Examining the Effect of Coarse Recycled Concrete Aggregate on Moisture Damage Resistance of HMA Mixtures

Hanaa Khaleel Alwan Al-Bayati[1]
Ph.D. Centre for Pavement and Transportation Technology (CPATT), Department of Civil and Environmental Engineering, Faculty of Engineering, University of Waterloo, 200 University Avenue West, Waterloo, Ontario, Canada N2L 3G1, Phone: +1-519-888-4567× 30187 , Fax: +1-519-888-4300, E-mail: halwan@uwaterloo.ca

Susan L. Tighe
Ph.D., P. Eng., President 2017-2018,
Canadian Society for Civil Engineering,
Ph.D., P. Eng., Professor, Norman W. McLeod Professor of Sustainable Pavement Engineering, Department of Civil and Environmental Engineering, Faculty of Engineering, University of Waterloo, 200 University Avenue West, Waterloo, Ontario, Canada N2L 3G1, Phone: +1-519-888-4567× 33152, Fax: +1-519-888-4300, E-mail: sltighe@uwaterloo.ca

Principal Author: Hanaa Khaleel Alwan Al-Bayati

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Abstract:

Moisture damage in asphalt mixtures has become a widely discussed topic due to its high influence on asphalt mixture behavior. Moisture damage is a phenomenon that relates to the loss of stiffness and strength of asphalt mixtures because of exposure to moisture under the influence of mechanical loading of traffic, which results in what is known as stripping. Moisture damage that leads to the deterioration in the integrity of asphalt pavement plays a key role in the occurrence of other distress types including fatigue cracking, rutting, etc. Therefore, this study aims to evaluate the influence of the addition of coarse recycled concrete aggregate (CRCA) on the tensile strength and moisture sensitivity of Ontario Superpave mixtures. Mix designs of asphalt mixtures were performed for two types of CRCA at various proportions (0%, 15%, 30%, and 60%). The impact of CRCA types on the tensile strength and moisture sensitivity of asphalt mixtures were evaluated. The obtained results also are statistically analyzed. The findings showed that the tensile strength of hot mix asphalt (HMA) mixtures that included different CRCA types with various proportions have higher values than the control mix. Additionally, the laboratory outcomes revealed that all TSR values for mixtures that included different CRCA types with various percentages are higher than the minimum required value of MTO specifications. This indicated a highly successful performance for these mixtures that included CRCA. The results of the ANOVA analysis showed that there is a statistically insignificant effect of CRCA type, and proportion on the TSR. However, the type of CRCA has a higher effect on the results of TSR compared to the CRCA percentage.

Key words: Asphalt mixtures, Coarse recycled concrete aggregate (CRCA), Moisture damage, Tensile strength.

1. Introduction

Asphalt concrete represents one of the main materials required for constructing road pavement (Liu et al., 2017). Generally, it consists of approximately 95% aggregate and 5% asphalt material. In asphalt pavement, the aggregate particles represent a structural framework (skeleton) for the mixture, whereas, the asphalt binder works like a sticky substance. The physical properties of both coarse and fine aggregates have a considerable influence on the asphalt pavement performance (Arabani & Azarhoosh, 2012). It was estimated that one kilometre of road approximately 150 mm thick and 10 m wide needs roughly 3750 tonnes of hot mix asphalt (HMA) mixture, whereas another study showed that a kilometre of pavement construction required 12,500 tonnes of natural aggregate (Zoorob and Suparma, 2000; Ektas and Karacasu, 2012).

In terms of natural resources, natural aggregates are quickly becoming exhausted worldwide due to an overwhelming demand for raw materials. Simultaneously, tremendous amounts of construction and demolition (C&D) waste are generated from various human activities including but not limited to construction, renovation and the demolition of aged buildings and civil engineering structures. Recently, the amount of C&D waste generated annually has been estimated at 1,183 million tonnes worldwide (Purushothaman et al., 2014). To solve various problems including lowering the consumption of virgin materials, decreasing waste materials in landfills (Hossain et al. 2016; Jin et al., 2017) and reducing environmental problems, the utilization of recyclable waste materials, especially recycled concrete, as a sustainable solution has become highly required and an urgent priority in the asphalt industry.

