Examining the Effect of Binder Types on Moisture Damage Resistance of HMA Mixtures Incorporating Recycled Concrete Aggregate

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Abstract

Moisture damage refers to the reduction in stiffness and strength in asphalt mixtures due to moisture exposure, compounded by the mechanical stress from traffic load, leading to a condition commonly known as stripping. Moisture damage, which causes a decline in the structural integrity of asphalt pavement, is a major factor in the emergence of various types of distress such as fatigue cracking, rutting, and more. Hence, the objective of this research is to assess the impact of different binder types and treatment methods of Coarse Recycled Concrete Aggregate (CRCA) on the tensile strength and moisture resistance of Hot Mix Asphalt (HMA) of Ontario Superpave mixtures. This study employs two kinds of binders: PG 64-28 and PG 52-34. Thermal treatment method, accompanied by short mechanical treatment, were carried out to improve the CRCA properties. Two different types of binders, 0.0% and 30% CRCA, were used to conduct mix designs of asphalt mixtures. At a 30% CRCA level, the emphasis was on evaluating the impact of binder types and treatment techniques. The tensile strength and moisture sensitivity of the asphalt mixtures were assessed in relation to the binder types and treated CRCA. The study found that when compared to the typical control mix, HMA mixtures with different types of binder combined with treated CRCA showed higher tensile strength. Additionally, the laboratory analysis showed that all TSR values for mixtures containing various binder types with CRCA treatment are higher than the MTO specifications' minimum demand value, except the control mixture containing PG 52-34. Furthermore, the outcomes demonstrated that mixes containing treated CRCA, and the PG 64-28 binder type had greater Tensile Strength Ratio (TSR) and Indirect Tensile Strength (ITS) than mixes containing the PG 52-34 binder type. These findings suggest that mixtures containing CRCA performed exceptionally well. The ANOVA analysis outcomes indicated that the type of binder has a higher impact on ITS and moisture susceptibility outcomes than treating CRCA. Furthermore, because of their negligible interaction, these parameters function independently of one another.

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

Introduction

Asphalt binders constitute only about 5% of asphalt mixtures alongside aggregates and air voids and play a crucial role in determining the mixture's resistance to cracking [Al-Bayati & Tighe, 2018]. Asphalt binder is another name for bitumen, the thick, black liquid left over after distilling crude oil. It acts as an adhesive to hold aggregate materials like sand, gravel, or crushed stone together in asphalt pavement mixtures. The binder gives the pavement the required cohesiveness and strength, allowing it to endure environmental influences and traffic loads. Viscosity, softening point, and ductility are essential characteristics to consider when assessing the lifespan and performance of asphalt pavements (Sultana & & Bhasin, 2014). The second HMA combination is aggregate, which makes up roughly 95% of the mix and has been extensively studied to understand its properties and impact on asphalt mixture performance (Xie et al., 2019; Uğurlu et al., 2021). Studies have shown that the physical characteristics of both fine and coarse aggregates significantly impact asphalt pavement performance. While these aggregates represent the structural skeleton of the asphalt mixture, the asphalt functions like an adhesive (Arabani & Azarhoosh, 2012, Al-Bayati & Tighe, 2019).

Over the past three decades, there has been a global rise in the demand for aggregates for various infrastructure projects. Consequently, the availability of virgin aggregates has dwindled, leading to increased costs. On the other hand, recycled materials are abundant, primarily from demolition and construction waste, which includes asphalt paving layer (Gopalam, et al., 2020). Due to the escalating demand for new highways, commercial structures, housing, and infrastructure, there is increasing volume and diversity of waste generated. This coupled with limited landfill capacity and natural resource depletion underscores the pressing need for innovative waste recycling and reuse solutions. Without effective recycling measures, vast quantities of waste are annually deposited in landfills, worsening resource depletion. Recycled concrete aggregate (RCA), one of these construction wastes is increasingly becoming a viable alternative to virgin aggregates in civil engineering applications (Al-Bayati et al., 2016).

Research on incorporating RCA into asphalt mixtures has yielded varying results in terms of performance, mainly due to the diverse sources of RCA. However, most studies agree that using RCA in hot mix asphalt (HMA) mixtures increases their moisture susceptibility. Specifically, Paranavithana et al., (2006) observed a notable rise in the stripping potential of coarse RCA asphalt mixtures post mixing and compaction. They attributed this to the ease of separating the mortar adhering to the RCA, resulting in a significant alteration in the aggregate gradation of RCA asphalt mixtures (Pérez & Pasandín, 2017).

The investigation of moisture damage in asphalt mixtures is gaining traction due to its notable influence on various pavement issues like fatigue cracking, potholes, raveling, and rutting (Moraes et al., 2011, D'Angelo and Anderson, 2003). Mechanical loading and the presence of moisture within asphalt mixtures are the culprits for moisture damage. Generally, moisture deteriorates mixtures through, weakening asphalt mastic cohesion, breaking the adhesive bond between aggregate and asphalt (known as "stripping"), and degrading the aggregate itself. The loss of cohesion or adhesive strength weakens the asphalt matrix, potentially causing stiffness and strength loss. While aggregate strength loss due to moisture is uncommon, matrix weakening can lead to permanent deformation (rutting) or cracking (Copeland et al., 2007). As a result, reducing the impact of moisture damage has become a major challenge for researchers, transportation agencies, and departments. Moisture damage in asphalt pavements refers to the degradation of mechanical properties like stiffness, durability, and strength caused by water presence (Al-Bayati, 2019, Pasandín & Pérez2013).

