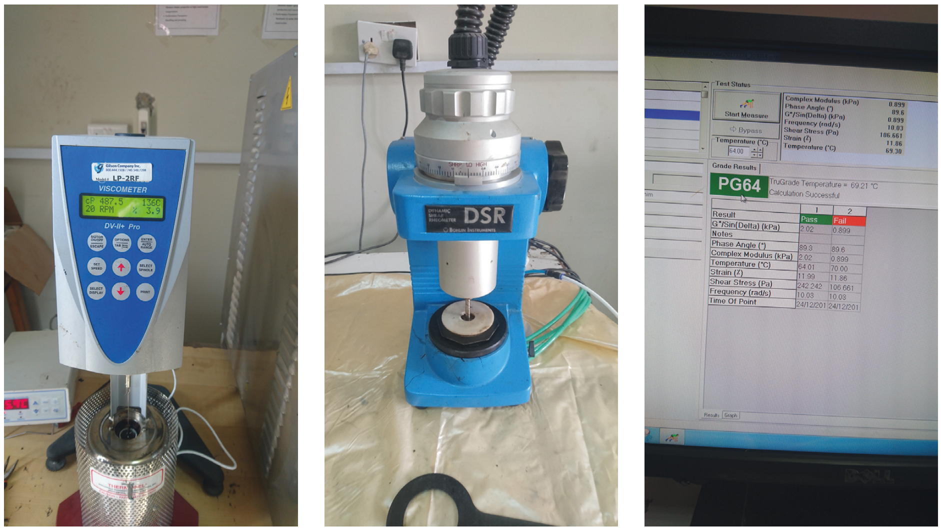
2. Materials

The raw materials which shall be used in the preparation of warm asphalt concrete mixtures for this study, namely, asphalt cement, aggregate, and mineral filler, were characterized using routine type of tests, and the results were compared with specification requirement to evaluate their suitability for job mix.

2.1. Asphalt Cement. The asphalt cement which was supplied from the Doura refinery (south-west of Baghdad) was tested as per the Superpave performance grade requirement, and the results are shown in Table 1. It is obvious from the results that the asphalt cement has a performance grade of PG 64-16. Photographs for the tests are shown in Figure 1.

2.2. Aggregate. Two types of coarse aggregates were used in the preparation of asphalt concrete mixtures (VA and RCA). The VA was crushed quartz obtained from the Al-Nibaie quarry (north of Baghdad) whereas the RCA was supplied from the concrete recycling factory in Alrathwanya district (near Baghdad International Airport); this type of aggregate was originally obtained from crushing of Texas T-wall barriers (Figure 2) with a design compressive strength of 30 MPa. The properties of the VA and RCA aggregate are shown in Table 2 which also presents the version fine aggregate test results. The coarse and fine aggregates used in this work were sieved and recombined in the proper proportions to meet the wearing course gradation as required by Iraqi standard specification (State Corporation for Roads and Bridges (SCRB)) [10]. The gradation curve for the aggregate is presented in Figure 3.

2.3. Filler. Limestone dust was used as the mineral filler for the preparation of warm mix asphalt concrete mixtures.



(a) (b) (c)

Figure 1: Photograph for asphalt cement PG test.

(a) (b)

Figure 2: Texas T-wall before and after crushing.

Table 2: Physical properties of aggregates.

Property	ASTM designation	Test results		SCRB specification
		VA	RCA	
Coarse aggregate				
1. Bulk specific gravity	C-127	2.632	2.331	—
2. Apparent specific gravity		2.636	2.501	—
3. Water absorption (%)		0.261	2.91	—
4. Percent wear by Los Angeles abrasion (%)	C-131	18	28	30 max
5. Soundness loss by sodium sulfate solution (%)	C-88	4.3	6.1	12 max
6. Fractured pieces (%)	D5821	97	100	90 min
Fine aggregate				
1. Bulk specific gravity	C-128	2.561		—
2. Apparent specific gravity		2.622		—
3. Water absorption (%)		0.809		—
4. Sand equivalent (%)	D-2419	59		45 min
5. Clay lumps and friable particles (%)	C142	1.2		3 max

The chemical and physical properties of the limestone dust are presented in Table 3.