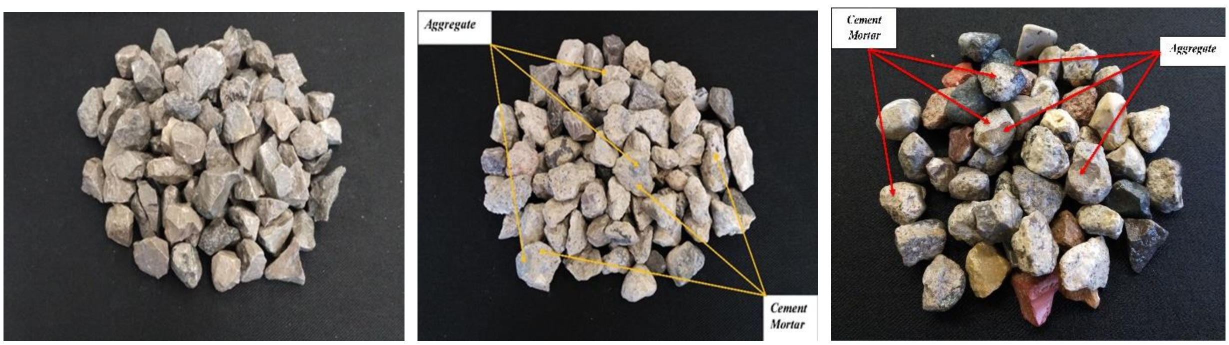
Numerous studies have been conducted to investigate the use of RCA in HMA mixtures (Shen & Du, 2004; Paranavithana & Mohajerani, 2006; Wong et al., 2007; Du & Shen, 2007; Pérez et al., 2009; Wu et al., 2013; Pasandín & Pérez, 2014; Radević et al., 2017). Pérez et al., (2009) evaluated the resistance of asphalt mixtures that included RCA with natural aggregate with respect to fatigue cracking and dynamic stiffness. The findings of the study revealed that the mixture that included RCA had a higher dynamic modulus than mixtures without RCA even if a large amount of bitumen is used. Zhu et al. (2012) concluded that the addition of CRCA without treatment causes poor moisture resistance and low-temperature flexibility. The addition of treated CRCA, using a pre-coating method with liquid silicone resin, works to improve these properties. The addition of treated CRCA improves strength, absorption, and adhesion with asphalt while it has a negative effect on the permanent deformation at elevated temperatures. However, mixture properties at elevated temperatures are still acceptable.

Moisture damage in asphalt mixtures has become a widely discussed topic due to its high influence on asphalt mixture behavior. Moisture damage plays an important role in many different types of distress including rutting, fatigue cracking, raveling, and potholes (Moraes et al., 2011; D'Angelo and Anderson, 2003). Therefore, the reduction of moisture damage impact is becoming one of the significant challenges for researchers, agencies and departments of transportation. In asphalt pavements, moisture damage can be defined as deterioration of mechanical properties such as stiffness, durability and strength due to the presence of water. Based on the literature review, it is noted that some studies indicated that asphalt mixtures which include RCA have higher moisture susceptibility than natural aggregate asphalt mixtures (Pasandín and Pérez, 2013). However, some other investigations revealed that the addition of RCA as a coarse or fine aggregate can improve the moisture susceptibility of asphalt mixtures (Du and Shen, 2007, Cho et al., 2011, Chen et al., 2011). Therefore, the main objective of this research is to evaluate the possible application of different types and various proportions of coarse recycled concrete aggregate (CRCA) in typical Ontario HMA mixtures in terms of tensile strength and moisture damage.

2. Materials and Methods

2.1 Materials

Natural aggregate and one filler type that is commonly utilized for preparing asphalt mixtures; namely, dust plant, were obtained from the Miller Group and one type of asphalt binder, namely, PG 64-28 was used. In this research, two different RCA types were utilized, RCA#1 was provided from a ready-mix concrete plant through the crushing process of concrete that has unsatisfactory properties, performance, and age. Hence, RCA#1 can be categorized as fresh concrete that has not been used in civil engineering works. The second type, RCA#2, is classified as a granular A according to the Ontario provincial standard specifications (OPSS.MUNI 1010). RCA#2 was produced by Steed and Evans Limited in St. Jacobs, Ontario. In this study, CRCA is defined as the sieve fraction retained between 4.75 and 19 mm. The optical images of natural aggregate, RCA#1 & RCA#2 are shown in Figure 1-a, b, and c, respectively.



1-a. natural aggregate 1-b. RCA#1 1-c. RCA#2

Figure 1: Optical images of natural aggregate & RCA types

2.2 Methods

2.2.1 Preparation of Natural Aggregate & CRCA

RCA was washed thoroughly so that all noticeable impurities such as wood chips and others were removed. Then, all-natural aggregate & RCA were dried in an oven at 105 ± 5 °C for 24 hr before the sieve analysis procedure. RCA was sieved with a 4.75 mm sieve to ensure that only the coarse aggregate was retained. The aggregate gradation of both of natural aggregate and RCA is provided in Figure 2.

