Hindawi
Advances in Civil Engineering
Volume 2021, Article ID 9558241, 11 pages
https://doi.org/10.1155/2021/9558241

*Research Article*

# Rutting Resistance of Hot Mix Asphalt Containing Coarse Recycled Concrete Aggregates Coated with Waste Plastic Bottles

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Received 28 April 2021; Revised 13 June 2021; Accepted 15 June 2021; Published 22 June 2021

Academic Editor: Peng Zhang



The use of recycled concrete aggregate (RCA) as a part of coarse aggregates in asphalt pavements confers economic and environmental benefits. Coarse RCA (CRCA) has inferior mechanical and physical properties compared to natural aggregates due to very porous and weakly adhered cement mortar. In this study, CRCA surfaces were coated with waste plastic bottles (WPB) and used at 15%, 30%, and 50% in the asphalt concrete. The Marshall, stiffness modulus, and dynamic creep tests were performed to determine the strength of hot mix asphalts against rutting. The results revealed that the use of untreated CRCA reduced the Marshall quotient and the rutting resistance of the asphalt concrete. The results of the stiffness modulus and dynamic creep tests indicated that CRCA incorporation increased permanent deformation in the tested specimens due to the reduction of asphalt concrete stiffness. However, the asphalt concrete containing treated CRCA had lower permanent deformation because WPB promotes CRCA stability by penetrating its void and reinforcing cement mortar. Furthermore, by raising the temperature, the strength of all asphalt concretes decreased against rutting, and the reduction rate was higher in the modified specimens.

## 1. Introduction

Sustainable development in various industries has motivated the use of waste materials in various forms as a substitute for raw materials. Due to the vastness of road networks, waste from various industries can be used in road pavement to help the environment and reduce costs, and this has motivated extensive research [1–3]. Expanded construction in developing and developed countries and the occurrence of natural events (earthquake, flood, etc.) have considerably increased construction and demolition waste production, of which the recycled concrete aggregate (RCA) has the highest share [4]. Substitution of part of natural aggregates with RCA in the pavement structure decreases the construction cost, lowers environmental pollutions, saves the capacity of landfills, and preserves natural resources [5].

Despite the abovementioned advantages, the bulk specific gravity and stiffness of RCA are lower than those of natural aggregates, and RCA has more abrasion, porosity, and water absorption [6]. These physical and mechanical properties adversely impact the suitability of using RCA instead of natural aggregates. Therefore, before incorporating RCA in the asphalt concrete, its quality should be improved via two methods: (1) physical strengthening method and (2) chemical strengthening method. The former follows the loss of the adhered cement mortar through heating, soaking in acidic solutions, etc., whereas the latter follows RCA coating via different materials to enhance the quality of the adhered cement mortar [7].

The service life of road pavement has significantly decreased in recent years due to a significant rise in traffic volume and vehicles' axial load. Permanent deformation is a major failure in hot mix asphalts (HMA) and is common in tropical regions. HMA performance and strength against different failures greatly depend on the characteristics of the main ingredients, i.e., bitumen and aggregates [8]. Since a further increment of temperature reduces bitumen viscosity and adherence to aggregates, the aggregate skeleton provides the major function for the resistance of asphalt concrete against rutting. Thus, when RCA with physical and mechanical characteristics weaker than those of natural aggregates is utilized in asphalt concrete, the rutting potential of the specimens should be evaluated.

*1.1. Literature Review.* Several studies have examined the use of RCA in asphalt concrete and surveyed its performance. Arabani et al. [9, 10], in multiple investigations using dynamic creep, stiffness modulus, indirect tensile strength, and fatigue test, showed that the incorporation of RCA as coarse aggregate reduced the performance of HMA. Using coarse RCA (CRCA) in HMA decreased stiffness and fatigue life and increased rutting potential and moisture susceptibility. Furthermore, utilizing RCA as fine aggregate and filler in optimized amounts improved asphalt concrete performance. Hence, RCA as fine aggregate, along with slag as coarse aggregate, was proposed for use in the asphalt concrete. In another study, the characteristics of asphalt concrete containing 25%, 35%, 50%, and 75% RCA were evaluated. The results of the wheel tracking test revealed that, compared to the control specimens, the specimens containing RCA had more rut depth, but all the specimens met the criterion of the maximum rut depth of 8 mm. In addition, by raising the amount of RCA in the modified specimens, moisture susceptibility increased, such that the specimens with 75% RCA had a tensile strength ratio (TSR) of <80% [11].

Paranavithana and Mohajerani [12] surveyed the volumetric characteristics of asphalt concrete containing CRCA, along with resilient modulus and rutting potential. The use of CRCA reduced all volumetric characteristics (except for the percentage of air void), stiffness modulus, and rutting resistance compared to the control specimen.

Furthermore, using two methods of heating and soaking in acidic solutions, RCA characteristics were improved and RCA was utilized as an alternative aggregate in HMAs. The volumetric characteristics of HMAs containing CRCA treated with two treatment methods were studied. Based on the findings, the physical strengthening method improved the volumetric properties of asphalt concrete containing treated CRCA [13].

Ma et al. [7] utilized waste cooking oil residue to coat the surface of RCA to enhance the mechanical and physical characteristics of the waste material used in the asphalt concrete. RCA and RCA pretreated with waste cooking oil residue as coarse and fine aggregates were utilized in the asphalt concrete, respectively. The performance of specimens containing RCA and RCW was evaluated against different failures and compared with the control specimens. Compared to RCA, the RCA pretreated with waste cooking oil residue had lower bitumen absorption; therefore, the specimens containing them had lower optimum bitumen content (OBC). Furthermore, compared to the control specimens, the asphalt concrete with RCW had higher resistance against thermal cracking, but demonstrated higher rutting potential and moisture susceptibility.

Since RCA has poorer mechanical and physical characteristics than natural aggregates, Pasandin and Pérez investigated RCA incorporation in the asphalt concrete along with different additives. Contents of 5%, 10%, 20%, and 30% of RCA coated with 5% bitumen emulsion were used as part of the aggregate. The results showed that specimens containing RCA coated with emulsion bitumen possessed a higher effective bitumen content and superior performance than those containing RCA [14].

