Influence of Coarse Recycled Concrete Aggregates on the Dynamic Modulus of Asphalt Concrete Mixtures

Hanaa Khaleel Alwan Al-Bayati[1]
Ph.D. Candidate, 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:

In the asphalt highway industry, a large number of innovative materials and technologies are explored in order to evaluate their suitability in the design, construction and maintenance of pavements. Billions of tonnes of concrete are extensively consumed in the construction of various structures including buildings, bridges, dams, roads, and others. For constructing the above-mentioned structures, massive amounts of construction and demolition (C&D) waste are generated. A sustainable solution has become highly required and an urgent priority in the asphalt industry to solve various problems including lowering the consumption of virgin materials, decreasing waste materials in landfills and reducing environmental problems, and the utilization of recyclable waste materials, especially recycled concrete. This research is conducted to investigate the possibility of using coarse recycled concrete aggregate (CRCA) in asphalt mixtures. Mix design of HMA mixtures is performed for CRCA at various percentages 15%, 30%, and 60%. After determining optimal asphalt content (OAC) of different mixtures, the stiffness resistance of Ontario Superpave asphalt mixtures is evaluated. Depending on the dynamic modulus test results, the rutting susceptibility and fatigue performance of different mixtures are also estimated. At high temperatures, the obtained results indicate that the use of CRCA can increase asphalt pavement resistance to rutting susceptibility compared to the control mixture. However, this resistance decreases with increasing CRCA proportion in the asphalt mixture. At low temperatures, asphalt mixtures including CRCA have a lower stiffness than the control mixture. This leads to minimizing fatigue and low-temperature cracking. The findings also revealed that the utilization of CRCA in the asphalt mixtures appears to be highly successful.

Key words: Asphalt mixtures, Coarse recycled concrete aggregate (CRCA), Stiffness modulus, Dynamic Modulus Test, Rutting and fatigue factors.

1. Introduction

Asphalt concrete represents one of the main materials required for constructing road pavement (Liu et al., 2017). Hot-mix asphalt (HMA) mixture is described as a complex mixture composed of three main components, namely, aggregate, asphalt binder, and air voids. In addition, different additives are typically used for improving its performance such as polymers and fibers (Poulikakos et al., 2017). In asphalt pavement, the aggregate particles represent a structural framework for the mixture, whereas, the asphalt binder works as a sticky substance. Generally, asphalt pavement consists of approximately 90–95% by weight and 75–85% by volume mineral aggregates. The physical properties of both coarse and fine aggregates have a considerable influence on the asphalt pavement performance (Arabani & Azarhoosh, 2012). According to the ministry of natural resources Ontario (MNRO), the average consumption of aggregate reached approximately 179 million tonnes per year in Ontario during the period 2000-2009, while this average is projected to amount to approximately 191 million tonnes between 2020 and 2029 (MNRO, 2010). Simultaneously, waste materials are increasing with the growth in the population due to rising demand for new highways, commercial buildings, housing developments, and infrastructure projects. This results in tremendous amounts of waste ending up in landfills every year. Due to considerable consumption and economic growth, the required natural resources will not only be depleted but will eventually be exhausted (Bolden, 2013). To reduce the consumption of natural materials, diminish waste materials in landfills, and minimize environmental concerns, the application of waste materials in asphalt mixtures is becoming increasingly utilized worldwide. Among different waste materials, recycled concrete aggregate (RCA) is the main waste material that has been successfully applied in base aggregates and Portland cement concrete (PCC) aggregates. However, there were limited investigations into the utilization of RCA in the asphalt pavement mixtures (Mills-Beale & You, 2010) due to the poor quality of RCA characteristics compared to natural aggregate (NA). As a comparison with natural aggregate, RCA is generally rough, irregular, porous, flat and, but in particular, it is characterized by a lower bulk and specific gravity, and a significantly higher water absorption, which results in inferior mechanical properties (Malešev et al., 2010; Lee et al., 2012; Pepe et al., 2014; Al-Bayati et al., 2016). The higher porosity characterizing the adhered mortar layer is the main reason behind this behaviour (Pepe et al., 2014). Due to the crushing process of the old concrete and existence of mortar, the texture of RCA surface consists of shaped particles with sharp edges. This leads to a better interaction and higher friction between the surface particles (Radević et al., 2017). In the sustainable development perspective, the utilization of RCA has many advantages including reducing waste amounts, lowering the environmental impacts, preservation of natural resources, and reducing the costs of waste disposal (Radević et al., 2017).

Recently, the utilization of RCA in the asphalt mixtures has gained more attention and become an attractive topic for many researchers worldwide (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). The successful use of RCA in the base and sub-base applications is the main reason behind examining the feasibility of using RCA in asphalt mixtures. It is believed that the problem related with RCA can be eliminated through the coating of RCA particles with a layer of asphalt cement (Zhang et al., 2016). Mills-Beale and You (2010) evaluated the effect of different proportions of RCA (25%, 35%, 50% and 75%) in place of total aggregate on the mechanical properties of asphalt mixtures. The obtained findings indicated that the dynamic stiffness of the mixtures is increased with decreasing ratios of RCA and test temperature influenced the resilient modulus more than the effect of RCA percentages. Pérez et al., (2009) evaluated the resistance of asphalt mixtures that included RCA with NA 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. Wong et al. (2007) reported that there is no considerable effect of a filler obtained from RCA on the stiffness and permanent deformation of asphalt mixtures. From the studies of Chen et al. (2011)

and Arabani et al. (2013), it was concluded that the application of RCA in the asphalt mixtures leads to increased resistance to permanent deformation (Radević et al., 2017).