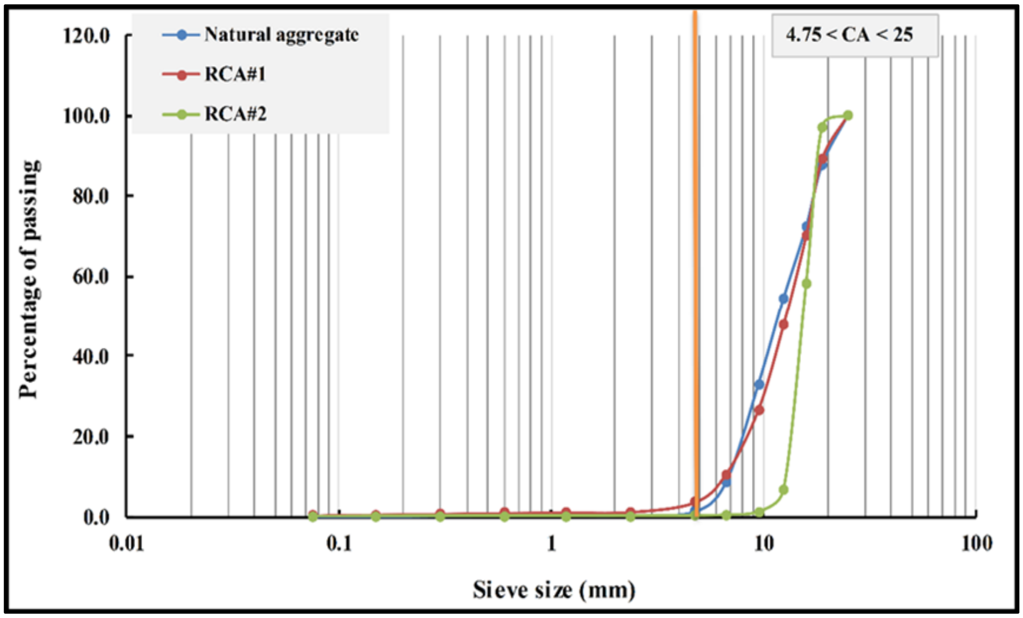


Figure 2: Particle size gradations of natural aggregate & RCA

2.2.2 Superpave Mix Design

The Superpave mix design was carried out based on AASHTO R 30-02 (2010). The design is equivalent to a single-axle load ranging between 10 and 30 million. Superpave mixture design procedure was performed according to the nominal maximum aggregate size (NMAS), 19 mm. As a partial substitute for coarse natural aggregate, four different proportions of CRCA (0%, 15%, 30%, and 60%) were added for the included CRCA mixtures. The gradation with different types and percentages of CRCA, targeted the mix design of Miller group, and ministry transportation Ontario (MTO) specifications are numerically tabulated in Table 1. Table 2 shows the volumetric properties of different HMA mixtures that were prepared in this study. All experimental tests were conducted in the Centre for Pavement and Transportation Technology (CPATT) in the University of Waterloo.

Table 1. Gradations with various CRCA proportions, targeted mix design, and MTO specifications

Sieve Size, mm	Passing (%) for Different CRCA Percentages						The Target of Mix Design	MTO Limitation
	0.0% CRCA	15% CRCA#1	30% CRCA#1	60% CRCA#1	30% CRCA#2	60% CRCA#2		
25	100	100	100.0	100.0	100	100.0	100	100
19	95.2	95.2	95.3	95.2	96.6	97.3	96.8	100 - 90
16	89.0	88.7	88.5	87.4	86.6	82.9	90.6	90 - 23
12.5	81.8	81.1	80.5	78.2	73.9	64.1	83	
9.5	73.2	72.3	71.8	69.0	67.8	59.1	73.3	
6.7	63.3	63.0	63.1	61.0	61.5	55.1	63.3	
4.75	57.1	56.7	55.9	53.8	56.0	51.7	55.9	
2.36	42.8	42.8	41.3	41.2	41.8	40.9	43.5	49 - 23
1.18	30.7	30.7	30.5	30.5	31.2	30.5	32.5	
0.6	22.9	23.0	23.6	23.6	24.3	23.6	25.1	
0.3	10.2	10.3	10.3	10.3	10.3	10.3	11.8	
0.15	5.4	5.5	5.6	5.5	5.5	5.5	5.5	
0.075	2.1	2.2	2.2	2.1	2.1	2.1	3.8	8 - 2

Table 2. Volumetric characteristics of mixtures with different types and percentages of CRCA

Aggregate Type / Property	0 % CRCA #1	15% CRCA #1	30% CRCA #1	60% CRCA #1	30% CRCA #2	60% CRCA #2	Acceptable Limitations of MTO Specification
OAC AC (%)	4.83	4.90	5.31	5.71	5.12	5.20	-
VMA (%)	14.50	13.60	13.66	16.18	14.00	13.27	13 min.
VFA (%)	72.50	70.80	70.70	74.80	71.40	70.03	65-75
Vv (%)	4.00	4.00	4.00	4.04	4.00	4.00	4.0
G_{mb}	2.400	2.395	2.373	2.351	2.384	2.367	-

