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RESEARCH

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Evaluating the Impact Performance of Environmentally Friendly Asphalt Concrete Slabs Containing Different Proportions of Recycled Concrete Aggregate and Corrugated Steel Fibers

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Abstract

The current research focuses on recycling construction waste by producing asphalt concrete mixtures containing varying proportions of recycled concrete aggregate (RCA), ranging from 0 to 50%. To ensure the improvement of the asphalt mixtures' properties in terms of Marshall stability, flow, bulk density, air void ratio, and splitting tensile strength, steel fibers were added at a volume fraction of 1.0%. The experimental program consisted of 12 asphalt cylinders with a diameter of 102 mm and a height of 64 mm, cast with different asphalt mixtures to study the effects of varying RCA proportions as well as the addition of steel fibers on the mechanical properties of the asphalt concrete mixtures. The stability of the asphalt mixtures decreased by 17.6%, 23.2%, and 28.8% when RCA was used at ratios of 30%, 40%, and 50%, respectively, compared to the reference mixture. The Marshall stability of asphalt mixtures containing steel fibers was higher than that of their counterparts without fibers. Moreover, 12 asphalt slabs were cast with different ratios of RCA in preparation for testing under the impact load resulting from the free fall of a 10-kg steel mass from a height of 2 m. The results revealed that the ratio between the back and front crater diameters for slabs containing 10%, 20%, 30%, 40%, and 50% RCA after incorporating steel fibers was 1.15, 1.17, 1.15, 1.28, and 1.36, respectively. These ratios were smaller than those of the counterpart slabs without steel fibers by 18%, 19%, 19%, 7%, and 18%, respectively. Moreover, due to the low accuracy of existing mathematical models for predicting the penetration depth of asphalt slabs made with RCA, this research presents a developed mathematical model capable of accurately predicting the penetration depth of such slabs. This model considers both the ratio of RCA and the steel fibers within the asphalt mixtures.

Keywords Asphalt mixtures, Recycled concrete aggregate (RCA), Steel fiber, Mechanical characteristics, Impact performance, Asphalt slabs, Analytical model

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1 Introduction

During the past two decades, asphalt concrete mixtures have been frequently used as a substitute for conventional asphalt mixtures in paving areas subjected to heavy traffic and high impact loads, such as highways, airport runways, harbors, and parking zones (Serin et al., 2012). Asphalt concrete mixtures have demonstrated a significant improvement in stability properties, compressive, and tensile strengths compared to traditional asphalt mixtures. This enhancement greatly increases the durability of pavement layers and extends their design life, thereby reducing construction costs (Dai et al., 2021; Katicha et al., 2010; Keshavarzi & Kim, 2016; Khanal & Mamlouk, 1492; Lv et al., 2018; Lytton et al., 2018; Nguyen et al., 2017).

Experimental and numerical studies have been ongoing to understand the influence of the proportions of components in asphalt concrete mixture on their mechanical properties. This effort aims to develop asphalt concrete mixtures characterized by better construction performance and lower costs. One of these attempts involved adding cement to the asphalt concrete mixture and utilizing the hydration products of cement to fill the voids present in the chemical composition of the asphalt concrete matrix (Nassar et al., 2016; Ouyang et al., 2017; Wang et al., 2014). After 4 h of curing, the compressive strength of cement asphalt mixtures constructed with 12% and 16% cement exceeded 10 MPa, representing approximately 50% of the compressive strength achieved after 28 days (Tian et al., 2020). Garcia et al. (2020) conducted a parametric study to investigate the relationship between aggregate gradation and the mechanical characteristics of asphalt concrete mixtures. The results revealed that the change in the gradation of the fine aggregate have a greater impact on the mechanical properties of asphalt concrete mixtures compared to the coarse aggregate. In 2023 and 2024, a mesoscale model for asphalt concrete was developed to study the effect of interaction between aggregate particles on stress transmission and the stiffness of asphalt concrete (Tan et al., 2023, 2024). The findings showed that strain was mainly localized in the matrix phase at lower frequencies, while stress was mostly concentrated in aggregates.