From the above discussion, it can be stated that the previous research studies were mainly focused on the effect of RCA on the mechanical properties of HMA mixtures such as stability, stiffness, moisture resistance, and dynamic modulus. Therefore, the main objective of this research is to evaluate the possible application of various proportions of coarse recycled concrete aggregate (CRCA) in typical Ontario HMA mixtures in terms of dynamic stiffness. Depending on the results of the dynamic modulus test, the rutting susceptibility and fatigue performance of different mixtures are also evaluated.

2. Materials and Methods

2.1 Materials

In this research, NA and one filler type, dust plant, that is usually used for preparing asphalt mixtures, were obtained from the Miller Group. One type of asphalt binder, namely, PG 64-28 was used. In this study, one RCA type was used, which was provided from a ready-mix concrete plant through the crushing process of concrete that has unsatisfactory properties, performance, and age. Therefore, RCA could possibly be classified as fresh concrete that has not been utilized in engineering applications. In this study, CRCA is defined as the sieve fraction retained between 4.75 and 19 mm. The optical images of NA & RCA are shown in Figure 1-a and b, respectively.

2.2 Methods

2.2.1 Preparation of NA & CRCA

RCA was washed thoroughly so that all noticeable impurities such as wood chips and others were removed. Then, all NA & 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 NA and RCA is provided in Figure 2.

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 NA, four different proportions of CRCA (0%, 15%, 30%, and 60%) were added for the included CRCA mixtures. The gradation with different percentages of CRCA, targeted the mix design of Miller group, and ministry transportation Ontario (MTO) specifications are numerically tabulated in

Table 1. All experimental tests were conducted in the Centre for Pavement and Transportation Technology (CPATT) in the University of Waterloo.

2.2.3 Dynamic Modulus Test

Based on AASHTO R 30-02 (2010), the loose HMA mixtures were exposed to a short-term condition at 135°C for a period of four hrs before compaction to simulate the plant mixing and placement effects. In accordance with AASHTO TP 62-07 specification, the test was carried out to characterize stiffness for HMA mixtures at different temperatures (-10, 4, 21.1, 37, and 54.4 °C) and various load frequencies (25, 10, 5, 1, 0.5, 0.1Hz). Elevated temperature and low frequencies are regarding with slow movement of traffic, which represent the conditions for rutting. At low temperatures, the mixtures were evaluated for thermal cracking, whereas the fatigue cracking of the mixtures was examined at moderate temperatures.

Using a Superpave gyratory compactor, the cylindrical specimens were compacted. Then, the specimens were cored and cut into dimensions of 150 mm height and 100 mm diameter with air void content of 7 ± 1% as shown in Figure 3. A master curve was used to evaluate the dynamic stiffness (MPa) versus the reduced frequency (Hz). Figure 4 shows the dynamic modulus test setup in CPATT.

3. Results and Discussion

3.1 Physical and Mechanical Properties of NA

Table 2 demonstrates the obtained results of the physical and mechanical properties of NA and CRCA. Generally, there is a considerable difference in the properties between the NA and CRCA. In terms of physical properties, namely, bulk relative density (BRD), apparent specific gravity, and water absorption, a significant difference is registered between NA and CRCA. These findings confirm the outcomes of previous investigations that found the absorption capacity of RCA is a significantly higher than NA (Ektas and Karacasu, 2012; Butler et al., 2013a; Wu et al., 2013; Younis and Pilakoutas, 2013; Pasandín and Pérez, 2014; Singh et al., 2014). Adhered mortar which has a higher porosity than NA, results in making RCA more susceptible to water absorption compared to NA (Tam et al., 2007). Hence, the presence of adhered mortar leads to increased water absorption, lowered density, and weaker bond strength (Wong et al., 2007). In the perspective of the mechanical properties, abrasion loss, adhered mortar loss, aggregate crushing value, and freezing and thawing, different issues can be observed. The outcomes indicate that the abrasion loss of CRCA has a higher value compared to NA. A higher abrasion loss percentage indicates losing a higher quantity of weak areas that are represented by the adhered mortar. After five cycles of freezing and thawing, it is interesting to note that a slight difference is registered in freezing and thawing loss between CRCA and NA. According to British standards (BS) (882:1992), the aggregates could be possibly utilized in various applications depending on the maximum crushing values as shown in the classifications presented in Table 3. Depending on the different categories, the obtained findings indicate that NA can be used for heavy-duty concrete applications, whereas CRCA can be utilized for pavement wearing layers.