2.2.3 Indirect Tensile Strength Test (Modified Lottman Test- AASHTO T283)

The adoption of this method was by AASHTO in 1985. It was a highly accepted method from many states and transportation departments therefore it was applied in the Superpave mix design procedures to evaluate moisture susceptibility of asphalt mixtures. The ITS was determined for mixtures that included both types of CRCA with various proportions in accordance with AASHTO T-283 method. By using a Superpave gyratory compactor with a height of 95 ± 5 mm, the samples with air voids of 7% ± 0.5 were compacted. The compacted samples were divided into two main groups in which three specimens for each group; namely, unconditioned (control) strengths and conditioned strengths. While the test temperature and loading rate were 25 °C and 50 mm/min, respectively, for the unconditioned samples, the other specimens were applied for moisture-conditioning. The conditioning firstly includes achieving a saturation between 70% and 80% for the samples. At a minimum period of 16 hrs, the samples then were placed in a freezer at a temperature of -18 ± 3 °C. After that, the specimens were placed in a hot water bath at 60 ±1 °C for 24 ±1 hr. After the hot water bath, the samples were kept in a water bath at a temperature of 25 ±0.5 °C for 2 hrs ±10 mins before the specimens were prepared for testing. Thus, the TSR ratio was determined by dividing conditioned strength by unconditioned strength. According to the standard OPSS 1151 (2007), the TSR value should be more than 80%. The ITS and TSR are calculated using the following equations (Solaimanian et. al., 2003; Zollinger, 2005):

$$ITS = \frac{2000 * P}{\pi * t * D} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where: ITS = indirect tensile strength, kPa; P = maximum load, N; t = sample thickness before test, mm; D = sample diameter, mm.

$$TSR = \frac{ITS_{conditioned}}{ITS_{control}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Where: TSR = tensile strength ratio; $ITS_{con.}$ = tensile strength of conditioned; ITS_{uncon}. = tensile strength of unconditioned.

3. Results and Discussion

3.1 Physical and Mechanical Properties of Natural Aggregate and CRCA

Table 3 presented the outcomes of the physical and mechanical properties of natural aggregate and CRCA for both different CRCA types. From the perspective of physical properties, namely, bulk relative density (BRD) and water absorption, a considerable difference is registered between natural aggregate and both CRCA#1& 2. In addition, a relative variation is observed in the physical properties between CRCA#1 and CRCA#2. These findings confirm the outcomes of previous investigations which demonstrated that the absorption capacity of RCA is significantly higher than natural aggregate (Wu et al., 2013; Pasandín & Pérez, 2014). Adhered mortar, which has a higher porosity than natural aggregate, results in the RCA being more susceptible to absorbing more water compared to natural aggregate (Al-Bayati et al., 2016). Hence, the presence of adhered mortar leads to increased water absorption, lowered density, and weaker bond strength (Wong et al., 2007).

In terms of mechanical properties, abrasion loss and adhered mortar loss various observations can be indicated. Compared to CRCA#1, the outcomes indicate that the abrasion loss of CRCA#2 is significantly lower and closer to the natural aggregate value, indicating a strong type of CRCA. Such a strong type of CRCA has a lower quantity of attached mortar; therefore, the findings of the adhered mortar loss are consistent with the abrasion loss results.

Table 3: Physical and mechanical properties of natural aggregate and CRCA

Aggregate Type	Bulk Relative Density (BRD) ASTM (C 127)	Absorption, %, ASTM (C 127)	Adhered Mortar, %, Without Steel Ball	Micro-Deval Abrasion Loss, %, ASTM (D6928)	Fractured Particles, % ASTM (D5821)
Natural aggregate	2.658	0.80	-	15.89	95.50
CRCA#1	2.295	5.91	3.02	23.57	89.90
CRCA#2	2.421	3.74	1.08	16.03	95.72

3.2 Influence of CRCA on the Tensile Strength

ITS is usually used to measure the tensile strength of asphalt mixtures, which could be further used for evaluating different relevant behaviours such as road surface cracking, permanent deformation, and stripping (Lee et al., 2012).

To evaluate the effect of CRCA types on tensile strength, Figure 3 demonstrates the average of the laboratory outcomes of conditioned and unconditioned ITS samples of the mixtures that included CRCA#1 and CRCA#2 with various proportions. For all cases, it is important to mention that the worst tensile strength is recorded for the control mixture (0% CRCA) among various tensile strength values, indicating a successful behaviour for the addition of various CRCA types with different proportions. It is observed that the mixtures that included CRCA#1 & 2 had the same behavior trend in terms of tensile strength. Generally, an increase in the CRCA percentages leads to a decrease in the ITS values. Additionally, the mixtures that included CRCA#2 up to 60% exhibited better tensile strength in both ITS conditioned and unconditioned state, indicating a higher tensile strength than the mixtures that included the same proportion of CRCA#1. It is interesting to note that the maximum ITS values recorded for 30% CRCA#2 for unconditioned and conditioned samples are 941.5 kPa and 856.5 kPa with an increase of 85.6% and 86.7%, respectively. This is followed by the ITS values of 60% CRCA#2 addition for both unconditioned and conditioned samples with an increase of 71.5% and 56.8%, respectively. This could be explained by the existence of a high proportion of adhered mortar attached to the CRCA#1 surface, which is more brittle under the impact of the compaction of wheel loads, resulting in a poor adhesion between the CRCA particles and asphalt binder. Hence, it can be stated that the type of CRCA has a considerable effect on the tensile strength of the mixture. In conclusion, the HMA mixtures that include CRCA with different types can tolerate higher strains before their failure, which means they are more likely to resist cracking compared to asphalt mixtures that include natural aggregate with a low tensile strain at failure.