Previous studies found that RCA HMA mixes have a higher moisture sensitivity than those with only natural aggregate mixes (Pérez et al., 2012 a, Mills-Beale & You, 2010, Pasandín & Pérez, 2013). Studies show that moisture susceptibility had a positive relationship with the quantity of RCA used within the HMA mixes due to higher asphalt content in the mixtures and RCA crushing (Mills-Beale and You, 2010, Wen and Bhusal, 2011). Zhu et al. (2012), Pérez et al. (2012a, 2012b), and Wu et al. (2013) further showed that incorporating RCA results in HMA with decreased resistance to moisture damage. Up to 20% RCA can be used in urban road pavements' wearing course, while up to 40% RCA may be suitable with anti-stripping additives (Ossa et al., 2016). Nevertheless, some other studies indicate that HMA mixtures containing RCA show improvements in performance characteristics, such as resistance to moisture-induced damage, rutting, fatigue life, and low-temperature cracking, similar to conventional bituminous mixtures (Radevic et al., 2017, Gopalam et al., 2020)

Improving the moisture resistance of RCA mixtures will entail improving RCA characteristics. As such, some studies have evaluated the impact of various RCA treatments. For example, precoating RCA with slag cement paste (Lee et al. (2012), or a propriety liquid silicon resin produced higher moisture-resistant mixtures compared with non-treated RCA mixtures (Zhu et al., 2012). In 2019, Al-Bayati's study discovered that a two-pronged strategy that includes presoaking in a weak acid (Acidic acid) and a 15-minute mechanical treatment greatly enhances Hot Mix Asphalt's (HMA) moisture resistance. Pasandín and Pérez (2013, 2014) employed a methodology that assessed the impact of two treatment types. First, they coated the RCA with 5% asphalt emulsion before mixing, then kept the loose mixture in an oven for 4 hours at 170°C before compaction. These resulted in greater moisture-resistant mixtures.

The asphalt binder property is another crucial factor that influences the moisture resistance of asphalt mixtures. Using asphalt with higher viscosity has been shown to result in mixtures with better moisture damage resistance. Thus, when HMA is used, the asphalt's higher viscosity improves its ability to withstand moisture damage (Xiao and Amirkhanian, 2009, Pérez and Pasandín, 2017).

Asphalt binder properties are commonly enhanced by incorporating additives like polymers to broaden their high and low-temperature grade range, aiming for better performance under specific conditions such as high traffic volumes. In the NCHRP project 90-07, the performance of polymer-modified asphalt binders was assessed using the same Superpave performance grade (PG) but with varying chemical properties. This approach offered a distinct method to evaluate the bond strength characteristics of modified binders independently from changes in PGs (Copeland et al., 2007).

The extensive literature review reveals that previous research predominantly examined the impact of recycled aggregates or binder types on moisture damage separately. Only a limited number of studies investigated the combined effects of different treatment methods for RCA and various binder types.

Therefore, this study primarily concentrates on assessing the influence of coarse recycled concrete aggregate (CRCA) treated with different treatments and binder types in typical Ontario HMA mixtures, specifically focusing on tensile strength and moisture damage.

Materials and experimental program

Materials

The present study examined and used two types of aggregate: natural aggregate (NAg) and RCA. The Miller Group provided the NAg and plant dust, a filler commonly used in asphalt mixtures. McAsphalt Industries in Toronto, Ontario, additionally provided two varieties of asphalt binders, PG 64-28 and PG 52-34. Table 1 provides a detailed description of these asphalt binders' physical characteristics. Table 1 demonstrates that PG 64-28 binder type has a comparatively higher viscosity than PG 52-34 binder type. "High viscosity of asphalt binder" refers to an asphalt binder with a thick, sticky consistency that makes it difficult to flow. This suggests that when left at room temperature, it does not pour or spread evenly. PG 64-28 has a higher flashing point and dynamic shear than PG 52-34 as a result.

The RCA was created by crushing concrete that was unsatisfactory in terms of its age, performance, or properties and had not been utilized in civil engineering projects. It was obtained from a ready-mix concrete facility. RCA can be categorized as fresh concrete that has not been used in civil engineering works. It is widely acknowledged in the literature that fine-recycled concrete aggregate (FRCA) retains more residual mortar than coarse recycled concrete aggregate (CRCA) (Akbarnezhad et al., 2013, Al-Bayati et al., 2024). As a result, CRCA is thought to possess better quality attributes than FRCA, potentially increasing the effectiveness of its application. Because of this, the CRCA component of RCA is the main subject of this study. The material retained between 4.75 mm and 19 mm sieve sizes is explicitly defined as CRCA. Figure 1 demonstrates the result of the sieve analysis for Nag and RCA and Figures 2-a and 2-b show the optical images of Nag and RCA, respectively.

Various tests and protocols were used to obtain the mechanical and physical properties of untreated CRCA and NAg. The results of the mechanical and physical properties of NAg and CRCA with treatment (RCT) and CRCA without treatment (RC) are shown in Table 2. There is a noticeable distinction between Nag, RC and RCT regarding physical attributes, specifically bulk relative density (BRD) and water absorption. These results validate the findings of earlier studies that showed RCA has a much higher absorption capacity than NAg (Wu et al., 2013, Pasandín and Pérez, 2014). The RCA is more likely to absorb more water than NAg because adhered mortar has a higher porosity than NAg (Al-Bayati et al., 2016). Accordingly, the presence of adhered mortar results in decreased density, weaker bond strength, and increased water absorption (Wong et al., 2007). Furthermore, there is a discernible difference in the physical attributes of RCT and RC. The primary physical characteristics of CRCA following a combination of heat treatment at 300 °C and a 15-minute mechanical treatment are presented in Table 2. These treatments significantly improve the properties of CRCA. Applying heat and mechanical treatment, in particular, substantially lowers the water absorption rate of CRCA from 5.91% to 4.13%, demonstrating an efficient treatment method with a reduction of 30.12%. The Bulk Relative Density (BRD) also exhibits a notable improvement. The results of the laboratory also indicate a significant decrease in the porosity of CRCA, which is down by roughly 25.59%.