3.2 Volumetric Properties of Asphalt Mixtures with CRCA Addition

Table 4 shows the volumetric properties of different HMA mixtures that were prepared in this study. The laboratory results indicated that the mix design for various CRCA proportions (0%, 15%, 30%, and 60%) successfully meet all the MTO requirements. As shown in Table 4, the optimum asphalt content (OAC) gradually increases when the CRCA percentage is increased. This is explained by the matter that CRCA has a higher absorption than NA due to the presence of adhered mortar. In contrast, there is a slight reduction in the bulk specific gravity (Gmb), voids in mineral aggregates (VMA), and voids filled with asphalt (VFA) of the mixes when the CRCA proportion reaches 30%.

3.3 Effect of CRCA on the Stiffness Modulus of Mixtures

The temperature and loading rate represent the primary factors related to the stress-strain behaviour of HMA mixture. The HMA mixtures response to various temperatures and loading rates was measured by utilizing the Dynamic Modulus test. By creating a master curve, the change in asphalt binder and mixture behaviour over time can be observed. The Master curve was built up by using the principle of the time-temperature superposition. Figure 5 demonstrates the outcomes of the dynamic modulus test which is presented as a complex modulus value $|E^*|$ versus the reduced frequency. Generally, the trend of the master curves was similar for all HMA Mixtures though the CRCA proportions in the mixtures were different. The dynamic modulus trend for various mixtures demonstrated that there is a reduction in the stiffness of HMA mixtures when the temperature is increased from -10 °C to 54 °C. When the load frequency increases from 0.1 Hz to 25 Hz, the stiffness of mixtures is increased. The average stiffness modulus of all mixtures that included CRCA was higher than of the control mixture at elevated and moderate temperatures and low-frequency loading. In contrast, there was a lower stiffness modulus at a lower temperature and a high load frequency. It is important to mention that it is difficult to discover the behaviour of various mixtures at some points at specific temperatures and frequencies. Therefore, the stiffness modulus of different mixtures is separately represented based on different temperatures and frequencies in Figure 6.

At low temperature (-10°C), the findings revealed that there is a variation in the stiffness modulus of mixtures that included different CRCA percentages. It is noteworthy that the mixture included 60% CRCA has a lower stiffness than the control mix at high and moderate frequencies. This means that there is an increase in the cracking resistance of the mixture and this will help to minimize fatigue and low-temperature cracking. However, the mixtures that included CRCA up to 30% have a higher stiffness than the control mix and this would reduce the mixtures resistance to cracking at low temperature. The main reason behind these variations is the RCA inhomogeneity and its inferior physical and mechanical properties compared with NA aggregate. More specifically, this is due to a higher porosity and a large surface area for RCA in comparison with NA. The presence of attached cement mortar leads to create various bitumen film thickness on the aggregate particles, resulting in changes in the stiffness modulus of the mixtures (Radevic´ et al., 2017). At moderate (4°C) and elevated temperatures (higher than or equal to 21°C), the obtained findings also showed that the utilization of CRCA with a proportion up to 60% would increase the stiffness of the mixture compared with the control mixture. This behaviour will be beneficial for the high-temperature performance, which is represented by a reduction of rutting potential. At low frequencies, the mixtures that included 60% CRCA have comparable stiffness values to the control mix at temperatures 37 ºC and 54 ºC.

Figure 7 presents the average |E*| ratios between the control mix and the remaining mixtures that included different percentages of CRCA at various temperature and frequencies. For all the temperatures and frequencies, the average ratios between the control mix and the mixtures that included different proportions of CRCA were less than 1.0, indicating that these mixtures have a higher |E*| values than the control mixture. However, it is interesting to note that the mixtures that included 60% CRCA have a different behaviour at low temperature (-10 C) and moderate and high frequencies, resulting in a higher |E*| ratio. This indicates that the mixtures that included 60% CRCA have a lower modules stiffness than the control mix at low temperature and moderate and high frequencies. As mentioned previously, the mixtures that included 60% CRCA have more resistance to low-temperature cracking

3.4 Evaluation of Rutting and Fatigue Factors

This study also evaluated the rutting factor (E*/sin δ) and fatigue factor (E*sin δ) depending on the results of the dynamic modulus |E*| of different HMA mixtures at specific temperatures and frequencies. The temperature of 54 ºC and loading frequency 5 Hz were used for measuring the rutting factor (E*/sin δ), whereas the fatigue factor (E*sin δ) was computed at the 21 ºC temperature and loading frequency 5 Hz (E*/sin δ) (Witczak et al., 2002). The outcomes refer to mixtures sensitivity to permanent deformation (rutting) and fatigue crack. The highest value of rutting parameter (E*/sin δ) indicates a lower susceptibility of mix to the impact of rutting, whereas a lower value of fatigue factor (E*sin δ) points out to a good resistance to fatigue cracking. Figure 8 demonstrates the rutting factor (E*/sin δ) of HMA mixtures that included different CRCA proportions. The outcomes showed that the mixtures that involved CRCA have a higher rutting factor values than the control mix. These results confirm the previous results of the |E*| which were shown in Figure 6. This indicates the mixtures included CRCA have a good resistance to the impact of the permanent deformation under the effect of traffic and moderate temperatures. The reason behind this could be due to the RCA properties which can be represented by a rough texture, shaped particles, and sharp edges, resulting in a better interaction and higher surface friction between aggregate particles (Radević et al., 2017). The results revealed that the mixture that included 30% CRCA has a higher value of rutting parameter. This is followed by the mixtures that included 15% CRCA and 60% CRCA, respectively.