Annually, many structures, roads, and bridges are demolished due to reaching the end of their design life and cannot withstand the design loads (Basha et al., 2023; Mansour et al., 2024a, 2024b; Saha et al., 2024; Sobuz et al., 2024), producing approximately 2317 million tons of waste, including concrete, bricks, timber, ceramic, glass, and steel reinforcement (Acosta Alvarez et al., 2019; Afshar et al., 2017; Bamigboye et al., 2021; Bastidas-Martínez et al., 2022; Huang et al., 2021; Zuluaga-Astudillo et al., 2021). The disposal of such waste in public landfills causes pollution of the surrounding environment and increases carbon emissions. To mitigate the negative effects of construction waste worldwide, researchers have collaborated to study the possibility of recycling concrete aggregates and using them as a substitute for natural aggregates in asphalt concrete mixtures. Abedalqader et al. (2021) experimentally investigated the mechanical characteristics of asphalt concrete mixtures manufactured using recycled coarse aggregates after exposure to temperatures of 20 °C, 200 °C, 400 °C, and 500 °C. The study concluded that the optimum mixture for use in elevated temperatures in terms of compressive, splitting tensile, and flexural strengths consisted of 80% natural aggregate and 20% recycled coarse aggregates. Generally, the stability, flow, and splitting tensile characteristics of asphalt concrete mixtures decreased as the ratio of recycled aggregate increased (Motter et al., 2015; Muduli & Mukharjee, 2019; Paranavithana & Mohajerani, 2006; Sanchez-Cotte et al., 2020; Zulkati et al., 2013). The properties of recycled aggregate, especially its shear strength, are greatly influenced by the characteristics of the structural element from which it is extracted, as well as the duration of its exposure to loading, environmental factors, and the demolition method used. Failure to consider proper engineering precautions during the demolition process can negatively affect the interlocking cohesion between recycled aggregate and natural aggregate (Al-Bayati et al., 2018; Arabani et al., 2013; Pasandín & Pérez, 2017; Pérez & Pasandín, 2017; Radević et al., 2017).

In order to improve the stability of asphalt mixtures, enhance resistance to impact loads, and compensate for the weakness of recycled aggregates due to their previous loading, various types of fibers have been added to asphalt concrete mixtures, whether polymers (ELWakkad et al., 2023; Eskandarsefat et al., 2019; Tam et al., 2023; Tayfur et al., 2007), plastics (Wu & Montalvo, 2021), rubber (Li et al., 2021; Tarsi et al., 2020), nanomaterials (Fang et al., 2013) or natural fibers (Imadi et al., 2014; Ismael et al., 2022; Sheng et al., 2019; Xia et al., 2021). The incorporation of high tensile strength fibers within the asphalt concrete mixtures bridges the developed cracks and delays their propagations, resulting in an increase in the tensile strength of the asphalt concrete mixture (Guo et al., 2023; Zahran & Fatani, 1999). Zhao et al. (2020) concluded that the mechanical characteristics of asphalt mixtures reinforced with basalt fibers were significantly higher than those of conventional asphalt mixture. The study also revealed that the optimum content of basalt fibers within the asphalt mixture was 0.3%, considering both the structural performance of the pavement and cost analysis. Asphalt concrete mixtures reinforced with 3-cm-long carbon fibers at a content of 0.025% by weight exhibited the best fatigue resistance and Marshall stability among all tested mixtures (Moghadas Nejad et al., 2014). Thanks to the carbon fibers, the tensile stiffness modulus of the reinforced mixture increased by 24.5% compared to the unreinforced mixture, while the fatigue life increased by 2.4 times (Vo et al., 2017; Wu et al., 2005).

The analysis of experimental programs and results from previous studies reveals two main gaps that have not been adequately addressed in the literature. The first gap is the lack of research on asphalt concrete mixtures containing steel fibers, despite their beneficial mechanical characteristics, such as high tensile strength and high modulus of elasticity, which enhance the Marshall stability and splitting tensile strength of asphalt mixtures containing RCA. The second gap is the scarcity of experimental studies that examine the impact behavior of asphalt concrete pavements manufactured from RCA and supplemented with steel fibers. Gao et al. (2023) investigated the impact toughness of recycled steel fiber-reinforced concrete cylindrical specimens. The drop weight, drop height of the impact drop hammer, and steel fiber content were the main parameters studied. The results concluded that as the recycled steel fiber ratio increased, the impact toughness of the concrete specimens significantly increased. Javaid et al. (2020) developed rigid pavement concrete mixtures incorporating both crumb rubber and steel fibers as partial replacements for fine aggregate. The flexural strength of pavement slabs with different ratios of steel fibers was investigated. The results revealed that the addition of 1% steel fibers exhibited the highest flexural strength among all tested mixtures, showing a 20.8% improvement compared with the normal mixture.

The current research presents an experimental program consisting of 12 asphalt concrete mixtures divided into two groups. The first group comprises six specimens cast without steel fibers, wherein natural aggregates were replaced with varying proportions of RCA ranging from 0 to 50%. The second group is similar to the mixtures in the first group in terms of the proportions of RCA used, but steel fibers were added to them at a volume fraction of 1%. The influence of the proportion of RCA and the presence of steel fibers on the Marshall stability, flow, bulk density, air void ratio, and splitting tensile strength of asphalt concrete mixtures was investigated. Additionally, the 12 mixtures were used to produce asphalt slabs containing RCA and steel fibers to study their impact response. This investigation aimed to determine the effect of the proportion of RCA and steel fibers on penetration depth, as well as the diameters of front and back craters. Furthermore, the experimentally recorded penetration depth values were compared with mathematical models from previous studies. An analytical model capable of predicting the penetration depth in asphalt slabs due to impact loading was then presented, taking into account the proportion of RCA and the presence of steel fibers.