2.4. Aspha-min. Aspha-min powder (shown in Figure 4) was used as an additive for the production of WMA; it is sodium aluminosilicate hydrothermally crystallized into fine powder. Aspha-min (containing approximately 21% water by weight) was added at a rate of 0.3% (by the weight of total mix) to the heated aggregate blend. The physical and chemical properties of the Aspha-min are presented in Table 4.

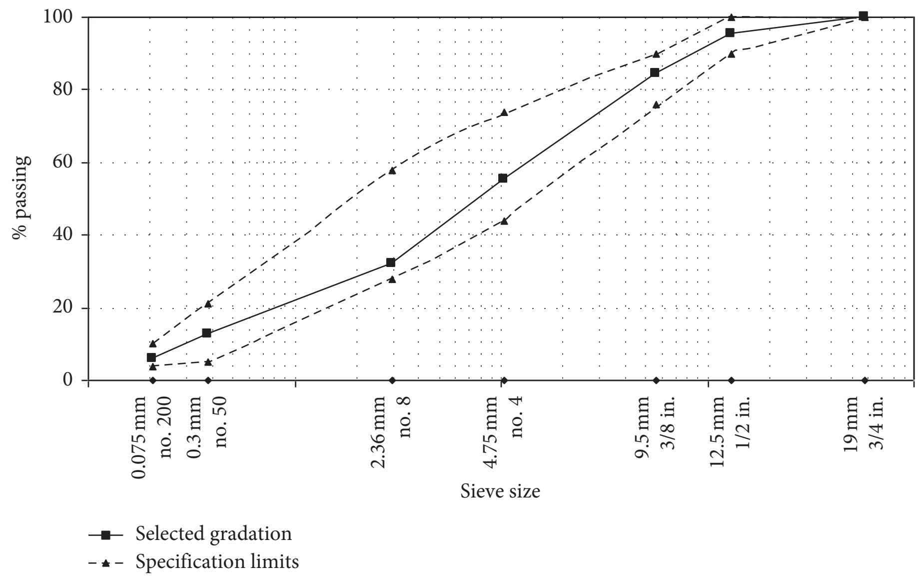


Figure 3: Selected aggregate gradation and specification limit.

Table 3: Properties of fillers.

Filler type	Chemical composition (%)							Physical properties		
	CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	SO_3	L.O.I	Specific gravity	Surface area* (m^2/kg)	% passing sieve no. 200 (0.075)
Limestone	29	10	6	16	1	0.12	37	2.84	247	95

*Blain air permeability method (ASTM C204).

3. Experimental Work and Specimen Preparation

Six replacement rates for the VA with RCA were investigated during laboratory works, and they are 0, 20, 40, 60, 80, and 100%. The specimens were labeled as WRU followed by the replacement percentage. The experimental work consists the use of the Marshall mix design method (ASTM D6926) to determine the optimum asphalt content for each replacement percentage. Then, the optimum asphalt content was used in the preparation of specimens for the indirect tension test to evaluate the moisture susceptibility of the warm mix asphalt.

According to the gradation requirements shown in Figure 3, the various fractions of aggregate (retained on each of the following sieve, 1/2, 3/8, no. 4, no. 8, no. 50, and no. 200) and the mineral filler were combined into a batch of 1150 gm on the mixing bowl and heated to a temperature of 120°C for 6 hours prior to mixing. Asphalt cement was also heated in a container to a temperature of 155°C (for 2 hours) which is corresponding to a viscosity of 170 cSt obtained from the viscosity-temperature relationship shown in Figure 5. Aspha-min was added to the heated aggregate with a rate of 0.3% (by the weight of total mix), the blend was thoroughly mixed for approximately 30 seconds, and then the exact amount of asphalt cement was poured to the mixing bowl and the bowl contents were thoroughly mixed for two minutes.