Figure 9 reveals the fatigue factor (E*sin δ) of different asphalt mixtures. It is found that the mixtures that included different proportions of CRCA have greater values of fatigue factor than the control mix. This indicates that the mixtures included CRCA have a higher susceptibility to the fatigue cracking than the control mix at the intermediate temperature. Compared to the control mixture, the mixture that included 15% CRCA has the highest value of (E*sin δ) with an increase of 17.3 %. This is followed by the mixtures that included 30% CRCA and 60% CRCA, with an increase of 16.5% and 11%. respectively. These findings confirm the results of stiffness modulus as previously shown in Figure 6.

For more explanation of the estimated fatigue factor, a higher frequency (10 Hz) at 21 °C was utilized in this study. In Figure 10, the findings demonstrated that the fatigue factors (E* Sin) at loading frequency 10 Hz have the same trend for the mixtures that included different CRCA proportions. However, slight differences are registered for the values of fatigue parameters compared to the obtained values at the loading frequency of 5 Hz.

Tables 5 & 6 summarize statistical aspects for both of rutting and fatigue parameters including standard deviation and coefficient of variation. In terms of rutting parameter, the statistical results generally revealed that the coefficients of variation of the dynamic stiffness |E*| at the temperature of 54°C have higher values than the coefficients of variation of the phase angle. This indicates that there is a possibility to use phase angle as a parameter to rank the rutting of HMA mixtures. Heterogeneity of CRCA and inferior properties such as the surface texture, porosity, and density could possibly have an effect on the dynamic stiffness value for different HMA mixtures. It is important to mention that the coefficients of variation of fatigue parameter had the same trend though the temperature is different (21°C).

The ANOVA analysis carried out of the dynamic stiffness at 5 Hz for temperatures of 21 °C and 54 °C, with a probability of 95%. The results of |E*| represented three replicate specimens of different HMA Mixtures. The statistical analysis revealed that a variance among the data is statistically significant, with F_{actual} (159.5) > $F_{critical}$ (4.1) and a p-value of (1.79 E-07) for the mixtures at a loading frequency of 5 Hz and a temperature of 54 °C, whereas F_{actual} (11.6) > $F_{critical}$ (4.1) and a p-value of (0.003) for the mixtures at a loading frequency of 5 Hz and a temperature of 21 °C. From the |E*| results that represent four asphalt mixture, it could be concluded that differences among the results are statistically significant, indicating an increase in the CRCA proportion has a significant effect on the dynamic stiffness, rutting and fatigue of the mixture.

4. Conclusions

Based on the obtained laboratory results, the following conclusions can be drawn:
1. Compared to NA, the CRCA has inferior physical and mechanical characteristics.

2. In terms of volumetric properties, the obtained results indicated that the addition of CRCA in the asphalt mixtures at different percentages is very successful.
3. The average stiffness modules of different mixtures that included different CRCA percentages were higher than the control mixture at elevated and moderate temperatures. This behaviour is beneficial for the high-temperature performance that is related to the reduction of rutting potential.
4. The mixture that included 60% CRCA has a lower stiffness than the control mix at high and moderate frequencies. This refers to an increase in the cracking resistance of the mixture and this will help to minimize fatigue and low-temperature cracking.
5. The mixtures that included different CRCA proportions have higher values of rutting factor values than the control mix. This indicates that the mixtures that included CRCA mixtures have a good resistance to the influence of the permanent deformation under the effect of traffic and moderate temperatures.
6. The findings revealed that all the mixtures that included different proportions of CRCA have higher values of fatigue factor than the control mix. This indicates that the mixtures included CRCA have a higher susceptibility to fatigue cracking than the control mix at the intermediate temperature.
7. The ANOVA statistical analysis results showed that the variation of the results is statistically significant, indicating that an increase in the CRCA percentage has a considerable influence on the dynamic stiffness, rutting, and fatigue cracking of the mixtures.

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

Sieve size	Passing (%) for different CRCA percentages				Target of mix Design	MTO limitation
mm	0.0% CRCA	15% CRCA	30% CRCA	60% CRCA		
25	100	100	100.0	100.0	100	100
19	95.2	95.2	95.3	95.2	96.8	100 - 90
16	89.0	88.7	88.5	87.4	90.6	90 - 23
12.5	81.8	81.1	80.5	78.2	83	
9.5	73.2	72.3	71.8	69.0	73.3	
6.7	63.3	63.0	63.1	61.0	63.3	
4.75	57.1	56.7	55.9	53.8	55.9	
2.36	42.8	42.8	41.3	41.2	43.5	49 - 23
1.18	30.7	30.7	30.5	30.5	32.5	
0.6	22.9	23.0	23.6	23.6	25.1	
0.3	10.2	10.3	10.3	10.3	11.8	
0.15	5.4	5.5	5.6	5.5	5.5	
0.075	2.1	2.2	2.2	2.1	3.8	8 - 2