Methods

Preparation of NAg & CRCA

To remove any obvious impurities, like wood chips, etc., the RCA was carefully cleaned. The NAg and RCA were dried in an oven at 105 ± 5 °C for 24 hours prior to sieve analysis, treatments, and testing. A 4.75 mm sieve was used to filter the RCA in order to ensure that only the coarse aggregate was left. In Figure 1, the aggregate gradation for RCA and NAg is displayed. In terms of treatment methodology, the untreated CRCA was tested at room temperature (20°C), and the treated CRCA was assessed using thermal treatment at 300°C for an hour, followed by mechanical techniques.

According to the results of a previous study (Al-Bayati 2019), the CRCA in this study was subjected to a 300°C thermal treatment followed by a brief mechanical treatment with balls. Al-Bayati (2019) found that a 300°C heat treatment for an hour combined with a short mechanical treatment (without balls) produced the best results. To improve the qualities of CRCA for use in asphalt mixtures, these techniques were chosen for additional testing and included a brief mechanical treatment (using balls). All CRCA samples that had been treated underwent a brief mechanical treatment. For 15 minutes, metal balls weighing 5000 grammes were placed inside a Micro-Deval apparatus. To ensure that only coarse aggregates were retained, the samples were then filtered through a 4.75-mm sieve.
The commonly asked query for which an answer is needed is: How practical is it to heat and mechanically treat CRCA on a project scale?
The specified answer depends on many factors; although high-quality CRCA can be produced by heating and mechanically crushing with steel balls, the following factors determine whether this is feasible on a project scale: The project's ability to finance and willingness to invest in advanced processing techniques. The availability of infrastructure and resources required to support energy-intensive processes. Adherence to environmental regulations and dedication to sustainable goals. The required quality standards and the expected volume of CRCA.
If these factors align well, the combined process can be a viable solution for producing high-quality CRCA on a project scale.

Preparation of Superpave mix design.

of simulating single-axle loads ranging from 10 to 30 million. A nominal maximum aggregate size (NMAS) of 19 mm was followed in the mix design. Two different proportions of CRCA (0% and 30%, both treated and untreated) were used in the CRCA mixtures, corresponding to each binder type (PG 64-28 and PG 52-34), as a partial replacement for coarse natural aggregate (NAg). According to earlier research (Al-Bayati, 2019), mixtures containing up to 30% CRCA for various CRCA types performed better than mixtures containing 15% and 60% CRCA. For this reason, 30% CRCA was used in this study. The gradation details are presented in Table 3 and correspond to the mix design specifications established by the Miller group and the Ministry of Transportation Ontario (MTO). These details include different types and percentages of CRCA. The volumetric characteristics of the various Hot Mix Asphalt (HMA) mixtures created for this investigation are shown in Table 4. The Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo was the site of all experimental testing.

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

An approach for determining the Indirect Tensile Strength (ITS) of asphalt mixtures is the Modified Lottman Test, or AASHTO T283. Numerous states and transportation departments have accepted this approach, which was first adopted by AASHTO in 1985. In order to evaluate the asphalt mixtures' susceptibility to moisture, it has been integrated into the Superpave mix design processes. The AASHTO T-283 method was used to determine the ITS of mixtures that contained two different types of binders (PG 64-28 and PG 52-34) and CRCA treated differently (thermal and mechanical). With the help of a Superpave gyratory compactor, the samples were compressed to a height of 95 ± 5 mm, with an air void goal of 7% ± 0.5. The two main categories, each with three specimens—unconditioned (control) and conditioned strengths—were then created from these compressed samples. Moisture conditioning was applied to the conditioned specimens, while the unconditioned samples were subjected to test conditions of 25 °C and 50 mm/min of load. Initially, a saturation level of 70% to 80% was reached to condition the samples. Following that, they were maintained for at least 16 hours at a temperature of -18 ± 3 °C in a freezer. Subsequently, the samples spent twenty-four hours (plus or minus one) in a hot water bath that was kept at 60 ± 1 °C. The samples were prepared for testing by immersing them in a water bath with a temperature of 25 ± 0.5 °C for about 2 hours ± 10 minutes after the hot water bath. Next, the conditioned strength was divided by the unconditioned strength to determine the Tensile Strength Ratio (TSR). According to the OPSS 1151 (2007) standard, the TSR value ought to be higher than 80%. Specific equations are used to carry out the ITS and TSR computations.

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

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

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

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

Analysis and Discussion of the Results of the Experiments.