Kareem et al. [15] evaluated the use of double-coated RCA (DCRCA) in HMA. Cement slag paste and Sika Tite-BE were utilized to reinforce weak particles and reduce RCA bitumen absorption, respectively. The results indicated that RCA coated with cement slag paste had more water absorption compared to uncoated RCA, but DCRCA had a 12.3% water absorption lower than the uncoated RCA. The results of dynamic tests also revealed that the specimens containing DCRCA possessed lower resistance against rutting compared to the control specimen. The use of DCRCA at high and low temperatures increased and decreased the dynamic modulus of the modified asphalt concrete, respectively.

*1.2. Problem Statement and Objectives.* Herein, to improve the mechanical and physical characteristics of CRCA, the chemical strengthening method was adopted, and the CRCA surface was coated with WPB. Next, the rutting potential of asphalt concrete containing CRCA with and without WPB was investigated using the Marshall, stiffness modulus, and dynamic creep tests. The main objectives of the present study were as follows:

(i) Coating CRCA with WPB and investigating its mechanical and physical characteristics
(ii) Determining the effect of CRCA with and without WPB on the mix design parameters
(iii) Evaluating the rutting resistance of HMAs containing untreated and treated CRCA via different tests
(iv) Providing a better understanding of the rutting performance of HMAs containing CRCA by conducting the dynamic creep test at different temperatures

## 2. Materials and Experiments

*2.1. Materials.* RCA was prepared from construction and demolition waste and could not be directly used in the asphalt concrete due to its large size. Therefore, it was crushed by different crushers (jaw and hammer crushers, respectively) after being transported to the laboratory so that the maximum size of the established aggregate gradations would be 19 mm. RCA was utilized as a portion of coarse aggregates in HMAs because, according to the literature, it has a lower content of adhered cement mortars and better properties [16, 17]. Subsequently, CRCA was thoroughly washed to remove all wastes from its surfaces. The washed CRCA was placed in the oven at approximately $100 \pm 5$°C for 24 h to completely dry. Finally, various tests were performed at room temperature (25°C) to assess its physical and mechanical characteristics. Control asphalt specimens, containing only natural aggregates, were also prepared.

Figure 1 displays the grading used for constructing the control and modified asphalt specimens. The bitumen used was a product of Pasargad Oil Company, and its physical characteristics are presented in Table 1.

Polymer WPB is a family of polyester materials that can be used in the production of synthetic fibers, beverages, foods, and containers for holding liquid materials. This material is a type of thermoplastic polymer resin that can also be utilized in manufacturing composite resins with glass fibers. It is obtained from the polymerase of two substances, ethylene glycol and terephthalic acid. These two months are affected by chemical catalysts under high temperatures [18].

As a type of WPB polymer, polyethylene terephthalate (PET) was utilized as a modifier of asphalt binder properties in HMA. For this purpose, the PET parts were crushed by a precision shredder to convert the particle size to the desired size. For better quality control, according to previous studies [19], sieves with sizes of 0.425 and 1.18 mm were employed. Table 2 lists the properties of the WPB polymer.

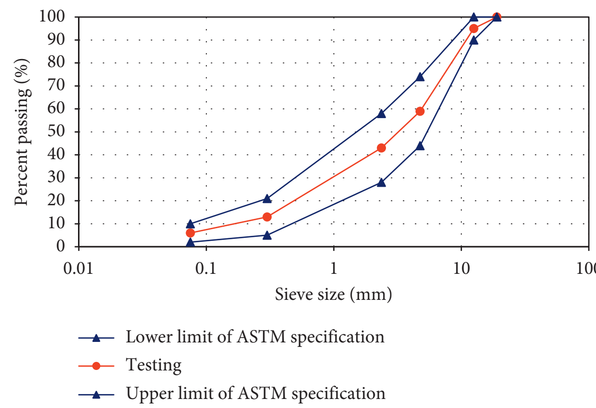



Figure 1: Aggregate gradation for sample production.

Table 1: Physical characteristics of the bitumen.

| Test | Standard | Result |
|---|---|---|
| Penetration (100 g, 5 s, 25°C), 0.1 mm | ASTM D5 | 67 |
| Ductility (25°C, 5 cm/min) (cm) | ASTM D113 | >100 |
| Softening point (°C) | ASTM D36 | 48.6 |
| Flash point (°C) | ASTM D92 | 275 |

Table 2: Properties of the WPB.

| Test | Standard | WPB |
|---|---|---|
| Density (g/cm$^3$) | ASTM D792 | 1.2 |
| Melting point (°C) | — | 235 |
| Water absorption, 24 hours (%) | ASTM D570 | 0.1 |
| Tensile elongation at yield (%) | ASTM D638 | 720–750 |
| Tensile strength (MPa) | ASTM D638 | 20.1 |

*2.2. Mix Design.* Based on the literature, the optimum amount of RCA in the asphalt concrete is 30–40% [13]. Therefore, herein, contents of 15%, 30%, and 50% RCA were utilized as a portion of coarse aggregates in HMAs. It has also been reported that the film of porous adhered cement mortar is the main cause of the inferior performance of RCA as aggregates in asphalt concretes [6, 20]. Accordingly, to reduce porosity and thereby decrease the water and bitumen absorption of CRCA (as the main reason for its limited use), its surface was coated with WPB. To this end, CRCA was first mixed with WPB at 5% by weight of CRCA and was then placed in the oven at 250–260°C for 2 hours. Next, the specimen was removed from the oven and stirred for 10 minutes to prevent aggregate lumping. Figure 2 illustrates the uncoated CRCAs and the CRCAs coated with WPB.

When the polymer is heated, it rapidly moves on the surface of the aggregate, sinking into the pores and absorbing the aggregate. The excess polymer is not usually placed on top of the previous polymer coating. Indeed, the WPB moves to find a porous space free of coating. The properties of WPB automatically provide a suitable coating of this material on the aggregate surface. To control the amount of polymer required, first, the specific surface area of the aggregates was obtained, and then, a WPB film thickness of 4–6 micron was considered. Using the aggregate specific surface area, aggregate mass, and polymer coating thickness, the polymer content required per unit mass of the aggregates was calculated. When placing the aggregate and polymer specimen in the oven, the aggregates were stirred several times to prevent the formation of excess polymer on the aggregate surface.