2 Materials and Methods

2.1 Characteristics of Materials

One of the current research goals is to study the influence of replacing natural coarse aggregate with recycled concrete aggregate using different replacement ratios on the properties of hot-mix asphalt mixtures. Hence, two types of coarse aggregates were used to produce 12 mixtures: the first type is natural coarse aggregate consisting of crushed dolomite with a maximum aggregate size of 20 mm, extracted from the mountains of Suez in Egypt. The second type is recycled concrete aggregate (RCA) resulting from the crushing of previously tested reinforced concrete (RC) slabs with a compressive strength of 25 MPa. During the crushing of the slabs, care was taken to obtain a uniform aggregate size distribution, with a maximum aggregate size not exceeding 20 mm. The fine aggregate in the proposed mixtures consisted of river sand with a maximum aggregate size of 5 mm. Fig. 1 shows that the grain size distribution of sand, dolomite, and RCA complies with the requirements of the Egyptian code for road works, Annex 4 (ECP (Egyptian Code of Practice) 2008).

The mineral filler material used in all mixtures was limestone powder, which has a bulk specific gravity of 2.75 gm/cm^3. In order to produce asphalt mixtures, Suiz asphalt with a penetration grade of 60/70 was used. According to the manufacturer, the cement exhibits a specific gravity of 1.022 gm/cm^3, a penetration of 63 decimillimeters, a kinematic viscosity of 385 cstoke at 135 °c, and a softening point of 54 °c. These properties of the cement used comply with the requirements specified in various design codes (ECP (Egyptian Code of Practice) 2008; Aashto, 1993). In an attempt to improve the mechanical properties of asphalt mixtures in terms of stability and indirect tensile strength, steel fibers were added to the asphalt mixtures at a volume fraction of 1%. The steel fiber used is of the corrugated segment type, with a length of 3.0 cm and a tensile strength of 1000

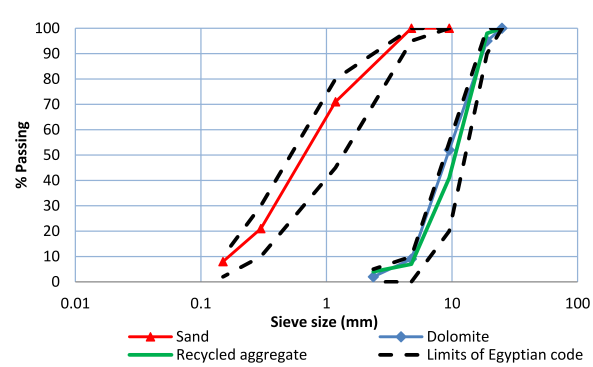


Fig. 1 Aggregate size distribution of fine aggregate, natural and recycled coarse aggregates

MPa. Fig. 2 displays all the materials used in producing the 12 asphalt mixtures.

2.2 Mixing Method

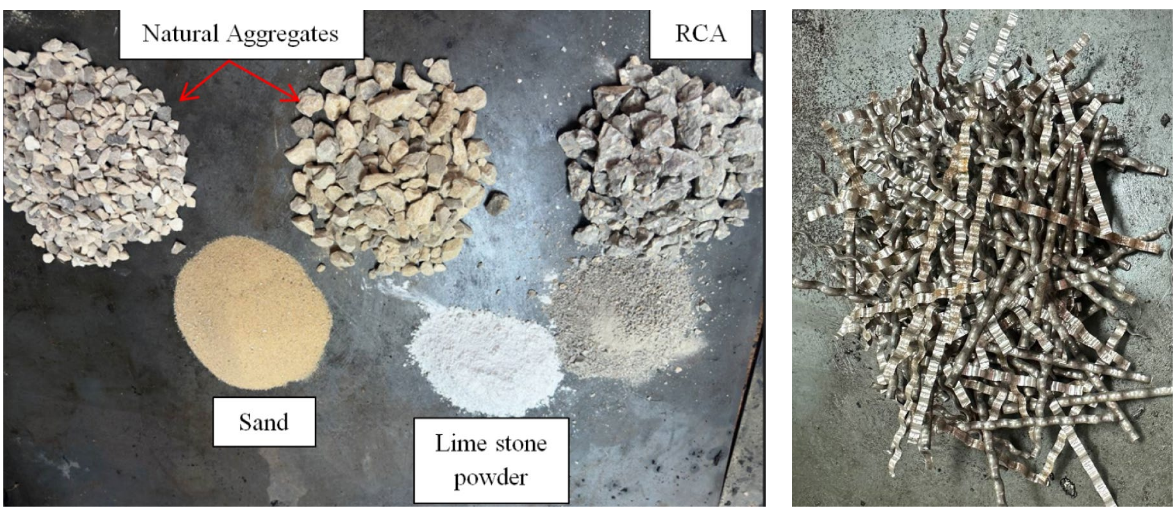
To produce a homogeneous asphalt mixture, a mechanical shear mixer was used to blend all the components together as follows: firstly, natural aggregate and RCA were continuously mixed for 5 min, followed by the addition of asphalt heated to a fluid condition (135°c). The aggregate and asphalt were continuously mixed for 10 min to ensure homogeneity, as depicted in Fig. 3a. Finally, sand and lime stone powder were added to the mixture, and mixing continued for an additional ten minutes. In mixtures containing steel fibers, the fibers were gradually added after thoroughly mixing all components together. Mixing continued for an additional 5 min to ensure that the fibers were homogeneously blended with the asphalt mixture components, as shown in Fig. 3b. The mixtures were subsequently placed into molds and compacted with 75 strikes on each side, following the specifications of the Marshall test (White, 1985).