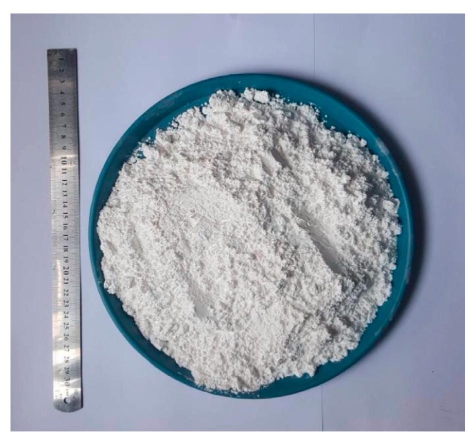


Figure 4: Aspha-min powder.

The mixing temperature was 125°C (30°C minus the HMA concrete temperature, 155°C). To bring the mixture to the compaction temperature 115°C (10°C minus mixing temperature), the bowl with its content was transferred to an oven and stored for 10 minutes in 115°C. In this period, the compaction mold (4 inches (101.6 mm) in diameter and 3 inches (76.5 mm) in height) which was preheated to 115°C is prepared, and then the mixture was poured into the compaction mold. For the Marshal mix design method, the compaction was achieved using 75 blows of the automatic

Table 4: Physical and chemical properties of WMA additive, Aspha-min.

Property	Result
Ingredients	$Na_2O.Al_2O_3.2SiO_2$ (sodium aluminosilicate)
SiO_2	32.8%
Al_2O_3	29.1%
Na_2O	16.1%
LOI	21.2%
Physical state	Granular powder
Color	White
Odor	Odorless
Specific gravity	2.03

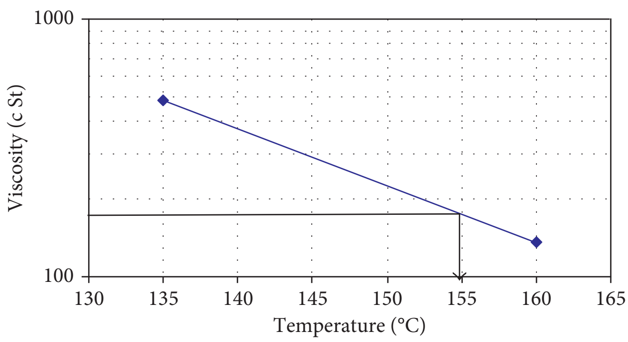
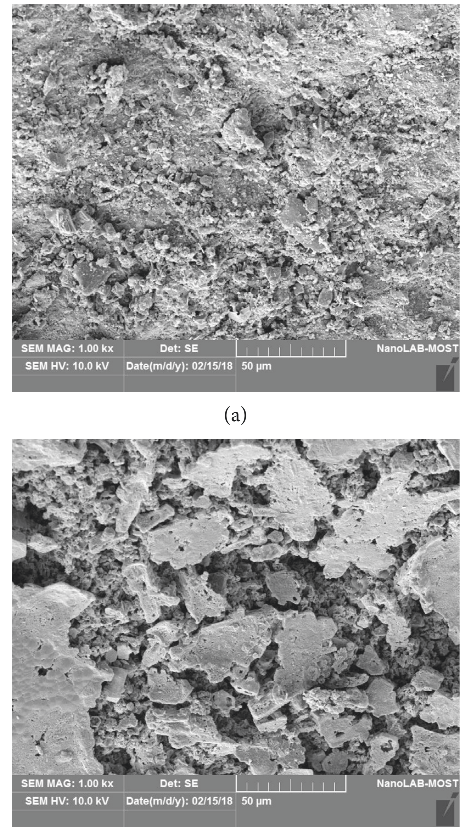


Figure 5: Viscosity-temperature chart of PG 64-16.



(a)

(b)

Figure 6: SEM images of the aggregates. (a) VA; (b) RCA.

Marshall compactor on each side of the specimen, whereas for the indirect tension test purposes, according to the RCA replacement rate, different numbers of blows per each side (44 to 61) were used to produce specimens with target air voids of 7 ± 1%.