Impact of binder types on HMA's volumetric characteristics

Table 4 demonstrates the lab outcome on the volumetric properties of the HMA mix design with various binder types and CRCA (RC and RCT) addition. According to the experimental findings, the mixes created for the two binder types, RC and RCT, satisfied all MTO requirements. Also, the results show that the optimum asphalt content (OAC) of PG 52-34, both with and without CRCA, is higher than that of PG 64-28. One possible explanation for this could be that PG 52-34 is engineered to operate at a lower maximum temperature (52°C) and a significantly lower minimum temperature (-34°C), in contrast to PG 64-28, which is engineered to operate at a higher maximum temperature (64°C) and a higher minimum temperature (-28°C). This difference frequently determines variations in binder composition and content. In addition to that high-viscosity binders have a reduced fluidity due to their thickness and stiffness. Because of this feature, they are not as effective at coating the aggregate particles as lower-viscosity binders are at doing so. Because of this, using a large amount of a high-viscosity binder may make it difficult to apply a uniform coat over the aggregates without oversaturating the mixture. In certain situations, such as during high temperatures, this may result in bleeding or drainage of the binder from the mixture. Surprisingly, other volumetric properties, such as voids in mineral aggregate (VMA), voids filled with asphalt (VFA), and Bulk specific gravity (G_{mb}) for various mixes with and without treated CRCA, are very close, even though OAC differs between the two types of binder. These observed behaviours may arise from the fact that both binders are engineered to possess the proper amount of stiffness and flexibility to endure a given temperature range. The viscoelastic nature of the binder affects these properties at operating temperatures, so formulations for VMA, VFA, and total voids (VTM) may result in similar volumetric properties. Furthermore, the aggregate type and mix design, which may have been tuned to work well with both kinds of binders, may also be the cause of the similarity in volumetric characteristics. The aggregate structure (gradation, shape, and texture), in conjunction with the binders' comparable viscoelastic properties at specific temperatures, can produce similar air voids and compaction levels. For both types of binder, the mixtures containing treated and untreated CRCA showed similar patterns and behaviours in terms of volumetric properties. VMA, VFA, and unit weight increased as the CRCA was treated, but the mixture's OAC decreased. Following treatment, reduced porosity, and water absorption of CRCA are primarily responsible for this.

It should be noted that three different types of two-binder mixtures are used: control mix with NAg (0.0% CRCA); MRC= Mix, which contains 30% CRCA without treatment; and MRCH= Mix, which contains 30% CRCA with heat treatment followed by a 15-minute mechanical treatment. They are called MNA1&2, MRC1&2,30%, and MRCH1&2,30%, respectively. Number 1 and 2 refers to (PG 64-28 & PG 52-34) respectively.

Impact of binder types on HMA's tensile strength

ITS is typically used to measure the asphalt mixtures' tensile strength, which can then be used to assess various relevant behaviours like stripping, permanent deformation, and road surface cracking (Lee et al., 2012). To examine the impact of the binder types (1 & 2) on the tensile strength of the asphalt mixtures, Figure 3 displays the average conditioned and unconditioned ITS of the mixtures with treated and untreated CRCA for both binder types when they were operating at the optimal asphalt content. It has been noted that the tensile strength behaviour trend of the mixtures containing PG 64-28 and PG 52-34 was similar. Concurrently, the PG 64-28 control mix demonstrated superior tensile strength compared to the PG 52-34 control mix in both ITS conditioned and unconditioned states. It is imperative to note that, out of all the mixes with different tensile strength values, the control mixture (0% CRCA) for both binder types have the lowest tensile strength, particularly mixes containing PG 52-34, which has the lowest value of all the mixes. These findings show that adding different CRCA types (with and without treatment) results in successful behaviour. An increase in the ITS values is typically observed upon adding both treated and untreated CRCA. Results regarding the impact of binder types revealed that all mixes containing PG 52–34 had lower tensile strength for ITS, for both conditioned and unconditioned, compared to mixtures containing PG 64–28, both with and without CRCA. The reason behind this could be attributed to PG 64-28's higher high-temperature grade (64 as opposed to 52), which implies that it can withstand higher stress levels at elevated temperatures without undergoing deformation, thereby leading to lower modulus. Moreover, at typical service temperatures, PG 64-28 usually has a higher stiffness modulus than PG 52-34 in terms of elastic recovery and stiffness. Being more rigid means that the binder can withstand deformation under stress more successfully, which usually results in a higher tensile strength.

In conclusion, compared to asphalt mixtures containing NAg, which show a lower tensile strain tolerance before failing, HMA mixtures incorporating different types of CRCA can withstand higher strains before failing, indicating a greater resistance to cracking.

Impact of binder types on HMA's moisture damage

Moisture sensitivity, also known as moisture damage, is a type of deterioration caused by exposure to water that mainly affects an asphalt mixture's mechanical properties (Pasandín & Pérez, 2013). Attaining a minimum TSR (Tensile Strength Ratio) value of 80% is required to produce an asphalt mixture that can resist moisture and water damage (Pérez et al., 2012). In order to examine how the type of binder affects the mixtures' moisture sensitivity, Figure 4 shows the lab results for TSR values of asphalt mixtures containing two distinct binder types, PG 64-28 and PG 52-34, as well as treated and untreated CRCA. The TSR values for both types of binder were notably higher than 80% in all mixtures, with the exception of the control mixture that used PG 52-34, which had a TSR that was lower than the MTO standard. Furthermore, it is noteworthy that the TSR behaviour trends of the mixtures containing PG 64-28 or PG 52-34 differ. With PG 64-28, the TSR increased with adding CRCA to reach a value of 92.28% for the mixture that included treated CRCA, whereas TSR did not follow consistent behaviour when adding CRCA for mixes with PG 52-34. The reason behind this could be that the mixtures containing PG 64-28 may result in improved aggregate interlock and optimized void structures, making them less vulnerable to damage and water infiltration. Efficient void distribution guarantees a mixture with less space for water to collect and erode the binder-aggregate adhesion. Alternatively, it might be the result of the study's aggregated gradation of mix design, which applied the mix design for mixtures with PG 64-28 to the second binder and may not have been appropriate for mixes with PG 52-34. Furthermore, the mixtures that included PG 64-28 exhibited better moisture resistance and registered a higher tensile strength ratio than the mixtures that included PG 52-34 with treated and untreated CRCA. These results strongly indicate a successful utilization of CRCA in asphalt mixtures. In conclusion, the results suggest that the moisture sensitivities of mixtures that included treated and untreated CRCA are highly affected by the type of binder.