2.3 Test Program and Test Set-up

The current research not only investigates the effects of using RCA or corrugated steel fibers on the stability and resistance of asphalt mixtures, but also examines the behavior of two-way asphalt slabs containing RCA as a partial substitute for natural aggregates, with or without the presence of steel fibers, when subjected to impact loads.

2.3.1 Asphalt Mixtures

Twelve cylinders, each with a diameter of 102 mm and a height of 64 mm, have been prepared to investigate the



(a) Fine and coarse aggregates *(b)* Corrugated steel fibers

Fig. 2 The materials used in casting mixtures. **a** Fine and coarse aggregates. **b** Corrugated steel fibers

(a) Mixing the aggregates and asphalt *(b)* Adding steel fibers

Fig. 3 Mixing the components of asphalt mixtures. **a** Mixing the aggregates and asphalt. **b** Adding steel fibers effect of using RCA and corrugated steel fibers on the Marshall stability, flow, bulk density, and air void ratio of the asphalt mixtures under study. Additionally, 12 cylindrical specimens with a diameter of 100 mm and a height of 200 mm have been cast to study the influence of the RCA ratio and corrugated steel fibers on the splitting tensile strength of asphalt mixtures. Table 1 presents the proposed experimental matrix for asphalt mixtures. Within this matrix, there are 12 mixtures that can be divided into two main groups, each group containing six mixtures that differ in the proportions of RCA. The first mixture is a reference mixture entirely cast using natural aggregates, while in the remaining mixtures, the natural aggregate has been replaced with 10%, 20%, 30%, 40%, and 50% RCA, respectively. The first group was completely cast without using any fibers, while corregauted steel fibers were added to the second group mixtures at a volume fraction of 1%.

The reason for using different proportions of RCA is due to the lack of clear and consistent behavior regarding the effect of RCA proportions on the performance of asphalt mixtures in previous studies. For example, Bidabadi et al. (2020) showed that replacing natural aggregate with 30% RCA did not significantly negatively affect the properties of asphalt mixtures, such as density, workability, and splitting tensile strength. Thus, a 30% replacement ratio can be considered the optimal percentage in the design of the mixture. On the other hand, Lu (2024) indicated that the optimal percentage for using RCA is 20%, ensuring that the compressive and tensile strengths do not significantly decrease compared to the reference mixture. Regarding the addition of steel fibers, previous studies (Gong et al., 2022; Wu et al., 2016; Yu et al., 2014) have shown that the workability of concrete mixtures is significantly reduced when the ratio of steel fibers is increased from 1 to 3%. Accordingly, the current experimental program included asphalt mixtures with 1% steel fibers to maintain good flowability.

To facilitate distinction between the different mixtures during result discussion and to quickly recall the properties of each mixture, a code has been assigned to each. The code starts with the letter "M" representing the word "Mixture", followed by the letter "R" accompanied by a number indicating the percentage of RCA in the asphalt mixture. Finally, there is the letter "F" indicating the presence or absence of fibers within the asphalt mixtures (0 for no fibers and 1 indicating the use of cooreguated steel fibers at a volume fraction of 1%). Fig. 4 depicts the setup of the Marshall stability test as well as the splitting tensile test for the asphalt mixtures.