4. Results and Discussion

4.1. Marshall Mix Design. A complete mix design was conducted using the Marshall method as outlined in Asphalt Institute series no. 2 [11]. Based upon this method, the optimum content for the asphalt cement is obtained by averaging the three asphalt cement contents which yield the maximum stability, maximum unit weight, and 4% air voids.

For each percentage of RCA, five Marshall specimens were prepared starting from 4.4% with a constant increment rate in asphalt cement content of 0.3%. But for RCA replacement rate of 80 and 100%, it was noted after plotting the Marshall properties, the stability and bulk density of the WRU specimens continuously increase as the asphalt cement content increases; therefore, further specimens were prepared with extra asphalt cement content, 5.9% for WRU 80% and 5.9 as well as 6.2% for the WRU 100%. The increase in asphalt cement content was mainly because of the more porosity of the RCA than the VA due to the cement hydration reaction. SEM images were taken for the VA and RCA particles to prove the higher porosity of RCA, and this can be easily seen in Figure 6. The higher the porosity of the aggregate particles, the higher the content of the asphalt cement absorbed. The extended specimens showed a bend in stability as well as bulk density curves; hence, the optimum content for asphalt cement was well defined.

The variation of Marshall properties with asphalt cement contents for each RCA replacement rate is exhibited in Figure 7. Examinations of the presented data suggest that the WRU specimens with the RCA content beyond 20% acquire higher asphalt cement content, stability peaks at 4.7% asphalt cement content for the specimens with RCA content of 0 and 20%, whereas for the remaining replacement rates, the asphalt cement content which yield the highest stability increased 0.3% for each 20% increase in the RCA content. This is attributed mainly to the higher absorption property for the RCA as compared to the VA (as shown previously in Table 2). This finding is in agreement with Mills–Beale and You [4], Motter et al. [7], and Al-Bayati et al. [8]. According to stability curves, the results indicate that all the WRU specimens satisfy the minimum stability requirements presented in the SCRB specification of 8 kN. But an improvement of 13% was obtained in case that the VA entirely replaced by RCA. This could be attributed to the rough surface texture of RCA as compared to the VA. The results are in agreement with Wong et. al. [3], Pérez et al. [9], and Zulkati et. al. [12]. Based on the Marshall flow results, it is obvious that there is a tendency to increase the mixture Marshall flow as the asphalt cement content increases. However, at the asphalt cement content which yields the peak stability value, it is possible to note that the flow value for the WRU 100% was quite similar to WRU 0%, and it was 3.02 mm for the former and 3.05 mm for the latter. Also, as the asphalt cement content increases,