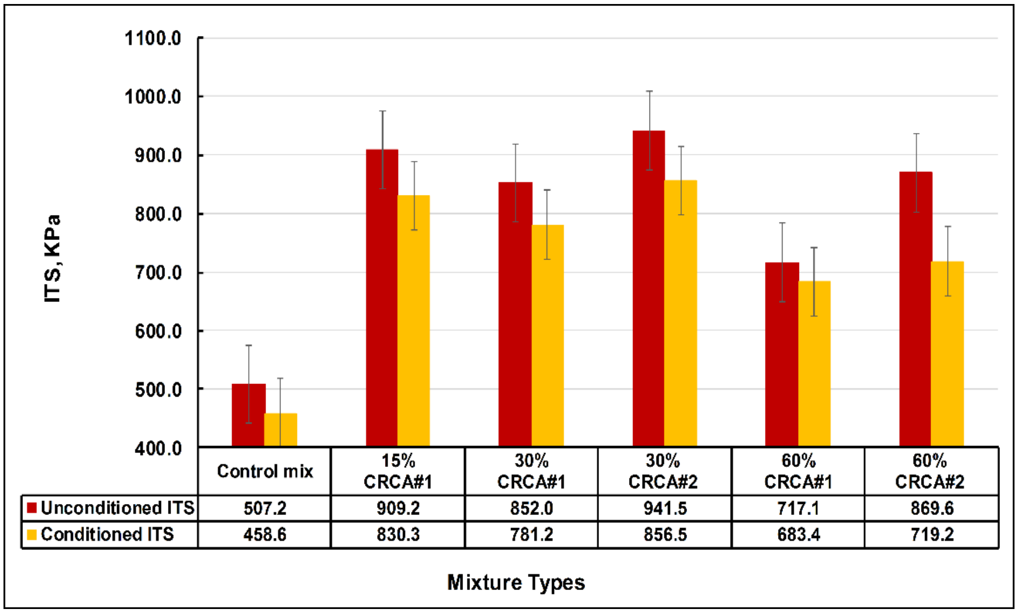


Figure 3: ITS for mixtures including different CRCA types with various proportions

3.3 Effect of CRCA Addition on the Moisture Damage

Moisture sensitivity, also known as moisture damage, refers to a type of degradation that mainly influences the mechanical characteristics of an asphalt mixture because of the presence of water (Pasandín & Pérez, 2013). To obtain an asphalt mixture that can successfully resist moisture and water damage, the minimum required TSR value should be 80 % (Pérez et al., 2012).

3.3.1 Influence of CRCA Proportion

Figure 4 shows the behaviour of TSR values of mixtures including different proportions of CRCA#1. The laboratory results demonstrated that all TSR values are higher than 80%, representing the minimum required value of MTO specification for HMA mixtures, resulting in a highly successful behaviour for different CRCA#1 proportion. The values of TSR increases when the CRCA addition is increased even with a high CRCA proportion of 60%. Surprisingly, among various TSR values, the worst TSR value is recorded for the mixture of control mix (0% CRCA). This could be attributed to a good adhesion of CRCA with asphalt binder due to the roughness of adhered mortar surface and the angularity of CRCA particles that can exist as a result of the impact of the crushing process. It is noteworthy that the values of TSR for mixtures that included various proportions of CRCA#1 are strongly correlated due to obtaining a considerable regression. A polynomial equation reflects well the behaviour of the relation between the TSR values and proportions of CRCA#1 addition. Due to the importance of the moisture sensitivity test for cold weather countries, these outcomes are very promising and important for RCA applications.