2.3.2 Two-Way Asphalt Slabs

The current research aims to study effect of partial replacements of natural aggregates using 0, 10, 20, 30, 40, and 50% RCA on the behavior of asphalt slabs exposed to impact load to assess the effectiveness of the proposed mixtures and their feasibility for practical application in real roads. The use of RCA within asphalt slabs, especially in high proportions, may weaken the cohesion between the aggregate particles themselves or even between the aggregate particles and the binding material. This weakening could potentially increase the void ratio within the asphalt slabs. Moreover, undoubtedly, the impact resistance of asphalt slabs will be negatively affected by the increase in the proportion of RCA. RCA having been previously subjected to high loads tends to develop cracks that significantly weaken its structural properties, especially its shear strength. Consequently, the incorporation of corrugated steel fibers in the second group of asphalt slabs aims to enhance the cohesion

Table 1 Asphalt mixtures design

Mixture ID	RCA	Natural coarse aggregate %	Sand %	Lime stone powder %	Asphalt 60/70 %	Corrugated steel fiber %
MR0F0	0%	59.0	25	16	4.5	0
MR10F0	5.9%	53.1	25	16	4.5	0
MR20F0	11.8%	47.2	25	16	4.5	0
MR30F0	17.7%	41.3	25	16	4.5	0
MR40F0	23.6%	35.4	25	16	4.5	0
MR50F0	29.5%	29.5	25	16	4.5	0
MR0F1	0%	59.0	25	16	4.5	1
MR10F1	5.9%	53.1	25	16	4.5	1
MR20F1	11.8%	47.2	25	16	4.5	1
MR30F1	17.7%	41.3	25	16	4.5	1
MR40F1	23.6%	35.4	25	16	4.5	1
MR50F1	29.5%	29.5	25	16	4.5	1

(a) Marshall stability test *(b)* Splitting tensile test

Fig. 4 Asphalt mixtures tests set-up. **a** Marshall stability test. **b** Splitting tensile test

between the aggregate particles and the binding material used in the slabs. This effort also aims to minimize internal voids, thereby enhancing the stability and impact characteristics of the asphalt slabs.

Table 2 presents the matrix of the experimental program for asphalt slabs. Twelve asphalt mixtures, previously designed, were employed to manufacture 12 two-way asphalt slabs in preparation for exposure to impact loads. All asphalt slabs have the same dimensions: 1000 mm width, 1000 mm length, and 120 mm thickness. After casting the asphalt slabs to the required dimensions, they were compacted using a mechanical light compactor, as depicted in Fig. 5. It is noted that the same IDs used for mixtures were utilized to distinguish between slabs, with the exception that the letter "M" was replaced by the letter "S" to indicate that they are asphalt slabs rather than mixtures.

Fig. 6 depicts the equipment required for conducting the impact test on asphalt slabs. A lifting wheel was installed on a wooden frame, with a steel cylinder weighing 10 kg attached to it, falling freely from a height of 2.0 m. The tested asphalt slab specimen was

Table 2 Experimental matrix of asphalt slabs containing RCA and steel fibers

Slab ID	Slab width (mm)	Slab length (mm)	Slab thickness (mm)	Percentage of natural aggregate replacement with RCA	Existence of steel fibers	Mixture used
SR0F0	1000	1000	120	0	No	MR0F0
SR10F0	1000	1000	120	10%	No	MR10F0
SR20F0	1000	1000	120	20%	No	MR20F0
SR30F0	1000	1000	120	30%	No	MR30F0
SR40F0	1000	1000	120	40%	No	MR40F0
SR50F0	1000	1000	120	50%	No	MR50F0
SR0F1	1000	1000	120	0	Yes	MR0F1
SR10F1	1000	1000	120	10%	Yes	MR10F1
SR20F1	1000	1000	120	20%	Yes	MR20F1
SR30F1	1000	1000	120	30%	Yes	MR30F1
SR40F1	1000	1000	120	40%	Yes	MR40F1
SR50F1	1000	1000	120	50%	Yes	MR50F1

Fig. 5 Preparation of asphalt slabs

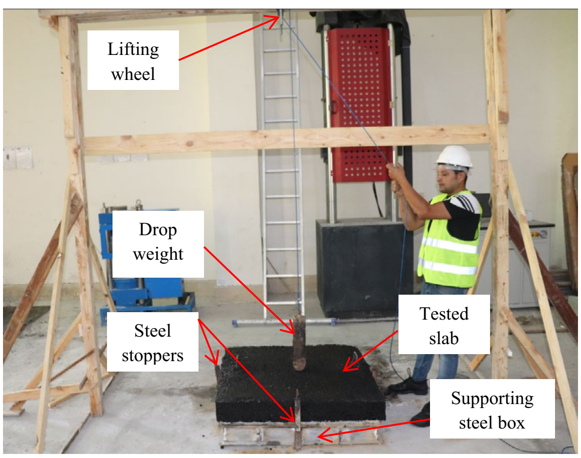


Fig. 6 The manual free fall impact test equipment

installed on a hollow steel box, to allow rotation of the slab. Steel rods were welded along the entire outer perimeter of the steel box to allow the slab to rotate. To prevent the slab from moving beyond the steel box boundaries, steel plates (stoppers) were welded to the steel box to prevent sliding of the asphalt slab. The asphalt slabs were positioned so that the steel weight falls as close to the middle as possible. After conducting the test, the impact performance of the tested slabs is evaluated based on the failure pattern, penetration depth, and the diameter of the front and back craters, to compare the performances of the different mixtures used.