The typical procedure designated as Marshall mix design was adopted to specify the OBC of the control and modified asphalt concretes [21]. The OBC in all types of specimens is the bitumen content corresponding to the air void of 4%. The other Marshall parameters for all types of asphalt concrete were controlled at the OBC with permissible values. The mixing and compaction temperatures were determined as 150–155°C and 130–135°C, respectively, using the temperature-viscosity graph.

*2.3. Stiffness Modulus Test.* Stiffness modulus is a common method for determining the stress-strain chart for the evaluation of materials' elastic characteristics [22]. The stiffness modulus of asphalt concrete is measured based on the BS EN 12697-26 standard with the indirect tensile method. The materials used in the structure of road pavement do not have elastic characteristics and suffer from permanent deformations upon load application. However, if the load is small compared to the strength of the material and is applied frequently, the deformation created in each loading cycle is completely reversible, and an elastic material is assumed [23].

Before testing, the specimens should be stored on a flat surface at a temperature not exceeding 20°C for 14–42 d from the time of their manufacture. The temperature of the climatic chamber, in the vicinity of the specimen, should be equal to the specified temperature to ±0.5°C. For each test temperature, unless check testing indicates that a consistent temperature is reached in a shorter period of time, the

(a) (b)

Figure 2: (a) Uncoated CRCAs and WPB; (b) CRCAs coated with WPB.

specimen should be placed in the climatic chamber for at least 4 h before testing [24].

In this test, the cylindrical sample is usually subjected to 50–200 loading cycles, and the chart of sample deformation in each cycle is plotted. A controlled rate displacement is applied to the specimen in direct tension to provide a constant strain rate. For direct tensile tests, at least one element test should be performed to determine the stiffness level of the specimen. The conditions include a temperature of 10°C, strain amplitude of 50 microstrains, loading force $F > 200$ N, and loading times 3 s and 300 s. The stiffness modulus is obtained using the following equation [24, 25]:

$$M_r = \frac{P(\vartheta + 0.27)}{t\Delta H}, \quad (1)$$

where $M_r$ is the stiffness modulus (MPa), $P$ is the maximum dynamic load (N), $\vartheta$ is the Poisson's ratio (0.35), $t$ is the specimen thickness (mm), and $\Delta H$ is the recoverable horizontal deformation (mm).

Herein, the number of loading cycles was considered as 100 cycles, and the test for each sample was performed at 25 and 40°C and at the stress level of 30% of the tensile strength. The horizontal deformation of the specimens in the last five cycles (cycles 96–100) was measured by two linear variable differential transformers (LVDT), and the average value was used for computing stiffness modulus. Furthermore, for each similar sample, the sample was loaded again and, in the second loading, the force was applied to a sample rotated 90 degrees to the first state. The mean of the results obtained from twice loading was used in the computation.

*2.4. Dynamic Creep Test.* So far, several tests have been introduced for determining asphalt concrete resistance against rutting. Some of the most popular tests include the wheel tracking test and the static and dynamic creep tests [18].

Here, the dynamic creep test was used, which is a suitable method for determining the rutting potential of HMAs. In this test, the sample is under the loading and unloading mode, and the changes of accumulated strain are computed in each cycle. Three separate regions can be detected in the curve obtained from the dynamic creep test (accumulated strain against cycles of loading chart). In the first region, the rate of accumulated strain and sample volume is decreased, and asphalt sample density is increased; in the second region, the rate of accumulated strain is almost constant; and in the third region, the rate of accumulated strain is increased until sample rupture [26].

Zhou et al. [27] showed that these laboratory stages practically occur in the location, and the type of failure in each stage was determined. The results indicated that microscopic and macroscopic cracks were generated in the second and third stages, respectively.

In this method, the flow number (loading cycle number at which the third region of the curve begins) correlated with the rutting potential of HMAs. This parameter further demonstrates a specific cycle in which the asphalt sample shear strength is lost, and specimen failure is initiated. To determine the flow number, the creep curve was fitted by the Francken model [28]:

$$\varepsilon_P(N) = aN^b + c\left(e^{dN} - 1\right), \quad (2)$$

where $\varepsilon_P(N)$ is the accumulated strain in any loading cycle, $N$ is the loading cycle number, and $a$, $b$, $c$, and $d$ are equation constants.

The dynamic creep test was performed on the control and modified cylindrical specimens with the height of $65 \pm 1$ mm and diameter of 101.6 mm at 40 and 60°C, based on the EN 12697-25a standard. Cylindrical specimens were placed under haversine axial loading, 0.1-second loading, and 0.9-second unloading, at a 300 kPa stress level. In addition, a preloading process, a static stress with the magnitude of 10% dynamic stress, was applied for 10 min before commencing the test. Moreover, the asphalt specimens' rupture was considered as the end of the experiment.

## 3. Results and Discussion

*3.1. Physical and Mechanical Characteristics of Aggregates.* Table 3 lists the results of the tests conducted on natural and recycled aggregates. CRCA, compared to natural aggregates, had a lower density and more water absorption. These characteristics are due to the presence of old porous cement mortar and other impurities in the CRCA. Moreover, coating the CRCA surface with WPB increased the bulk specific gravity and decreased water absorption. This is because WPB permeated the CRCA voids, its weight per unit volume increased, and it acted as an insulator on CRCA surfaces and reduced its permeability. In addition, CRCA exhibited lower resistance against abrasion compared to natural aggregates, which is mainly attributed to the presence of weak cement mortar on the surface of the waste material.

As presented in Table 3, the level of abrasion observed in the Los Angeles abrasion test (approximately 35%) did not provide a standard value (the maximum value of 30%) for consumption in HMA. Furthermore, using a layer of WPB on CRCA surfaces could reduce the abrasion level to values as low as 27%. According to the results of the durability test, CRCA had less stability to atmospheric agents than natural aggregates, and this parameter was significantly increased using WPB.