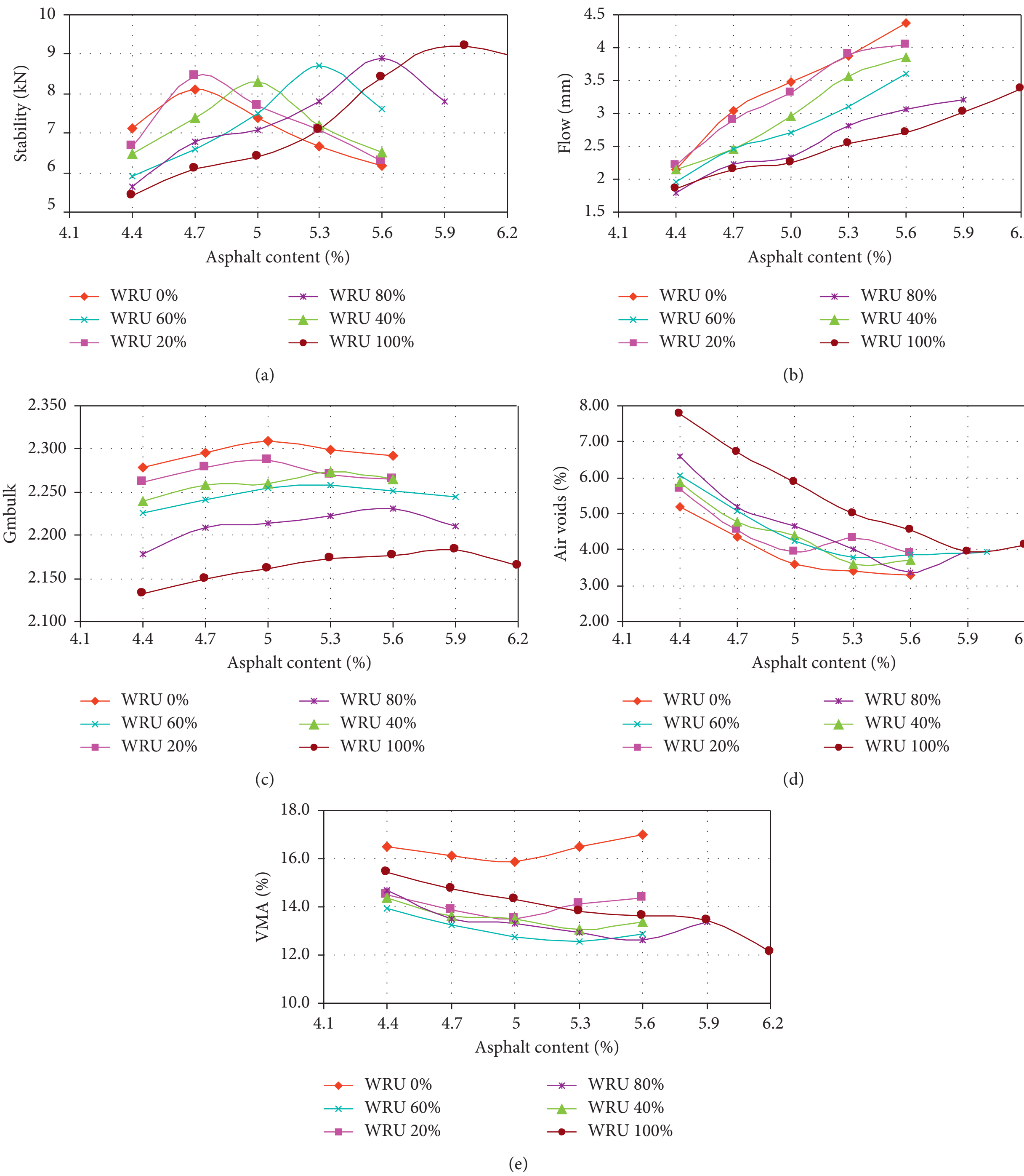


Figure 7: Marshall properties for WRU mixes.

the divergence in flow values becomes higher. All the flow values that belong to peak stability value satisfy the requirement for the SCRB specification flow requirement (2–4 mm). The flow value findings are in agreement with Pérez et al. [13] and Rafi et al. [6]. Regarding the bulk specific gravity results graphically shown in Figure 7, it is obvious that there is a trend of increasing bulk specific gravity as the asphalt cement content increases to a certain point, beyond which further increase in asphalt cement leads to reduction in the bulk specific gravity (Gmbulk). Also, it could be observed that this relationship follows the same trend of that between the RCA content and Marshall stability. As the RCA replacement rate increases, the Gmbulk of the specimens decreases. The peak value of Gmbulk corresponding to WRU 100% (at 6.2% asphalt cement content) was lower than that of WRU 0% (at 5.0% asphalt cement content) by 5.45%. This could be attributed to the lower density of the RCA grain as compared to the VA (as presented in Table (2)). Comparable behavior that agrees with this finding was obtained by Motter et al. [7], Rafi et al. [6], and Bhusal et al. [14]. The volumetric property, air voids (AV), results revealed that there is a trend of reduction in AV as the asphalt cement content increases. Also, the mixes with higher RCA content possess higher AV. At the asphalt contents which yield the peak Gmbulk values, the AV for the WRU 100% was higher than that of WRU 0% by approximately 10%. This was expected since the RCA grains have higher absorption than that of the VA. This finding is comparable with that obtained by Motter et al. [7] and Rafi et al. [6]. Nevertheless, all the AV values for the WRU mixes at the peak Gmbulk are within the range of the SCRB specification requirement (3–5%). The voids in mineral aggregate (VMA) results as presented in Figure (7) showed that the mixes with VA have higher VMA values than those containing RCA. The average VMA for the WRU 0% over the entire asphalt cement content was 16.4 which is higher than that of WRU 100% by 17%. The inspection for the VMA expression which is given in (1) and reviewing the data presented in Table (2) and Figures (3) and (7) revealed that the rate of decrease in denominator is higher than that of the numerator, Therefore, it is possible to argue that the VMA decreases as the percentage of RCA replacement increases.