Table 2: Physical and mechanical properties of NA and CRCA

Types of aggregate / Aggregate properties	NA	CRCA
Bulk relative density (BRD), (ASTM C 127)	2.658	2.295
Apparent specific gravity, (ASTM C 127)	2.714	2.638
Absorption, %, (ASTM C 127)	0.8	5.91
Micro-Deval abrasion loss, %, (ASTMD6928)	15.89	23.57
Adhered mortar, %	-	3.02
Fractured particles, %, (ASTM D5821)	95.5	89.9
Aggregate crushing value (BS 812-110)	19.48	27.42
Freezing & thawing (LS- 614)	17.4	18.03

Table 3: ACV classifications based on BS (882:1992)

ACV	Applications
< 25%	Aggregate could be used in the production of heavy-duty concrete floor finishes
Between 25%-30%	Aggregate type could be utilized in the concrete used for pavement wearing surfaces
Between 30%-45%	Aggregate could be utilized in concrete used for other applications

Table 4. Volumetric characteristics of mixtures with different percentages of CRCA

Aggregate type / property	0 % CRCA	15% CRCA	30% CRCA	60% CRCA	Acceptable limitations of MTO specification
OAC AC (%)	4.83	4.9	5.31	5.71	-
VMA (%)	14.5	13.6	13.66	16.18	13 min.
VFA (%)	72.5	70.8	70.7	74.8	65-75
Vv (%)	4.0	4.0	4.0	4.04	4.0
G_{mb}	2.4	2.395	2.373	2.351	-

Table 5: Statistical analysis of the results of rutting parameter

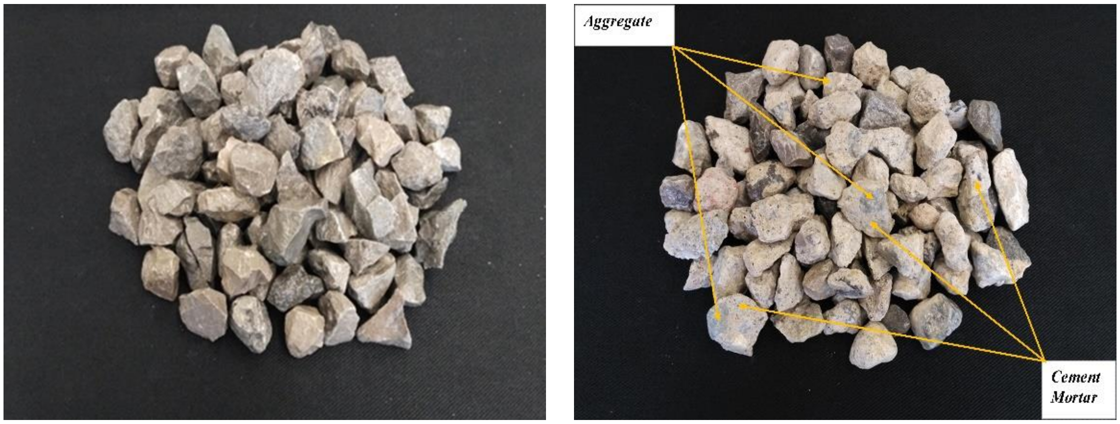
Mixture	Std. dev. for |E*| @ 5 Hz & 54°C	COV for |E*| @ 5 Hz & 54°C (%)	Std. dev. for δ @ 5 Hz & 54°C	COV for δ @ 5 Hz & 54°C (%)
C.M. (0% CRCA)	121.5	17.0	2.0	12.6
15% CRCA	41.9	4.33	0.6	2.9
30% CRCA	35.7	4.1	1.7	8.3
60% CRCA	632.6	11.5	0.1	0.4

δ = Phase angle

Table 6: Statistical analysis of the results of fatigue parameter

Mixture	Std. dev. for |E*| @ 5 Hz & 21°C	COV for |E*| @ 5 Hz & 21°C (%)	Std. dev. for δ @ 5 Hz & 21°C	COV for δ @ 5 Hz & 21°C (%)
C.M. (0% CRCA)	505.8	11.0	0.5	2.7
15% CRCA	455.0	6.6	0.5	2.4
30% CRCA	267.7	4.4	0.2	1.2
60% CRCA	632.6	11.5	0.1	0.4