Statistical Analysis of the Obtained Results

The coefficient of variation and standard deviation are included in the summary of ITS statistics in Table 5. Most mixtures had coefficients of variation for the unconditioned ITS at 25 °C that were higher than those for the conditioned ITS, according to the statistical results. According to this, ranking the tensile strength of HMA mixtures may be accomplished by employing conditioned ITS as a parameter. A two-way ANOVA analysis was performed for various mixtures to investigate the impact of different parameters on ITS and TSR values to gain a better understanding. The parameters that are mentioned are different binder types (PG 64-28 & PG 52-34) and different CRCA conditions (30% treated and 30% untreated). Remarkably, the results showed that the binder type and CRCA's condition had an insignificant interaction with a p-value of (0.397) > (0.05), suggesting that the effects of these variables act independently. When it comes to examining the effects of binder type and CRCA condition, treating CRCA has a lower influence on the outcomes of ITS than the binder types. Table 6 displays the results of the two-way ANOVA analysis of the ITS values.

Regarding how binder type and CRCA condition (treated or untreated) affect moisture susceptibility (TSR), statistical Two-way ANOVA analysis showed that both conditions have an insignificant impact on TSR, with Factual (1.5632) < Fcritical (5.3177) and a p-value of (0.2465); Factual (0.1215) < Fcritical (5.3177) and a p-value of (0.7364), at that respective. The value of (SS) based on the CRCA condition (10.44398) is lower than the value of (SS) based on the type of binder, which is registered at (134.4117). This suggests that statistically, indicating that the type of binder—rather than the CRCA condition—has a greater influence on the moisture susceptibility (TSR) of the HMA mixtures. According to the statistical analysis, however, the impact of the CRCA condition and the type of binder on the TSR of asphalt mixtures was statistically insignificant. An insignificant interaction between the parameters mentioned causes these parameters' effects to act independently. Possible effects on TSR of various asphalt mixtures could come from the heterogeneity of CRCA and its inferior qualities, like surface texture, porosity, and density. In Table 7, the outcomes of a two-way ANOVA analysis are tabulated numerically (Al-Bayatiy & Tighe, 2019).

This investigation is limited to evaluating the effects of various CRCA treatment techniques and binder types on the moisture resistance and tensile strength of HMA; a cost analysis is not included in this study. The next research will thoroughly address this in addition to the Life Cycle Assessment (LCA). As a point of comparison, Al-Bayati (2019) offers a comprehensive examination of the financial aspects pertinent to this subject, whose results provide essential information on these topics and support the current research framework. The materials cost, and CRCA treatment cost for producing 1 m3 of different asphalt mixtures were determined in the Al-Bayati (2019) study. Hence, it was possible to determine the overall cost of making 1 m3 of varying asphalt mixtures. According to the results, the overall cost of asphalt mixture typically rises in proportion to price fluctuations when the CRCA proportion also does. The cost of mixtures containing 30% treated CRCA is remarkably similar to that of mixtures containing 30% untreated CRCA, with a difference of less than $1 and this is quite interesting. The study's conclusions also demonstrated that mixtures containing 30% untreated CRCA had a negative cost savings of roughly $-3.00 compared to the control mixture's cost savings, as shown in Figure 5. Furthermore, the cost savings of mixtures containing 30% treated CRCA are very similar, roughly equal to those of mixtures containing 30% untreated CRCA, for a range of fluctuations, see Figure 5. This suggests that there is little to no impact on cost-savings from the cost of CRCA treatment.
Conversely, they concluded that cost savings are significantly influenced by the proportion of untreated CRCA additions. In brief, Al-Bayati's (2019) study found that the cost of heat treatment was quite reasonable. This amounts to noticeable economic benefits and indicates that these treatments could be applicable.

Conclusions

The moisture susceptibility (TSR) of Ontario Superpave mixtures was examined in this study in relation to binder types (PG 64-28 & PG 52-34) and CRCA conditions (treated and untreated). The following conclusions can be drawn about the primary findings of this study:

- Based on the experimental results, all MTO requirements of the volumetric properties were satisfied by the mixes prepared for the two binder types, RC and RCT, except for the TSR for binders 52–34, which was below the required level (80%).
- The findings demonstrate that PG 52-34's OAC is greater than PG 64-28's, both with and without CRCA. Even though OAC varies between the two types of binder, it's surprising that other volumetric properties (VMA, VFA, and G_{mb}) for different mixes with and without treated CRCA are relatively similar. These behaviours could be attributed to the fact that both binders are designed with the right amount of stiffness and flexibility to withstand a specific temperature range.
- For both types of binder (PG 64-28 & PG 52-34), the mixtures containing treated and untreated CRCA displayed comparable patterns and behaviours in terms of volumetric properties. As the CRCA was treated, the mixture's OAC dropped, but its VMA, VFA, and unit weight increased. This is mainly because of the CRCA's decreased porosity and water absorption after treatment.
- The mixtures containing PG 64-28 and PG 52-34 exhibited a similar trend in their tensile strength behaviour. Meanwhile, in both the ITS conditioned and unconditioned states, the PG 64-28 control mix outperformed the PG 52-34 control mix in terms of tensile strength.