3 The Effect of RCA on the Properties of Asphalt Mixtures

In order to study the effect of the RCA content and the addition of corrugated steel fibers on the properties of asphalt mixtures, a Marshall test, as well as splitting tensile test, was conducted to determine Marshall stability, flow, bulk density, and air void ratio of these mixtures compared to the reference mixture that does not contain RCA or corrugated steel fibers.

3.1 Stability

The Marshall stability test expresses the resistance of an asphalt mixture to distortion, displacement, and shearing stresses. The Marshall stability test determines the maximum load that an asphalt mixture can withstand before collapsing. During the test, the applied load is gradually increased until reaching the maximum value. Once the maximum value is surpassed and the applied load begins to decrease, the test is stopped, and the maximum load value (Marshall stability) is recorded. Fig. 7 shows the influence of RCA ratio and the incorporation of corrugated steel fibers on the Marshall stability value of asphalt mixtures. In general, the findings indicated that increasing the ratio of RCA has a detrimental effect on the stability of asphalt mixtures, even with the addition of steel fibers. This is attributed to the reduced internal friction resistance (interlocking) of the RCA, caused by cracks formed along the surface of the recycled aggregates due to previous loading. These cracks hinder the formation of a strong bond between the aggregate particles themselves or between the aggregate particles and the asphalt,

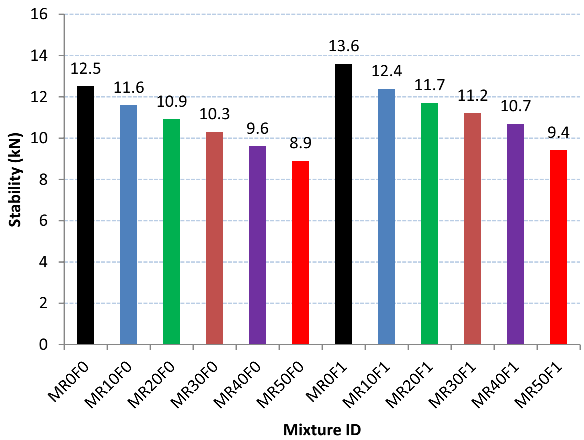


Fig. 7 Effect of RCA ratio and corrugated steel fibers on Marshall stability

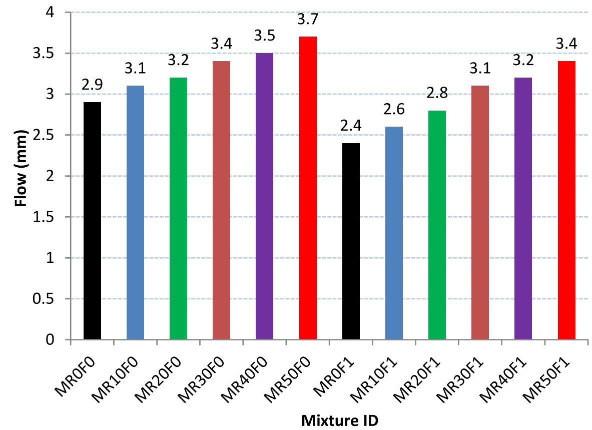


Fig. 8 Effect of RCA ratio and corrugated steel fibers on Marshall flow

resulting in weak points within the asphalt mixture from which failure initiates. El-Tahan et al. (2018) revealed that the stability of asphalt mixtures is impacted by the age of RCA. Previous studies (Bastidas-Martínez et al., 2019; Motter et al., 2015; Pasandín & Pérez, 2013) have attributed the decrease in the stability of asphalt mixtures to the lower resistance of RCA caused by the mortar coating. In particular, the stability of asphalt mixtures significantly improved with the addition of corrugated steel fibers compared to mixtures without steel fibers. The steel fibers act to intercept the initiated cracks, thereby preventing their propagation and reducing their spread on the interfacial surface between aggregate particles. Slowing down the spread of cracks increased the load-bearing capacity of asphalt mixtures and delayed the occurrence of collapse, leading to an increase in the stability of asphalt mixtures.