δ = Phase angle



1-a. NA 1-b. RCA

Figure 1: Optical images of NA & RCA

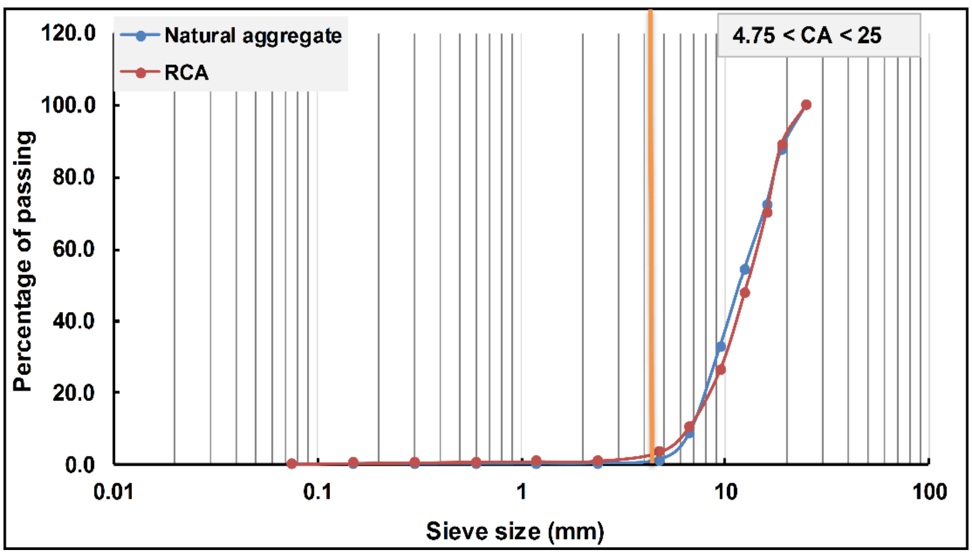


Figure 2: Particle size gradations of NA & RCA

Figure 3: Gyratory compacted specimen before and after cutting and coring

Figure 4: Typical dynamic modulus test setup

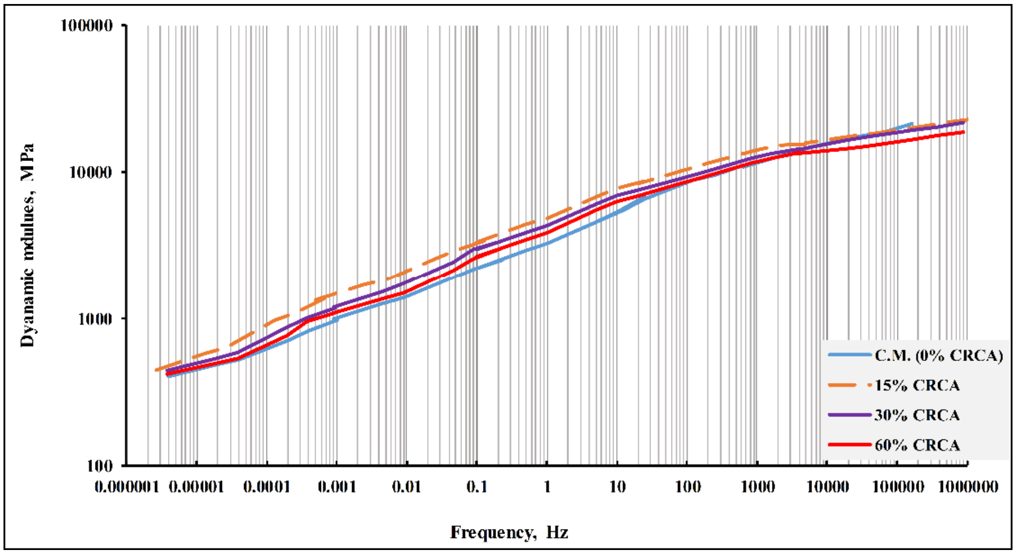


Figure 5: Dynamic modulus (master curves) of different HMA mixtures

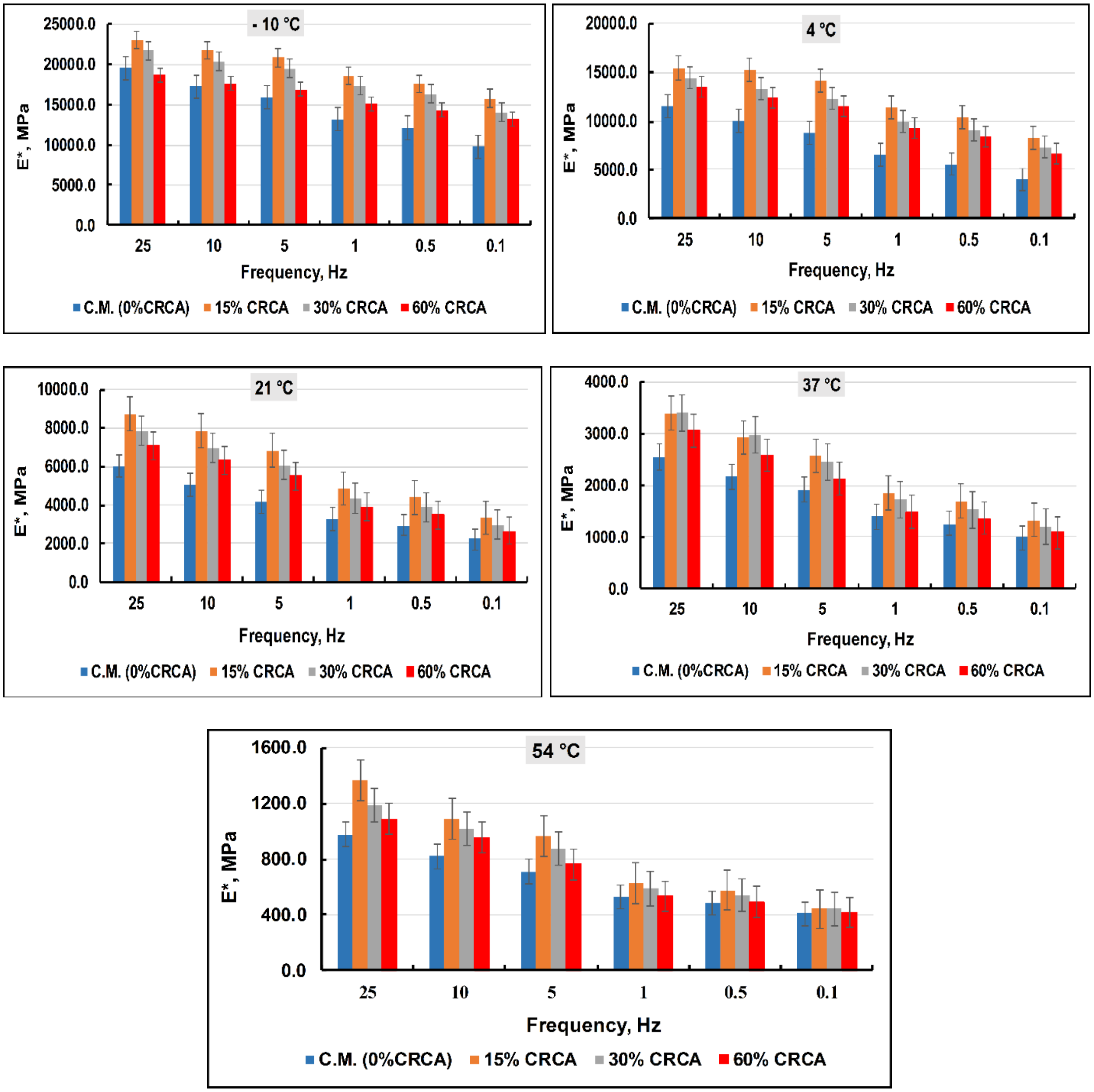


Figure 6: Dynamic modulus values for all mixtures at different temperatures and frequencies.