$$\mathrm{VMA} = 100 - \left(\frac{\mathrm{Pa} \times \mathrm{Gmbulk}}{\mathrm{Gabulk}}\right), \tag{1}$$

where Pa = aggregate percentage in mix (by mass), Gmbulk = specimen bulk density, and Gabulk = aggregate bulk density.

The optimum asphalt cement content for the WRU mixes with all the replacement rates which was calculated based on averaging the three asphalt cement contents which yield the maximum stability, maximum unit weight, and 4% air voids is shown in Table 5. These contents will be used for specimen preparation for the moisture susceptibility evaluation.

4.2. Moisture Susceptibility. The adopted procedure to evaluate the moisture susceptibility of WMA and HMA specimens is ASTM D 4867. For each mix type, six specimens were compacted; one subset of the specimens (three specimen) was tested at temperature of 25°C (unconditioned specimens) in the indirect tension test, whereas the other subset was subjected to one cycle of freezing and thawing (16 hrs in −18 ± 2°C and then, 24 hrs in 60 ± 1°C) and then tested the same as the first subset (conditioned specimens). During the indirect tension test, the specimen is loaded along the diameter and the splitting force is recorded (as shown in Figure 8. The test parameters are calculated as follow:

$$\begin{aligned} \mathrm{ITS} &= \frac{2P}{\pi t\, D}, \\ \mathrm{TSR} &= \frac{\mathrm{C.ITS}}{\mathrm{UC.ITS}}, \end{aligned} \tag{2}$$

where P = splitting load, t = specimen height (thickness), D = specimen diameter, C.ITS = conditioned indirect tensile stress, and UC.ITS = unconditioned indirect tensile stress.

Based on the results exhibited in Figures 9 and 10, it is obvious that there is a distinct trend for the increase of tensile strength (unconditioned) as the RCA replacement rate increases. The tensile strength for the WRU 100% was higher than that of WRU 0% by 36.8%. This increase in tensile strength is mainly due to the surface texture of the aggregate, and this impacts the bond between asphalt and aggregate particle. It is clearly shown in Figure 11 that the failure occurs in the mastic zone of the WRU 0% while it breaks the RCA particles in the WRU 100% sample, which refers to a better bond.

Table 5: Optimum asphalt content for WRU mixes.

RCA (%)	0	20	40	60	80	100
Optimum asphalt content (%)	4.83	4.88	5.15	5.23	5.5	5.88

Figure 8: Indirect tension test for the WRU specimen.

It was observed that the WRU 100% specimen splitting surface included broken RCA, whereas the WRU 0% failure plane passes through the VA-asphalt cement interface; this reflects the increase in tensile strength of the RCA over the VA. Reminding that the minimum acceptable limit for the TSR is 80%, the replacement of the entire coarse aggregate with the RCA resulted in improvement of the TSR by 18%, and this was the only case which satisfies the TSR minimum limit. This finding was comparable with that obtained by Motter et al. [7] and Paranavithana and Mohajerani [15].