The stability of the reference mixture (MR0F0), which does not contain RCA or steel fibers, was 12.5 kN. When replacing 10% of the natural aggregate in the reference mixture with RCA, the stability of the asphalt mixture MR10F0 decreased to 11.6 kN, representing a 7.2% decrease compared to the reference mixture. The stability of the asphalt mixtures significantly decreased when using RCA at ratios of 20%, 30%, and 40%. Specifically, the recorded decrease in stability of mixtures MR20F0, MR30F0, and MR40F0 was 12.8%, 17.6%, and 23.2%, respectively, compared to the reference mixture. The decrease in the stability of the asphalt mixture reached its peak when using RCA at a ratio of 50%. The stability of the asphalt mixture MR50F0 was 28.8% lower than that of the reference specimen.

Among all tested mixtures, specimen MR0F1, which was entirely manufactured using natural aggregates along with the addition of steel fibers, achieved the highest stability of 13.6 kN, 8.8% higher than the reference mixture. Despite all asphalt mixtures containing RCA and steel fibers exhibited lower stability than the reference mixture, the stability of asphalt mixtures containing steel fibers was higher than their counterparts without fibers. The addition of steel fibers to the asphalt mixture containing 10% and 20% RCA (MR10F1 and MR20F1) improved stability by 6.9% and 7.3%, compared to mixtures MR10F0 and MR20F0, respectively. The presence of corrugated steel fibers within asphalt mixtures, particularly when using high proportions of RCA, mitigates the decrease in stability compared to specimens without fibers. The stability of asphalt mixtures containing steel fibers and having 30% and 40% RCA was higher by 8.7% and 11.5%, respectively, compared to their counterparts without fibers. When replacing 50% of the natural aggregate with RCA, the addition of steel fiber did not significantly improve the stability of mixture MR50F1 compared to its counterpart without fiber (MR50F0). The improvement ratio was only 5.6%. This may be due to the reduced strength of RCA, as they have been previously loaded, compared to natural aggregates, Additionally, the presence of cement paste around the RCA prevents good bonding between the aggregate particles and the asphalt.

3.2 Flow

During the Marshall stability test, the vertical displacement at the maximum load was recorded to assess the flow characteristics of the asphalt mixtures. Fig. 8 compares the flow properties of asphalt mixtures made with RCA to the reference mixture and illustrating the effect of adding steel fibers on the Marshall flow of asphalt mixtures. The reference mixture exhibited the lowest Marshall flow value of 2.9 mm among all mixtures in the first group, which were made without the use of steel fibers. This reveals a stronger interlocking bond among natural aggregate particles compared to the weaker cohesion between natural aggregate and RCA particles. Using RCA at small proportions ranging from 10 to 20% did not significantly change the flow properties of asphalt mixtures. The Marshal flow of mixtures MR10F0 and MR20F0 was 3.1 and 3.2 mm, respectively, which were 6.9% and 10.3% higher than that of the reference mixture. Continuing to increase the proportion of RCA reduced the efficiency of asphalt mixtures, as evidenced by a significant increase in the Marshall flow value compared to the reference mixture. The flow values of the asphalt mixtures MR30F0, MR40F0, and MR50F0 were 17.2%, 20.7%, and 27.6% higher than that of the MR0F0 mixture, respectively. The increase in the flow of asphalt mixtures with a higher ratio of RCA is due to the decrease in their stability, leading to reduced stiffness and deformation resistance. The results of previous studies (Ma et al., 2022; Naser et al., 2022; Wang et al., 2021) are consistent with the findings of the current research.

By adding corrugated steel fibers to asphalt mixtures, interlocking bond between natural aggregate particles and RCA particles remarkably enhanced. Consequently, the flow properties of asphalt mixtures have improved, even with the use of high proportions of RCA within the asphalt mixtures. The Marshal flow of the reference asphalt mixture decreased from 2.9 mm to 2.4 mm due to the addition of steel fibers. The results also showed that the addition of steel fibers significantly improved the flow of asphalt mixtures containing RCA at proportions of 10% and 20%, compared to the reference mixture. The flow values of the asphalt mixtures MR10F1 and MR20F1 were 10.3% and 3.4% lower than that of the MR0F0 mixture, respectively. Furthermore, the flow of asphalt mixtures containing 30%, 40%, and 50% RCA improved with the addition of steel fibers compared to counterpart mixtures without steel fibers. The decrease in the flow of asphalt mixtures MR30F1, MR40F1, and MR50F1 was 8.8%, 8.5%, and 8.1%, respectively, compared to mixtures MR30F0, MR40F0, and MR50F0, respectively.