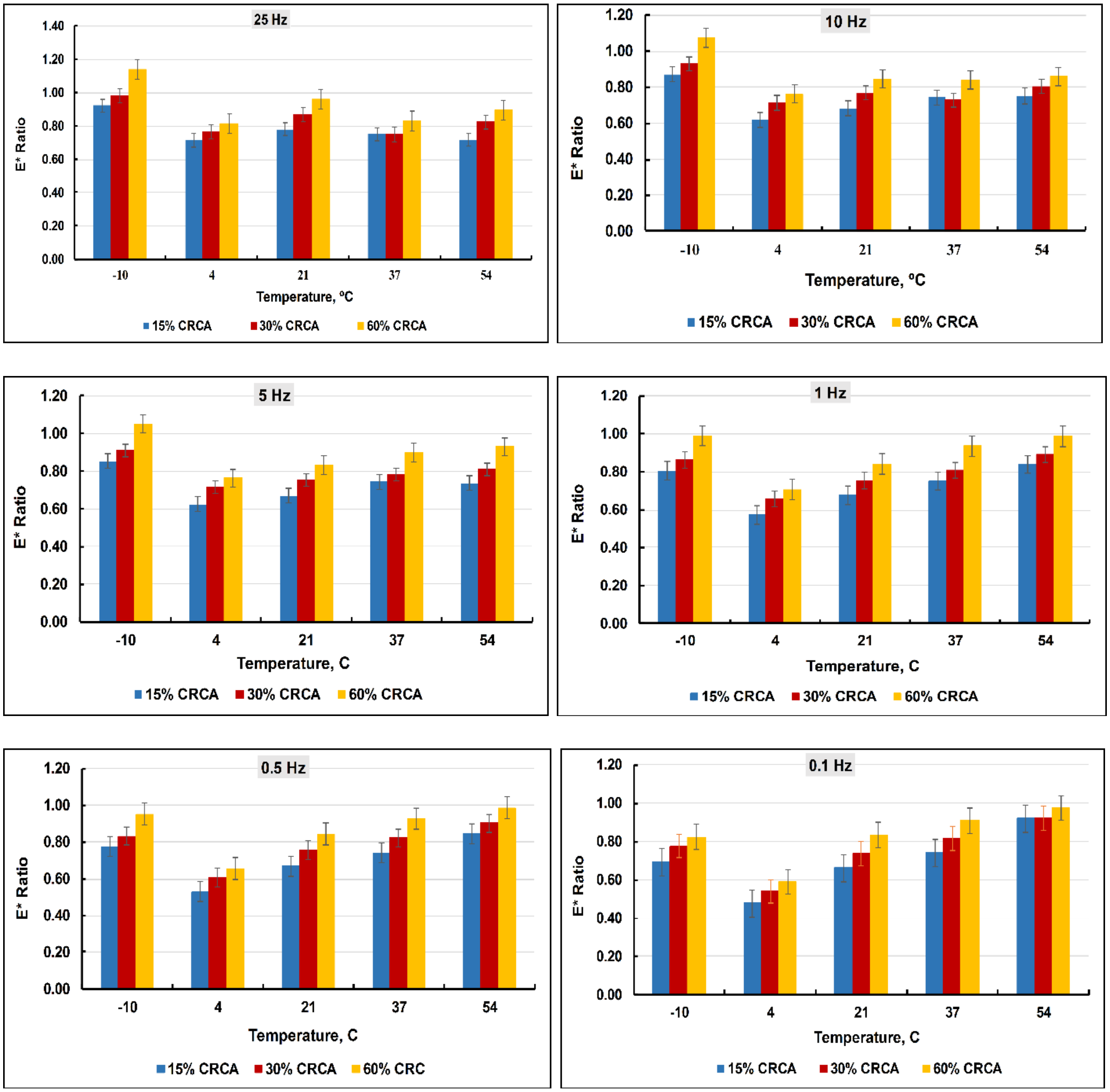


Figure 7: Average |E*| ratios between the control mix and the remaining mixtures.

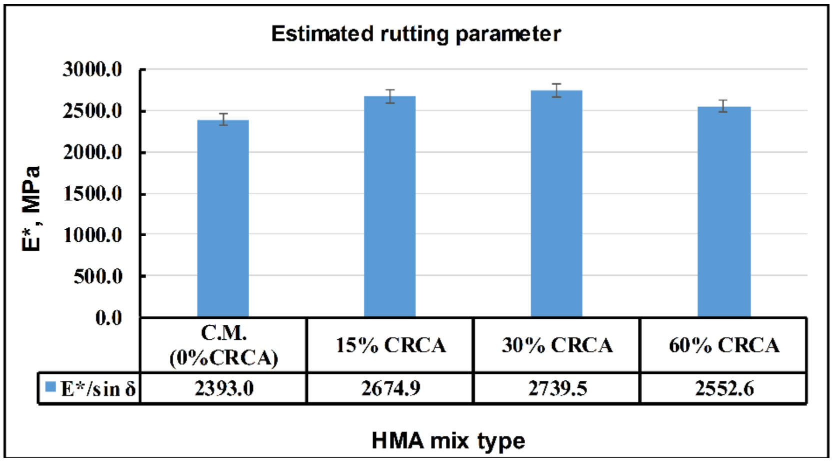


Figure 8: Rutting parameter of different mixtures at 5 Hz and 54 ºC