*3.2. Mix Design Results.* Table 4 gives the parameters of the Marshall mix design for different specimens, containing natural aggregates and CRCA. The OBCs for specimens containing 15%, 30%, and 50% untreated CRCA were 5.3%, 5.8%, and 6.3%, respectively. The OBCs were lower for the specimens containing treated CRCA, but were higher than the control specimen. However, the amount of effective bitumen was almost the same for all the specimens. This confirms that more OBC in the asphalt concrete containing CRCA is due to its high bitumen absorption compared to natural aggregates. Moreover, CRCA use reduced the unit weight of asphalt concrete, because it has less density compared to natural aggregates.

Based on the results, the values of Marshall stability for all the specimens were higher than the minimum value, except for the specimen containing 50% untreated CRCA, and the stability of asphalt concrete increased by using WPB. Moreover, CRCA incorporation had a negative effect on the Marshall flow value such that the control specimen had the lowest, and the specimen containing 50% untreated CRCA had the highest value. Therefore, CRCA use reduced the Marshall quotient and elevated the rutting potential in the asphalt concrete (Figure 3). The results also revealed that the incorporation of WPB raised the Marshall quotient in the modified asphalt concrete.

The amount of voids in mineral aggregate (VMA) in the control and modified specimens indicated that it was reduced by using untreated and treated CRCA. This can be attributed to the higher bitumen absorption and lower density of CRCA compared to natural aggregates. Moreover, by increasing the value of CRCA in the asphalt concrete, the values obtained for voids filled with asphalt (VFA) decreased. Furthermore, since the use of WPB coating reduced the bitumen absorption of CRCA, it increased VFA in the asphalt concrete containing treated CRCA. The values of VFA for all the specimens were based on the standard in the 65–75% interval, but the amount of VMA for the specimen with 50% untreated CRCA did not meet the minimum value of 14%.

*3.3. Stiffness Modulus Test Results.* Figure 4 depicts the results of the stiffness modulus test for control and modified specimens at 25 and 40°C. The use of CRCA in all values decreased the stiffness modulus of the asphalt concrete at 25°C. Indeed, CRCA has lower quality than natural aggregates (Table 3), which is mainly attributed to the presence of very porous and weak cement mortar. In addition, the OBC in the specimens containing CRCA was more than the control specimen (Table 4). Based on the literature, these two factors can reduce the stiffness modulus [12]. Furthermore, the use of WPB raised the stiffness modulus in the modified asphalt concrete due to the improved CRCA characteristics and decreased percentage of optimum bitumen utilized in the modified specimens containing CRCA.

The effect of temperature rise was higher on decreasing the stiffness modulus of the specimens containing CRCA, and it had a direct relationship with increasing its amount. By increasing the temperature, the viscosity of bitumen dropped, and the performance of the asphalt concrete considerably depends on the quality of aggregates. The decrease rate of stiffness modulus in the asphalt concrete containing treated CRCA was lower because the use of WPB improved CRCA quality. Since the stiffness of asphalt concrete containing untreated and treated CRCA at 40°C was lower than that of the control specimen, it was expected that these specimens should have lower rutting resistance.

*3.4. Dynamic Creep Test Results.* Figure 5 displays the creep curve of the control and modified specimens at 40 and 60°C. Since the gradient of the creep curve was almost constant in the second region, when a line in this region was fitted on the curve, the highest and lowest slopes at both test temperatures belonged to the sample with 50% CRCA and the control sample, respectively. Thus, using a higher percentage of CRCA accelerated the failure process of the modified specimens. Moreover, using CRCA modified with WPB reduced the slope and increased the strength of the asphalt concrete against rutting due to having higher quality than CRCA.

As expected, the rutting potential of the control and modified specimens increased as long as the temperature rose to 60°C. Meanwhile, the rate of increment was more significant in the modified specimens. Indeed, bitumen exhibits lower viscosity at higher temperatures, and consequently, aggregate characteristics play a vital role in asphalt pavement loading capacity. Hence, temperature changes were more effective on the rutting resistance of asphalt concrete containing CRCA, and WPB incorporation improved the performance due to the enhancement of CRCA's mechanical and physical characteristics.

Flow number, which is a suitable index for determining HMA rutting potential, was computed using the Francken method. For this purpose, the Francken models were fitted to the rutting data, and the results are presented in Figure 6. The fitting parameters are also given in Table 5. The addition of CRCA until 50% decreased the asphalt concrete's flow number and rutting resistance. Using the WPB elevated the flow number values at both characterized temperatures for

Table 3: Physical and mechanical properties of natural and recycled aggregates.

| Test | Standard | Natural aggregate | Untreated CRCA | Treated CRCA | Specification limit |
|---|---|---|---|---|---|
| Bulk specific gravity (coarse agg.) | ASTM C127 | 2.671 | 2.233 | 2.387 | — |
| Maximum water absorption (%) | ACTM C127 | 1.14 | 5.49 | 3.56 | Max 2 |
| Los Angeles abrasion (%) | ASTM C131 | 18 | 35 | 27 | Max 30 |
| Flat and elongated particles (%) | ASTM D4791 | 7 | 13 | 12 | Max 15 |
| Soundness in $NaSO_4$ (%) | ASTM C88 | 4 | 10 | 6 | Max 12 |

Table 4: Mix design results for different specimens.

| Specimen type/property | Control | 15% CRCA | | 30% CRCA | | 50% CRCA | | Specification limit |
|---|---|---|---|---|---|---|---|---|
| | | Untreated | Treated | Untreated | Treated | Untreated | Treated | |
| Optimum asphalt content (%) | 5.1 | 5.3 | 5.2 | 5.8 | 5.4 | 6.3 | 5.6 | — |
| Unit weight (g/cm$^3$) | 2.371 | 2.344 | 2.356 | 2.315 | 2.327 | 2.263 | 2.294 | — |
| Marshall stability (kg·f) | 1470 | 1295 | 1386 | 1062 | 1204 | 712 | 901 | Min 800 |
| Marshall flow (mm) | 2.23 | 2.57 | 2.34 | 3.15 | 2.68 | 3.71 | 3.29 | 2–3.5 |
| Air void (%) | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3–5 |
| VMA (%) | 15.76 | 14.80 | 15.02 | 14.13 | 14.87 | 13.52 | 14.37 | Min 14 |
| VFA (%) | 74.62 | 72.97 | 73.38 | 71.69 | 73.10 | 70.42 | 72.16 | 65–75 |
| Dp (P0.075/Pbe) | 0.68 | 0.75 | 0.71 | 0.93 | 0.82 | 1.14 | 1.01 | 0.6–1.2 |