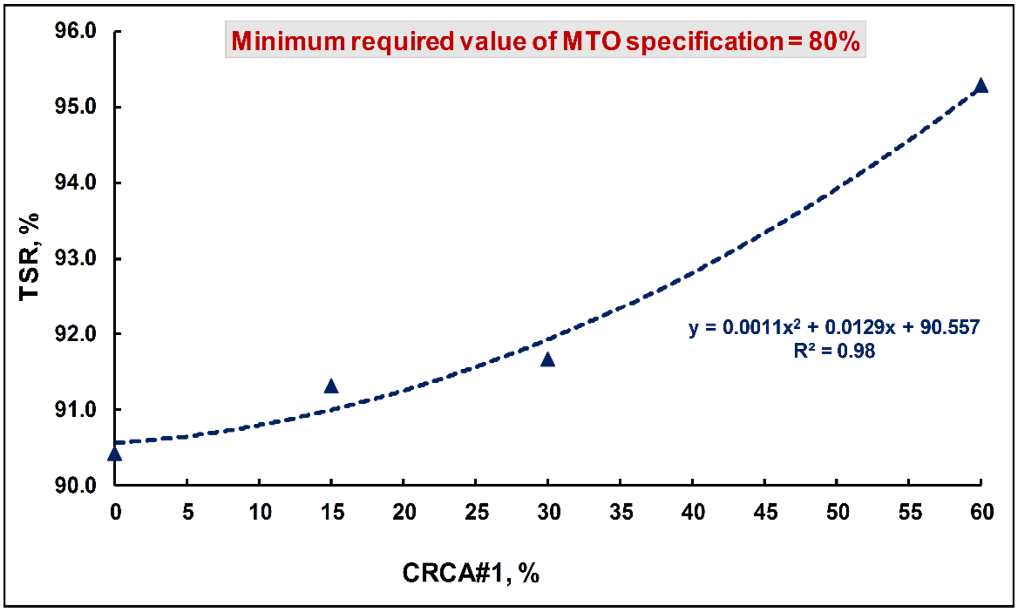


Figure 4: TSR values for mixtures including various proportions of CRCA#1.

3.3.1 Effect of CRCA Types

Figure 5 displays the laboratory outcomes of TSR values of asphalt mixtures that included different CRCA types with various proportions to explore the effect of CRCA type on the moisture sensitivity of mixtures. For both types of CRCA, it is interesting to note that the TSR values are higher than 80% for all proportions. These results strongly indicate a successful utilization of CRCA in asphalt mixtures. Additionally, it is important to note that the mixtures that included CRCA#1 or CRCA#2 have different behaviour trends in terms of TSR. With CRCA#1 addition, the TSR gradually increased to reach a value of 95.3% for the mixture that included 60% CRCA#1, whereas TSR followed an opposite behaviour when CRCA#2 addition reached a similar proportion. Furthermore, the mixtures that included CRCA#1 up to 60% exhibited a better moisture resistance and registered a higher tensile strength ratio than the mixtures that included the same proportion of CRCA#2. Therefore, it can be stated that the outcomes of moisture sensitivity seem to be completely opposite compared to the ITS test regarding the influence of the type of RCA. In conclusion, the results indicate that the moisture sensitivities of mixtures that included CRCA are highly affected by the type of CRCA.

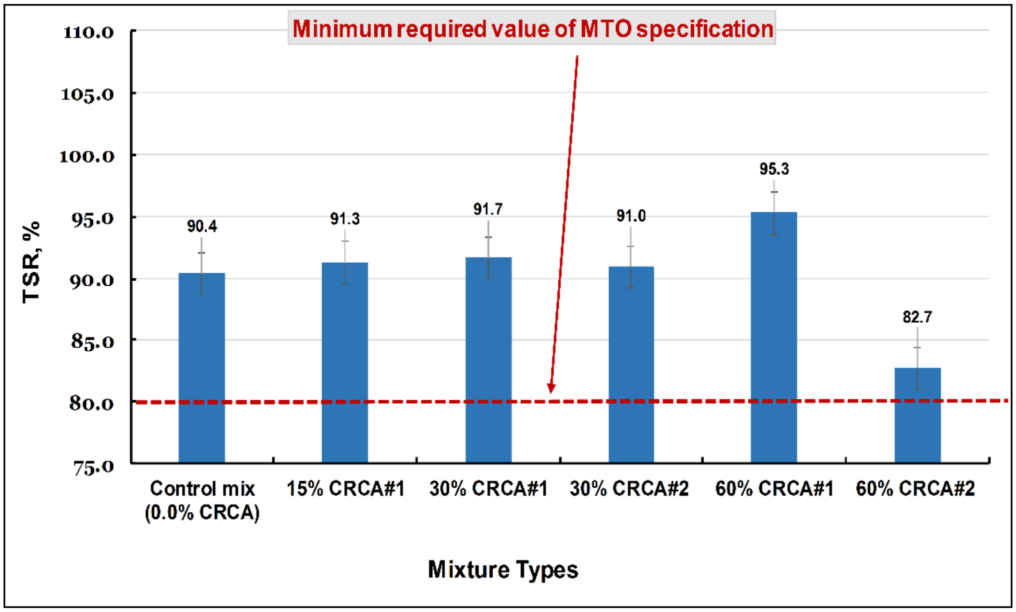


Figure 5: TSR values for mixtures including different CRCA types with various proportions.

3.4 Statistical Analysis of the Obtained Results

Table 4 summarizes statistical aspects of ITS including standard deviation and coefficient of variation. The statistical results generally revealed that the coefficients of variation of the unconditioned ITS at the temperature of 25 °C are higher values than the coefficients of variation of the conditioned ITS. This indicates there is a possibility to use conditioned ITS as a parameter to rank the tensile strength of HMA mixtures. However, there is some opposite expectation to the behaviour of mixtures that included 60% CRCA#2. Heterogeneity of CRCA and its inferior properties such as surface texture, porosity, and density could possibly have an effect on the ITS value for different asphalt mixtures.