- The control mixture (0% CRCA) for both types of binder have the lowest tensile strength of all the mixes with varying tensile strength values; in particular, mixes containing PG 52-34 have the lowest value of all the mixes. This is important to understand. These results demonstrate how adding various CRCA types with and without treatment leads to successful behaviour.
- All mixtures, except the control mixture containing PG 52-34, had TSR values for both types of binder that were significantly higher than 80%. This mixture's TSR value was below the MTO standard. It is also noteworthy that the mixtures containing PG 64-28 or PG 52-34 exhibit different TSR behaviour trends. Additionally, compared to mixtures containing PG 52-34 with treated and untreated CRCA, those containing PG 64-28 showed superior moisture resistance and registered a higher tensile strength ratio. These findings clearly show that CRCA can be successfully added to asphalt mixtures.
- The ANOVA analysis findings from the standpoint of ITS showed that the binder type has a higher impact on ITS outcomes than treating CRCA.
- The statistical two-way ANOVA analysis results show that the type of binder influences the moisture susceptibility (TSR) of the HMA mixtures more than the CRCA condition. Nevertheless, the effects of these parameters operate independently of each other due to an insignificant interaction between them.

Table 1. Physical characteristics of the various binders that are used.

Binder type	PG 64-28	PG 52-34
Tests on the original binder		
Specific gravity, 15 °C	1.025	1.0247
Rotational viscosity @ 135 °C, Pa.s	0.533	0.235
Flash point, °C	282	230^{+}
Dynamic shear, G*/sin δ, KPa	1.55^{1}	1.295^{2}
Tests on the RTFO residue		
Dynamic shear, G*/sin δ, KPa	4.11^{1}	3.188^{2}

1 Dynamic shear at 64 °C, 2 Dynamic shear at 52 °C, RTFO = The Rolling Thin-Film Oven test

Table 2. Physical and mechanical properties of Nag and CRCA

Aggregate Properties/ Aggregate Types	Unit		NAg	Untreated CRCA (RC)	Treated CRCA* (RCT)	Specification
Bulk relative density (BRD)	-	Physical Properties	2.658	2.295	2.447	(ASTM C 127)
Water absorption	%		0.8	5.91	4.125	(ASTM C 127)
Porosity	%		-	13.56	10.092	Adapted from Abbas et al., 2009
Micro-Deval abrasion loss	%	Mechanical Properties	15.89	23.57	-	(ASTMD6928)
Aggregate crushing value			19.48	27.42	-	(BS 882)
Freezing & thawing			17.4	18.03	-	(LS- 614)

* Treated at 300 C follow by 15 min. mechanical treatment.

Table 3: Targeted Mix Design, MTO Specifications, and Gradations of CRCA

Sieve Size, mm	0.0% CRCA	30% CRCA	The Target of Mix Design	MTO Limitation
25	100	100.0	100	100
19	95.2	95.3	96.8	100 - 90
16	89.0	88.5	90.6	90 - 23
12.5	81.8	80.5	83	
9.5	73.2	71.8	73.3	
6.7	63.3	63.1	63.3	
4.75	57.1	55.9	55.9	
2.36	42.8	41.3	43.5	49 - 23
1.18	30.7	30.5	32.5	
0.6	22.9	23.6	25.1	
0.3	10.2	10.3	11.8	
0.15	5.4	5.6	5.5	
0.075	2.1	2.2	3.8	8 - 2

Table 4. Volumetric characteristics of mixtures with different types of binder.

Binder type	Mix type	Volumetric characteristics				
		OAC (%)	VMA (%)	VFA (%)	VTM (%)	G_{mb}
PG 64-28	MNA1	4.83	14.5	72.5	4.0	2.4
	MRC1,30%	5.31	13.66	70.7	=	2.373
	MRCH1,30%	5.21	13.88	70.9	=	2.393
PG 52-34	MNA2	5.28	14.5	72.3	4.0	2.414
	MRC2,30%	5.5	13.8	71.0	=	2.374
	MRCH2,30%	5.28	14.3	71.8	=	2.384
MTO Specification Acceptable Limitations	-	-	13.0 min	65-75	4.0	-

MNA= Control mix with NAg (0.0% CRCA); MRC= Mix includes 30% CRCA without treatment; MRCH= Mix includes 30% CRCA with heat treatment followed by 15 min mechanical treatment; OAC= optimum asphalt content; VMA= voids in mineral aggregate (VMA); VFA= voids filled with asphalt (VFA); VTM= total voids; Gmb= Bulk specific gravity.

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Table 5: Statistical Analysis of the Results of ITS