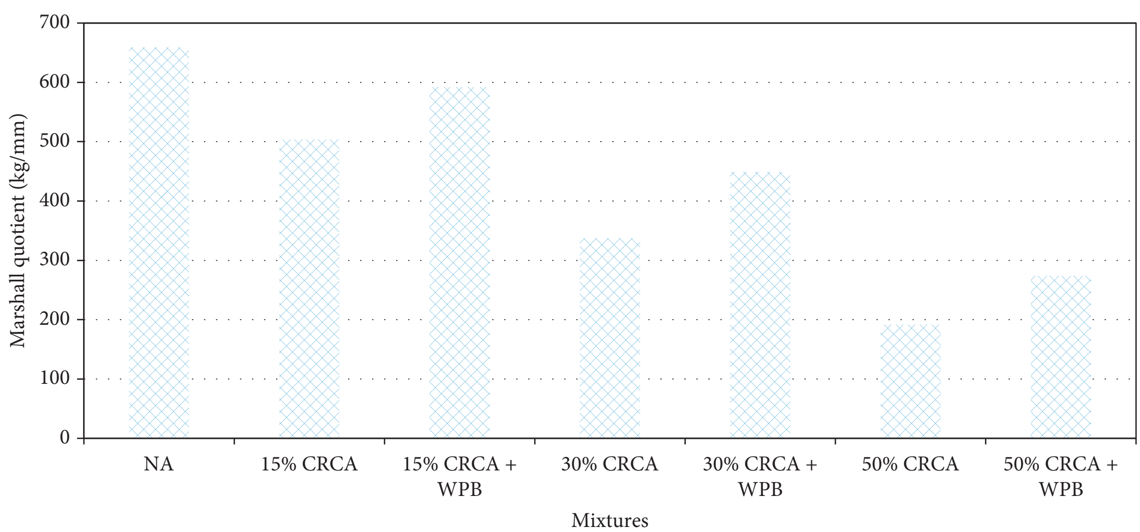



Figure 3: Marshall quotient values for control and modified asphalt concretes.

conducting the test. The results of different tests confirmed the adverse effect of CRCA on the rutting potential of asphalt concrete.

*3.5. Statistical Analysis.* To analyze the effect of different amounts of CRCA on permanent deformation results of controlled and modified asphalt concrete, Levene's test and *t*-test were performed in SPSS 16.0. Before performing the *t*-test, based on the data in this study, three assumptions of (a) continuous or ordinal scale, (b) volume of data, and (c) normal data distribution had to be checked. If the *p* value of Levene's test falls below the desired confidence level (often 0.05), the variance of the two datasets is unequal, and the second row of the data should be used; otherwise, the first row of the data should be used. In fact, if the variance is equal, the assumption is confirmed; otherwise, corrections should be made.

Based on the first and second columns of Table 6, in specimens with 15% CRCA, the results of permanent deformation in specimens with and without WPB polymer were compared. Levene's test results were equal to 0.831, which is greater than the desired significance level of 0.05, and first-row data had to be used. The value of *t*-test statistics in the first row was 0.001, which is less than the significance level of 0.05. Thus, this analysis showed that WPB polymer use significantly reduced the permanent deformation of the modified asphalt concrete specimens compared to the control asphalt concrete specimens. This value indicated that the WPB coating significantly decreased the amount of