5. Conclusions

According to the presented works in this research and within the limitation of the test program and the materials used, the following salient conclusions can be drawn:

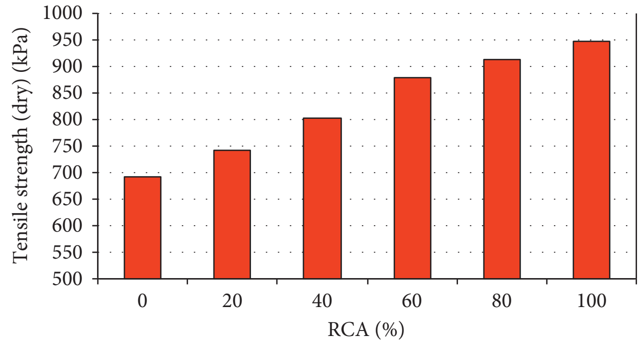
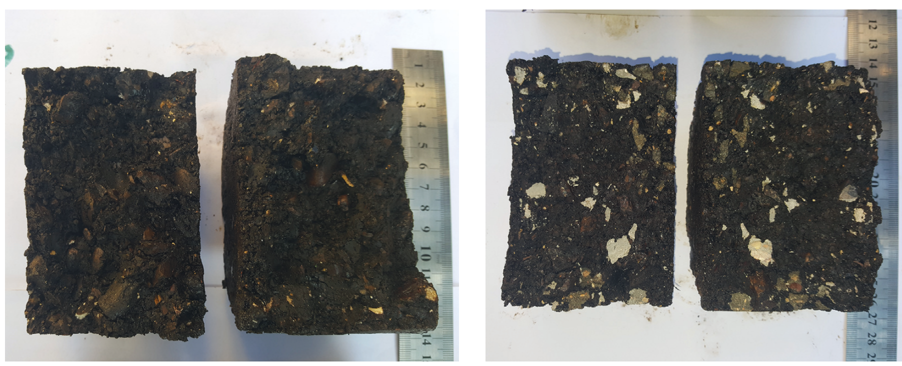


Figure 9: Unconditioned indirect tension test results specimen.



WRU 0%

(a)

WRU 100%

(b)

Figure 10: Tensile strength ratio results.

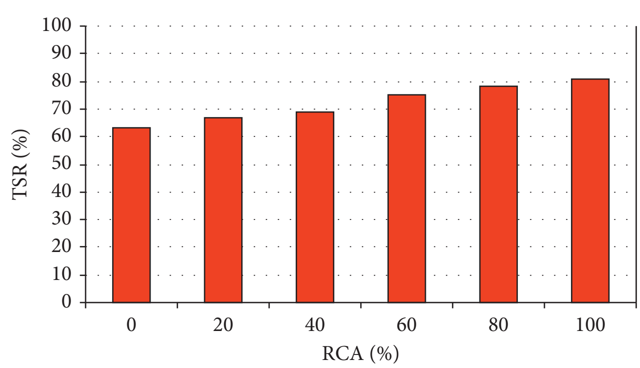


Figure 11: WRU unconditioned specimens after the indirect tension test. (a) WRU 0%; (b) WRU 100%.

(a) The use of different replacement rates for the RCA has a significant influence on the Marshall mix design properties, and some of the obtained results can be summarized as follows:

(1) The mixes with higher percentage of RCA possess higher optimum asphalt content, the highest optimum asphalt cement content (5.88%) belongs to WRU 100% indicating that for each 20% increase in RCA replacement percent beyond the 20%, the asphalt cement demand increases by 0.2%.

(2) An improvement of 13% in Marshall stability was obtained in case that the VA entirely replaced by the RCA, the Marshall stability for the WRU 100% was the highest (9.8 kN) in comparison with all other RCA replacement values.

(3) At the peak stability, the Marshall flow value for the WRU 100% was quite similar to WRU 0%, and it was 3.02 mm for the former and 3.05 mm for the latter.

(4) The air voids for the WRU 100% was higher than that of WRU 0% by approximately 10% at the peak Gmbulk, but both satisfied the specification requirements (3–5%).

(b) The replacement of the entire coarse aggregate in WRU mixes with the RCA resulted in improvement of the TSR by 28%, and the moisture susceptibly was for WRU 100% satisfied the TSR minimum limit (80%). Also, the unconditioned tensile strength for the WRU 100% was higher than that of WRU 0% by 36.8%.

(c) The use of RCA instead of VA has shown a significant improvement in moisture susceptibility of warm mix asphalt prepared using Aspha-min additive and has added to the local knowledge the possibility of producing more durable mixes against the moisture damage mode of failure.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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