A one-way ANOVA analysis was performed to examine the influence of CRCA proportion (0%, 15%, 30%, and 60%) on the TSR value of asphalt mixtures. The results indicated that the CRCA percentage has an insignificant impact on TSR with a p-value of (0.971) and Factual (0.076434) < Fcritical (4.066). This indicates that the variation in the CRCA content will not affect the moisture sensitivity of HMA mixtures.

To obtain a better understanding, a two-way ANOVA analysis was carried out for different mixtures to investigate the influence of various parameters on TSR values. The mentioned parameters include: different CRCA proportions (30%, and 60%); various CRCA types. Surprisingly, the findings indicated that the effects of these variables act independently due to an insignificant interaction between the CRCA type and CRCA's percentage with a p-value of (0.2843). However, the type of CRCA has a higher effect on the results of TSR than the CRCA percentage in terms of studying the impact of CRCA type and its proportion. The findings of two-way ANOVA analysis of TSR values are presented in Table 5.

Table 4: Statistical Analysis of the Results of ITS

Mixture	Std. dev. for Unconditioned ITS	COV for Unconditioned ITS (%)	Std. dev. for Conditioned ITS	COV for Conditioned ITS (%)
Control mix (0% CRCA)	58.11	11.46	24.55	5.35
15% CRCA#1	87.09	9.58	31.52	3.80
30% CRCA#1	32.84	3.85	24.30	3.11
60% CRCA#1	69.31	9.67	64.26	9.40
30% CRCA#2	110.12	11.70	63.93	7.46
60% CRCA#2	16.13	1.85	15.66	2.18

Table 5: Results of Two-Way ANOVA Analysis: P-Value and Sum of Squares of TSR

Source of Variation		TSR, %
CRCA type	P-value	0.1282
	SS	169.501
	F	2.8795
	F- critical	5.3177
CRCA%	P-value	0.7300
	SS	7.5208
	F	0.1278
	F- critical	5.3177
Interaction	P-value	0.2843
	SS	77.521
	F	1.3169
	F- critical	5.3177

4. Conclusions

Based on the obtained laboratory results, the following conclusions can be drawn:

- The mixtures that included CRCA#1 or CRCA#2 have the same behavior trend in terms of ITS for both conditioned and unconditioned states. Generally, when CRCA increases, the ITS decreases. However, the mixtures that included CRCA#2 up to 60% exhibited a better tensile strength for both ITS conditioned and unconditioned states, registering a higher tensile strength than the mixtures that included the same proportion of CRCA#1

- It is interesting to note that the maximum ITS values recorded for 30% CRCA#1 and CRCA#2 for both unconditioned and conditioned samples, registered increases of 68%, 70%, 85.6%, and 86.7%, respectively. This is followed by the ITS values of the mixtures that included 60% CRCA1# and CRCA#2 for both unconditioned and conditioned samples with increases of 41.4%, 49.0% 71.5% and 56.8%, respectively.
- The findings indicated that all TSR values for mixtures that included CRCA with different types and proportions are higher than the minimum required value of MTO specifications. However, it is important to note that the mixtures that included CRCA#1 or CRCA#2 have different behaviour trends in terms of TSR.
- From the perspective of the type of CRCA, the mixtures that included CRCA#1 or CRCA#2 exhibited different behaviour trends in terms of TSR. Additionally, the mixtures that included CRCA#1 up to 60% exhibited a better moisture resistance and registered a higher tensile strength ratio than the mixtures that included the same proportion of CRCA#2.
- From the perspective of TSR, the results of the ANOVA analysis revealed that there is no significant effect of CRCA type and proportion, on the TSR values. However, the type of CRCA has a higher effect on the results of TSR compared to the CRCA percentage.

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References:

Al-Bayati, H. K. A., Das, P. K., Tighe, S. L., and Baaj, H. 2016. "Evaluation of various treatment methods for enhancing the physical and morphological properties of coarse recycled concrete aggregate." *Construction and Building Materials.* 112: 284-298.

Arabani, M., and Azarhoosh, A. R. 2012. "The effect of recycled concrete aggregate and steel slag on the dynamic properties of asphalt mixtures". *Construction and Building Materials.* 35: 1-7.

Chen, M., Lin, J., and Wu, S. 2011. "Potential of recycled fine aggregates powder as filler in asphalt mixture". *Construction and Building Materials.* 25 (10). 3909-3914.

Cho, Y. H., Yun, T., Kim, I. T., & Choi, N. R. 2011. "The application of recycled concrete aggregate (RCA) for hot mix asphalt (HMA) base layer aggregate". *KSCE Journal of Civil Engineerin*g, 15(3), 473-478.