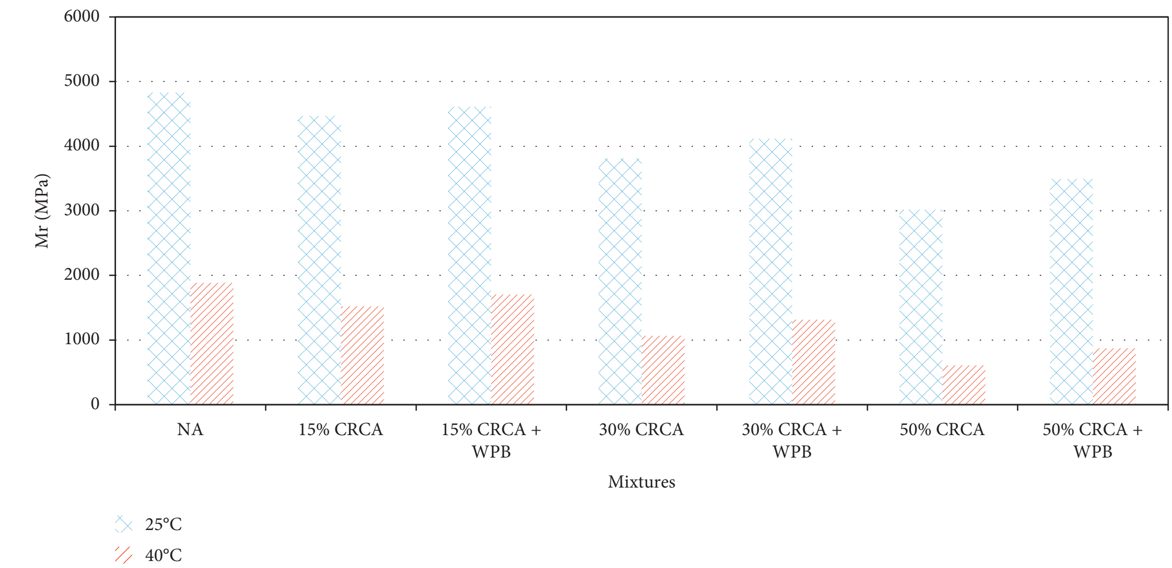
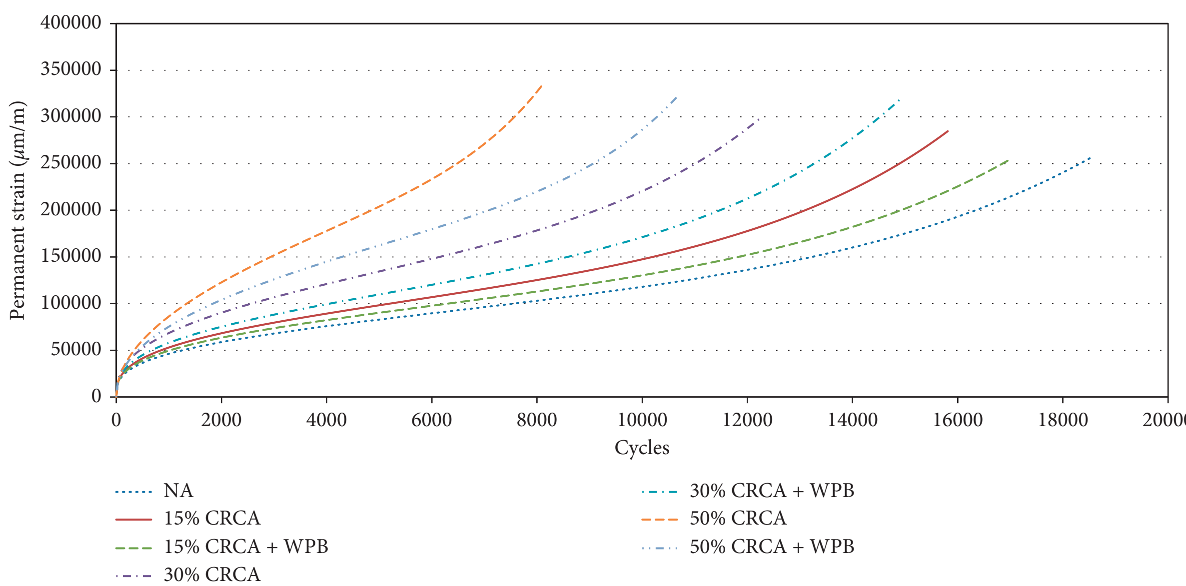
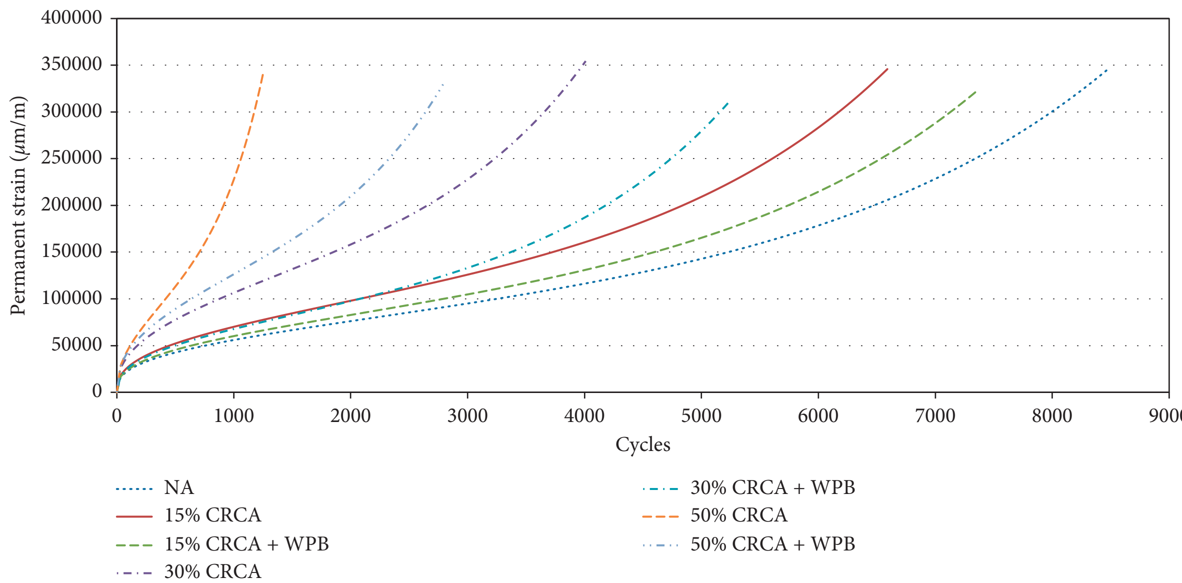



Figure 4: Stiffness modulus test results for different mixes at two temperatures.




(a)

Figure 5: Continued.




(b)

Figure 5: Permanent strain versus the number of loading cycles at testing temperatures (a) 40°C and (b) 60°C.