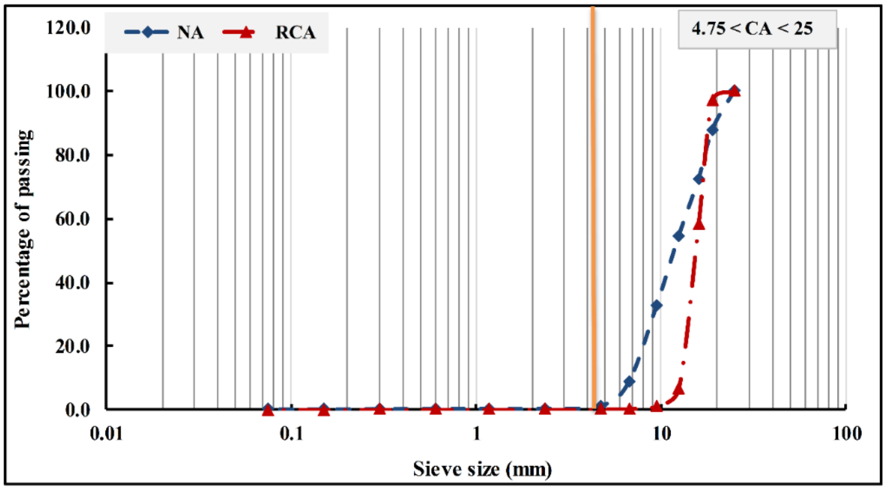
Binder type	Mixture type	Std. dev. for Unconditioned ITS	COV for Unconditioned ITS (%)	Std. dev. for Conditioned ITS	COV for Conditioned ITS (%)
PG 64-28	MNA1	58.11	11.46	24.55	5.35
	MRC1,30%	32.84	3.85	29.76	3.81
	MRCH1,30%	102.32	10.83	67.61	7.75
PG 52-34	MNA2	21.33	5.49	0.51	0.17
	MRC2,30%	25.42	6.56	24.12	7.00
	MRCH2,30%	8.94	2.13	0.04	0.01

Table 6: Results of Two-Way ANOVA Analysis: P-Value and Sum of Squares of ITS.

Source of Variation		**ITS, % (Unconditional)**
Binder type	P-value	1.141E-06
	SS	784590.8217
	F	169.9225082
	F- critical	5.317655072
CRCA condition	P-value	0.178393027
	SS	10048.41895
	F	2.176233145
	F- critical	5.317655072
Interaction	P-value	0.396593
	SS	3703.911
	F	0.802173
	F- critical	5.3177

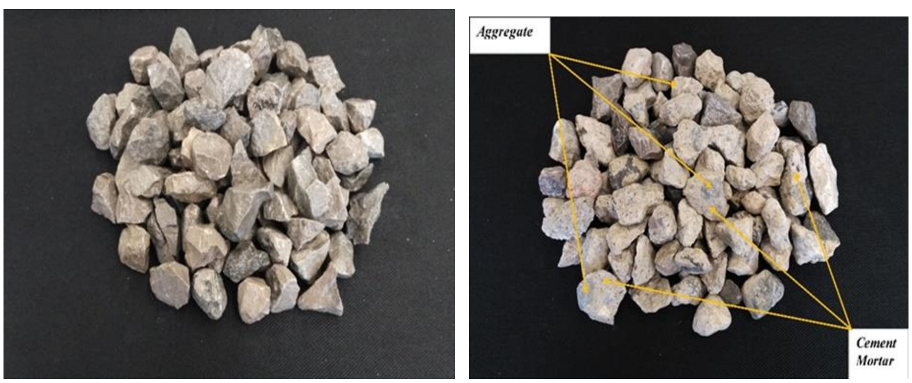
Table 7. Results of Two-Way ANOVA Analysis: P-Value and Sum of Squares of TSR

Source of Variation		TSR, %
Binder type	P-value	0.246527
	SS	134.4117
	F	1.563210
	F- critical	5.317655072
CRCA condition	P-value	0.7364465
	SS	10.44398
	F	0.1214637
	F- critical	5.317655072
Interaction	P-value	0.49646515
	SS	43.63838
	F	0.50751522
	F- critical	5.3176551



CA = Coarse aggregate

Figure 1. The RCA and NAg particle sizes gradations.



2-a. NAg 2-b. RCA

Figure 2. Optical images of NAg & RCA

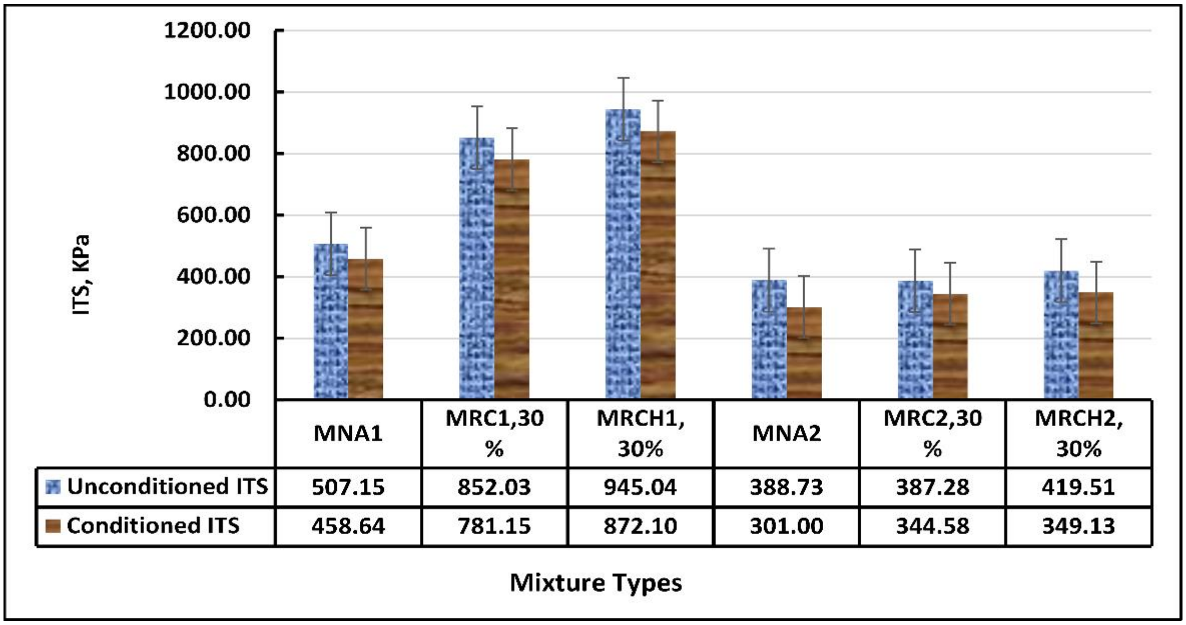


Figure 3. ITS for mixtures that include different binder types with treated and untreated CRCA.