D’Angelo, J. O. H. N., & Anderson, R. M. 2003. “Material production, mix design, and pavement design effects on moisture damage”. In Moisture Sensitivity of Asphalt Pavements: A National Seminar (pp. 187-201).

Du, J. C., and Shen, D. H. 2007. “Evaluation of Construction Material Recycling for Hot Mix Asphalt”. *Journal of Environmental Engineering & Management.* 17 (4): 243-248.

Ektas, S., and Karacasu, M. 2012. “Use of Recycled Concrete in Hot Mix Asphalt and an ANN model for Prediction of Resilient Modulus”. *Ekoloji.* 21 (83): 53-60.

Hossain, M.U., Poon, C.S., Lo, I.M., Cheng, J.C. 2016. “Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA”. *Resour. Conserv. Recycl.* 109, 67–77.

Jin, Ruoyu, Li, Bo, Zhou, Tongyu, Wanatowski, Dariusz, Piroozfar, Poorang. 2017. “An empirical study of perceptions towards construction and demolition waste recycling and reuse in China”. *Resour. Conserv. Recycl.* 126 (2017), 86–98.

Lee, C. H., Du, J. C., and Shen, D. H. 2012. “Evaluation of pre-coated recycled concrete aggregate for hot mix asphalt”. *Construction and Building Materials.* 28 (1). 66-71.

Liu, J., Zhao, S., Li, P., Saboundjian, S. 2017. “Variability of composition, volumetric, and mechanic properties of hot mix asphalt for quality assurance”. *J. Mater. Civ. Eng.* 29 (3). D4015004.

Moraes, R., Velasquez, R., & Bahia, H. 2011. “Measuring the effect of moisture on asphalt-aggregate bond with the bitumen bond strength test”. *Transportation Research Record: Journal of the Transportation Research Board*, (2209), 70-81.

Paranavithana, S., and Mohajerani, A. 2006. “Effects of recycled concrete aggregates on properties of asphalt concrete”. *Resources, Conservation and Recycling.* 48 (1): 1-12.

Pasandín, A. R., & Pérez, I. 2013. “Laboratory evaluation of hot-mix asphalt containing construction and demolition waste”. *Construction and Building Materials*, 43, 497-505.

Pasandín, A. R., and Pérez, I. 2014. “Mechanical properties of hot-mix asphalt made with recycled concrete aggregates coated with bitumen emulsion”. *Construction and Building Materials.* 55: 350-358.

Pérez, I., Pasandín, A. R., & Medina, L. 2012. “Hot mix asphalt using C&D waste as coarse aggregates”. *Materials & Design*, 36, 840-846.

Pérez, I., Toledano, M., and Gallego, J. 2009. “Construction and demolition debris in hot mix asphalt”. In *Road Pavement Material Characterization and Rehabilitation: Selected Papers from the 2009 GeoHunan International Conference*: 141-146.

Purushothaman, R., Amirthavalli, R. R., & Karan, L. 2014. “Influence of treatment methods on the strength and performance characteristics of recycled aggregate concrete”. *Journal of Materials in Civil Engineering*. 27(5): 04014168.

Radević, A., Đureković, A., Zakić, D., and Mladenović, G. 2017. “Effects of recycled concrete aggregate on stiffness and rutting resistance of asphalt concrete”. *Construction and Building Materials*. 136. 386-393.

Shen, D. H., and Du, J. C. 2004. “Evaluation of building materials recycling on HMA permanent deformation”. *Construction and building materials.* 18 (6): 391-397.

Solaimanian, M., Harvey, J., Tahmoressi, M., & Tandon, V. 2003. “Test methods to predict moisture sensitivity of hot-mix asphalt pavements”. In Moisture Sensitivity of Asphalt Pavements-A National Seminar California Department of Transportation; Federal Highway Administration; National Asphalt Pavement Association; California Asphalt Pavement Alliance; and Transportation Research Board. 77-110.

Wong, Y. D., Sun, D. D., and Lai, D. 2007. “Value-added utilisation of recycled concrete in hot-mix asphalt. Waste Management”. 27 (2): 294-301.

Wu, S., Zhong, J., Zhu, J., and Wang, D. 2013. “Influence of demolition waste used as recycled aggregate on performance of asphalt mixture”. *Road Materials and Pavement Design.* 14 (3): 679-688.

Zhu, J., Wu, S., Zhong, J., & Wang, D. 2012. “Investigation of asphalt mixture containing demolition waste obtained from earthquake-damaged buildings”. *Construction and Building Materials*, 29, 466-475.

Zollinger, C. J. 2005. “Application of surface energy measurements to evaluate moisture susceptibility of asphalt and aggregates” (Doctoral dissertation, Texas A&M University).

Zoorob, S.E., and Suparma, L.B., 2000. “Laboratory design and investigation of the properties of continuously graded asphaltic concrete containing recycled plastics aggregate replacement”. *Journal Cement & Concrete Composites*, Vol. 22, pp 233–242.