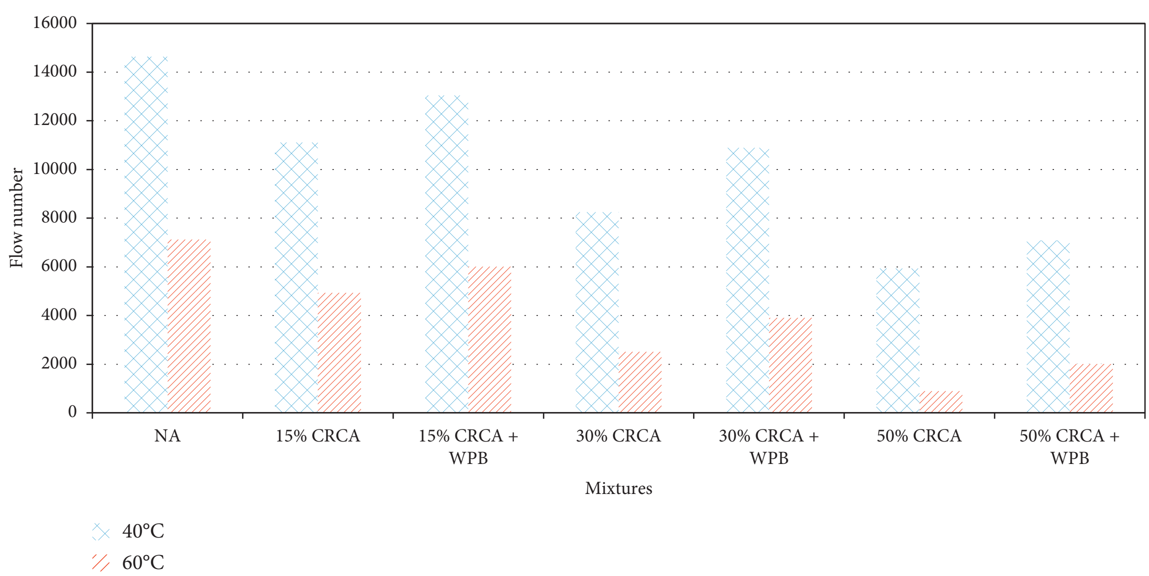



Figure 6: Flow number of modified and controlled asphalt concretes at two temperatures.

permanent deformation. This trend was also present in specimens with 30 and 50% CRCA, suggesting that the effect of WPB coating was also significant in them.

Table 7 presents the results of $t$-test to evaluate the effect of WPB coating on the aggregate surface on stiffness modulus values at two temperatures. Statistically, a significant difference between the stiffness modulus values in the controlled and modified specimens was found as a result of WPB coating. This significance was confirmed in the data of both temperatures.

A $t$-test was run to compare flow number values in the specimens of untreated and treated asphalt mixes. Table 8 lists the comparisons between the comparison data performed. The Sig. values for all the data were <0.005, indicating that the WPB coating effectively increased the flow numbers of the treated specimens compared to the untreated specimens.

*3.6. The Results of Economic Analysis.* The cost of producing 1 $m^3$ of different HMAs was calculated, and Figure 7 illustrates the values saved for producing the modified asphalt mixtures compared to the control mixture. The use of CRCA in all the values enhanced cost-saving, and using 50% CRCA had the highest effect. According to the geographical location of Iran and the relatively low price of bitumen, the

Table 5: Parameters of the Francken model.

| Temperatures | Specimens | Parameters | | | |
|---|---|---|---|---|---|
| | | *A* | *B* | *C* | *D* |
| 40°C | Control | 0.302 | 0.332 | 0.187 | 0.00022 |
| | 15% CRCA | 0.306 | 0.351 | 0.162 | 0.00027 |
| | 15% CRCA + WPB | 0.305 | 0.342 | 0.170 | 0.00024 |
| | 30% CRCA | 0.313 | 0.385 | 0.144 | 0.00035 |
| | 30% CRCA + WPB | 0.311 | 0.361 | 0.173 | 0.00029 |
| | 50% CRCA | 0.175 | 0.504 | 0.032 | 0.00066 |
| | 50% CRCA + WPB | 0.204 | 0.463 | 0.027 | 0.00053 |
| 60°C | Control | 0.297 | 0.355 | 0.488 | 0.00042 |
| | 15% CRCA | 0.306 | 0.383 | 0.465 | 0.00053 |
| | 15% CRCA + WPB | 0.301 | 0.362 | 0.476 | 0.00047 |
| | 30% CRCA | 0.413 | 0.397 | 0.492 | 0.00082 |
| | 30% CRCA + WPB | 0.302 | 0.377 | 0.418 | 0.00068 |
| | 50% CRCA | 0.383 | 0.439 | 0.621 | 0.0025 |
| | 50% CRCA + WPB | 0.434 | 0.407 | 0.515 | 0.0012 |

Table 6: Results of *t*-test to investigate the effect of CRCA percentage on the Marshall quotient.

| CRCA (%) | Dataset | Levene's test for equality of variances | | | *t*-test for equality of means | | |
|---|---|---|---|---|---|---|---|
| | | Variance | *F* | Sig. | *t* | df | Sig. |
| 15 | Set 1: untreated | Assumed | 0.052 | 0.831 | −9.847 | 4 | 0.001 |
| | Set 2: treated | Not assumed | | | −9.847 | 3.900 | 0.001 |
| 30 | Set 1: untreated | Assumed | 0.159 | 0.710 | −17.286 | 4 | 0.000 |
| | Set 2: treated | Not assumed | | | −17.286 | 3.710 | 0.000 |
| 50 | Set 1: untreated | Assumed | 0.240 | 0.650 | −21.223 | 4 | 0.000 |
| | Set 2: treated | Not assumed | | | −21.223 | 3.583 | 0.000 |

Table 7: Results of *t*-test to investigate the effect of CRCA percentage on the stiffness modulus.

| Temperatures | CRCA (%) | Dataset | Levene's test for equality of variances | | | *t*-test for equality of means | | |
|---|---|---|---|---|---|---|---|---|
| | | | Variance | *F* | Sig. | *t* | df | Sig. |
| 25°C | 15 | Set 1: untreated | Assumed | 0.002 | 0.968 | −1.848 | 4 | 0.013 |
| | | Set 2: treated | Not assumed | | | −1.848 | 3.996 | 0.013 |
| | 30 | Set 1: untreated | Assumed | 0.012 | 0.919 | −4.678 | 4 | 0.009 |
| | | Set 2: treated | Not assumed | | | −4.678 | 3.977 | 0.010 |
| | 50 | Set 1: untreated | Assumed | 0.043 | 0.846 | −8.943 | 4 | 0.001 |
| | | Set 2: treated | Not assumed | | | −8.943 | 3.917 | 0.001 |
| 40°C | 15 | Set 1: untreated | Assumed | 0.026 | 0.879 | −7.014 | 4 | 0.002 |
| | | Set 2: treated | Not assumed | | | −7.014 | 3.984 | 0.002 |
| | 30 | Set 1: untreated | Assumed | 0.087 | 0.783 | −12.773 | 4 | 0.000 |
| | | Set 2: treated | Not assumed | | | −12.773 | 3.835 | 0.000 |
| | 50 | Set 1: untreated | Assumed | 0.248 | 0.645 | −21.544 | 4 | 0.000 |
| | | Set 2: treated | Not assumed | | | −21.544 | 3.572 | 0.000 |