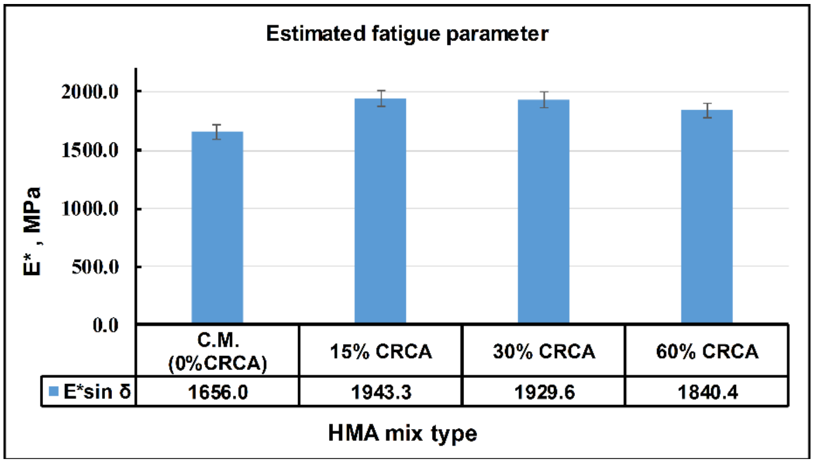


Figure 9: Fatigue parameter of different mixtures at 5 Hz and 21°C

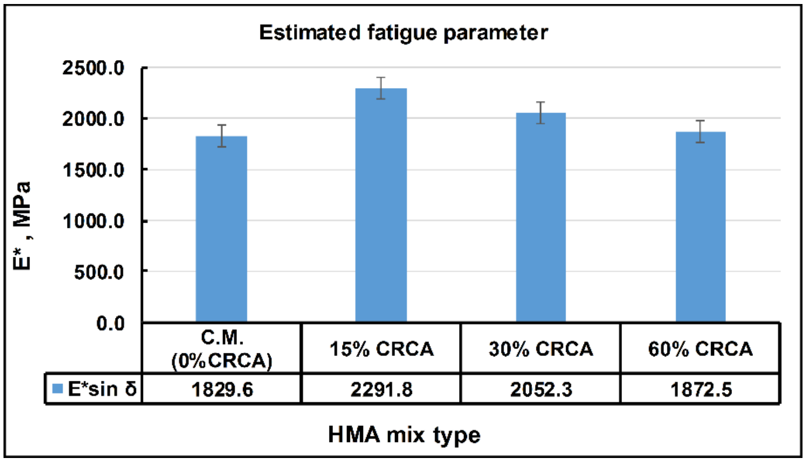


Figure 10: Fatigue parameter of different mixtures at 10 Hz and 21°C