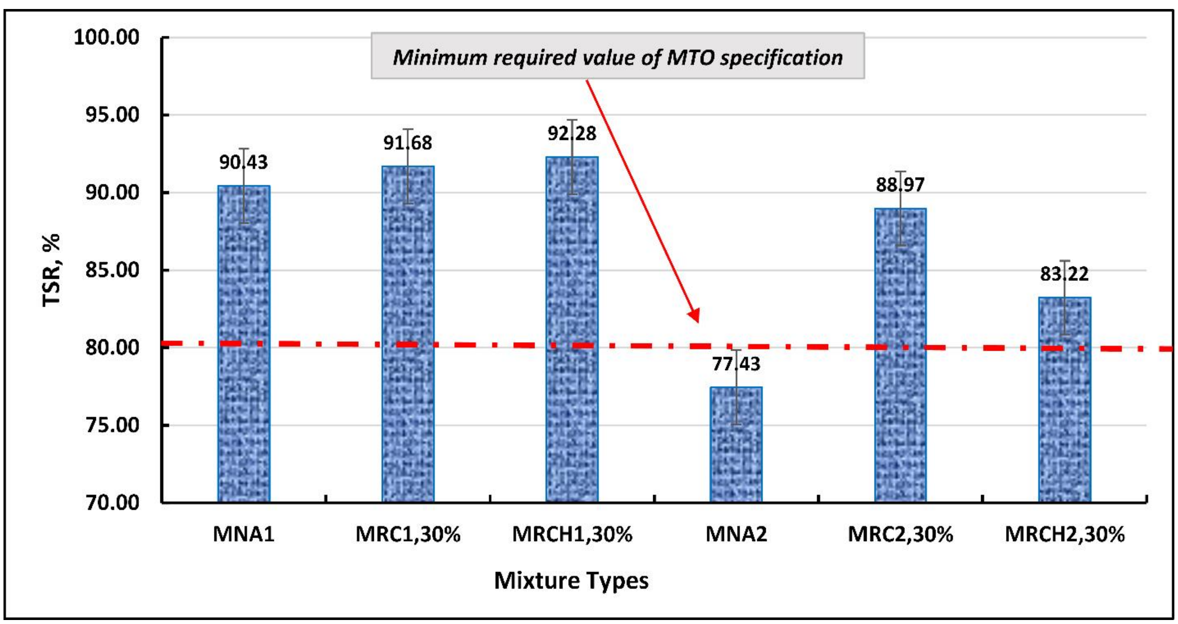


Figure 4. TSR for mixtures that include different binder types with treated and untreated CRCA.

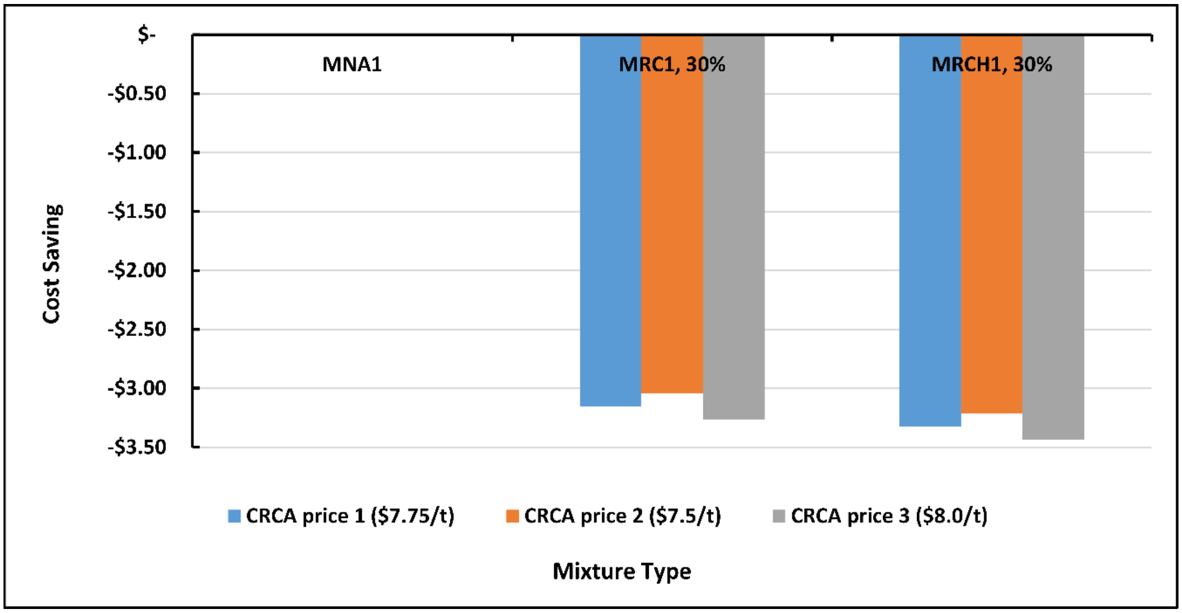


Figure 5. The cost savings of HMA with both treated and untreated CRCA for generating a 1 cubic meter volume.

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