Table 8: Results of *t*-test to investigate the effect of CRCA percentage on the flow number.

| Temperatures | CRCA (%) | Dataset | Levene's test for equality of variances | | | *t*-test for equality of means | | |
|---|---|---|---|---|---|---|---|---|
| | | | Variance | *F* | Sig. | *t* | df | Sig. |
| 40°C | 15 | Set 1: untreated | Assumed | 0.051 | 0.832 | −9.794 | 4 | 0.001 |
| | | Set 2: treated | Not assumed | | | −9.794 | 3.901 | 0.001 |
| | 30 | Set 1: untreated | Assumed | 0.150 | 0.718 | −16.758 | 4 | 0.000 |
| | | Set 2: treated | Not assumed | | | −16.758 | 3.726 | 0.000 |
| | 50 | Set 1: untreated | Assumed | 0.062 | 0.815 | −10.815 | 4 | 0.000 |
| | | Set 2: treated | Not assumed | | | −10.815 | 3.880 | 0.000 |
| 60°C | 15 | Set 1: untreated | Assumed | 0.076 | 0.796 | −11.960 | 4 | 0.000 |
| | | Set 2: treated | Not assumed | | | −11.960 | 3.854 | 0.000 |
| | 30 | Set 1: untreated | Assumed | 0.360 | 0.581 | −25.983 | 4 | 0.000 |
| | | Set 2: treated | Not assumed | | | −25.983 | 3.413 | 0.000 |
| | 50 | Set 1: untreated | Assumed | 1.039 | 0.366 | −44.140 | 4 | 0.000 |
| | | Set 2: treated | Not assumed | | | −44.140 | 2.755 | 0.000 |

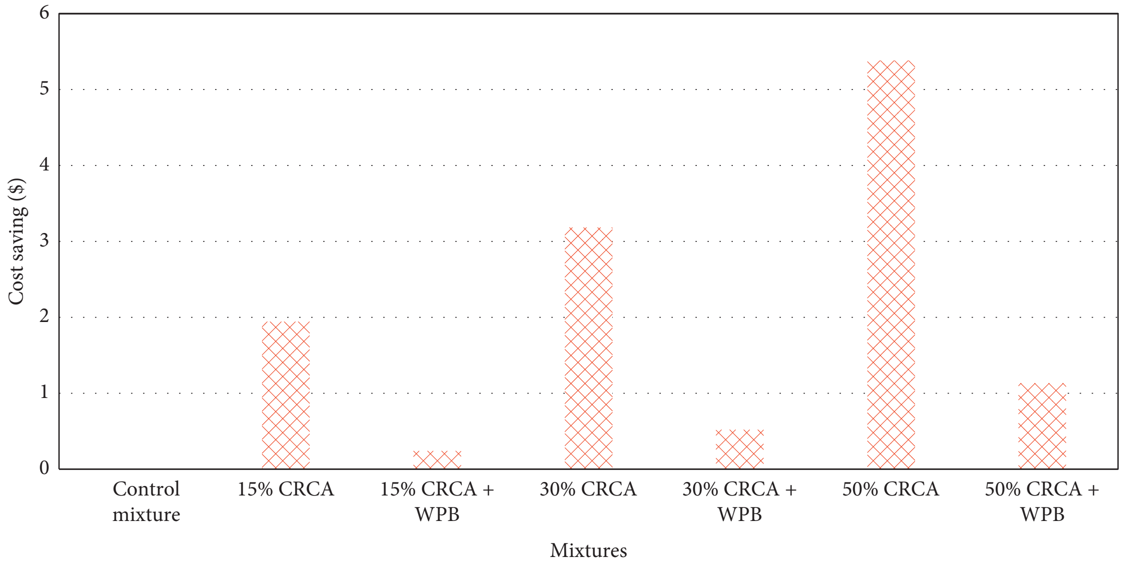



Figure 7: Cost-savings for producing asphalt mixes containing different amounts of CRCA compared to the control mixture at a volume of 1 $m^3$.

cost of HMA production is considerably influenced by aggregate cost. Asphalt mixtures containing treated CRCAs have a higher production cost than those containing untreated CRCAs due to the relatively high price of WPB. However, they always have a lower but similar production cost compared to the control mixture. Thus, if performance specifications are met, CRCA incorporation in road pavements should be seriously considered in Iran due to the relatively low price of bitumen.

## 4. Conclusions

Herein, Marshall, stiffness modulus, and dynamic creep tests were performed to evaluate the rutting potential of HMAs containing 0%, 15%, 30%, and 50% untreated and treated CRCA. Based on the laboratory data and analyses, the following conclusions are drawn:

(i) Despite the lower quality of CRCAs compared to natural aggregates, the physical and mechanical characteristics of CRCA used in the asphalt concrete are improved when the waste material is coated with WPB.

(ii) The Marshall test results showed that the asphalt concrete containing treated CRCA has lower OBC and flow and higher stability than the specimens containing untreated CRCA. Coating CRCA with WPB diminishes its adsorption capacity, reinforces the cement mortar due to penetration into the voids, and improves its mechanical properties.

(iii) Based on the Marshall test results, the asphalt specimens containing untreated and treated CRCA have lower Marshall quotient and resistance against rutting compared to the control specimen.

(iv) By raising the temperature, the stiffness modulus of all asphalt concretes is decreased, but the reduction rate is higher in all the modified specimens. At high temperatures, by decreasing bitumen viscosity, the asphalt concrete performance is affected by aggregate characteristics, and CRCA has an inferior quality compared to natural aggregates.

(v) The flow number at 40 and 60°C indicated that using untreated and treated CRCA reduces this index and increases the rutting potential in the asphalt concrete.

## Data Availability

The data used to support the findings of this study are currently under embargo while the research findings are commercialized. Requests for data, 3 months after publication of this article, will be considered by the corresponding author.

## Disclosure

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## Conflicts of Interest

The authors declare that they have no conflicts of interest or personal relationships that could have appeared to influence the work reported in this paper.

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