3.3 Bulk Density

Bulk density is considered one of the important characteristics that not only reflects the efficiency of compaction, but also indicates the porosity state of asphalt mixtures. Bulk density represents the weight of a specific volume. In the current study, the volume unit used for all asphalt mixtures is the volume of Marshall cylinders. In general, as the bulk density of asphalt mixtures increases, the compaction efficiency tends to be higher, and the internal voids ratio tends to be lower compared to asphalt mixtures with lower bulk density. Fig. 9 compares the bulk densities of the reference mixture and the specimens incorporating RCA. The same figure also illustrates the effect of using corrugated steel fibers on bulk density, allowing for the assessment of each asphalt mixture's efficiency individually.

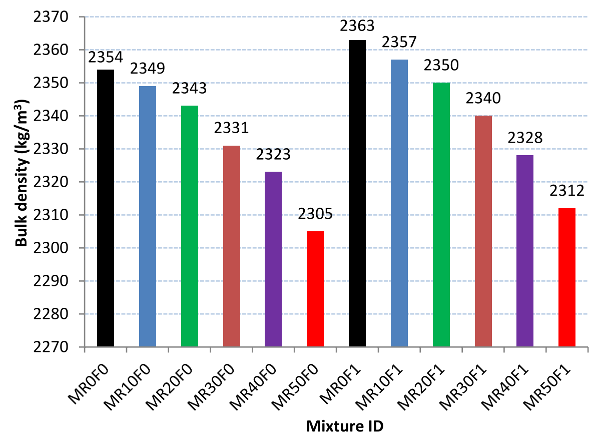


Fig. 9 Effect of RCA ratio and corrugated steel fibers on bulk density of asphalt mixtures

The results of the bulk density align with the Marshall stability and Marshall flow properties, indicating that increasing the percentage of RCA adversely affects the characteristics of the asphalt mixture. The asphalt mixtures containing RCA have lower bulk densities than those with natural aggregate due to the presence of old mortar attached to its surface. As a result, mixtures containing RCA have lower densities than similar mixtures containing natural aggregate (Chakradhara Rao et al., 2011; Thomas et al., 2018; Yang et al., 2017). The reference asphalt mixture (MR0F0), composed entirely of natural aggregates with a well-graded particle size distribution and similar physical properties, achieved the highest bulk density among asphalt mixtures without steel fibers, with a value of 2354 kg/m^3. This is attributed to the good interlocking between the natural aggregate particles, which helped reduce the interstitial void ratio. The bulk density did not significantly decrease for asphalt mixtures incorporating RCA up to 20% compared to the reference mixture. Specifically, the bulk density for mixtures MR10F0 and MR20F0 was only 0.2% and 0.5% lower than that of the MR0F0 mixture, respectively, with values of 2349 and 2343 kg/m^3. As the percentage of RCA increased within asphalt mixtures, irregularities in the shapes of those particles led to an increase in the interstitial voids between them and the natural aggregate particles. Consequently, the weight of the asphalt mixture decreased, resulting in a further decrease in bulk density compared to lower RCA ratios. The bulk density of mixtures MR30F0, MR40F0, and MR50F0 was 2331 kg/m^3, 2323 kg/m^3, and 2305 kg/m^3, respectively.

Steel fibers can effectively fill the interstitial voids between the particles of RCA and natural aggregates due to their small diameters. Consequently, the weight and bulk density of asphalt mixtures containing steel fibers increase compared to specimens without fibers. Mixture MR0F1, which was entirely consisted of natural aggregate and contained steel fibers, recorded the highest bulk density among all tested mixtures, with a value of 2363 kg/m^3. Despite the addition of steel fibers not preventing a decrease in the bulk density of asphalt mixtures with increasing percentages of RCA, all asphalt mixtures containing steel fibers had a higher bulk density than their counterparts without steel fibers. The recorded bulk densities of steel fiber-reinforced asphalt mixtures MR10F1 and MR20F1 containing 10% and 20% RCA were 2357 kg/m^3 and 2350 kg/m^3, respectively. Higher percentages of RCA, ranging from 30 to 50%, consistently lead to significant deterioration in asphalt mixture properties when compared to the reference mixture containing steel fibers (MR0F1). When the RCA is added to asphalt mixtures containing steel fibers at percentages of 30%, 40%, and 50%, respectively, the bulk density decreased to 2340 kg/m^3, 2328 kg/m^3, and 2312 kg/m^3, respectively.

3.4 Air Voids

The air voids ratio is considered an important characteristic that reflects not only the efficiency of compaction, but also indicate the permeability of the asphalt mixture and the extent to which it can be affected by the attack of various fluids over the design life of the asphalt. Generally, an increase in the volume of air within the asphalt mixture results in a corresponding increase in voids volume. This leads to decreased compaction efficiency due to reduced bulk density. As a result, the structural performance of asphalt is negatively affected by the damage caused by various fluids encountered in daily traffic. Fig. 10 illustrates the effect of using RCA at different proportions, as well as the use of steel fibers on the air voids ratio in asphalt mixtures. The results show that the air voids ratio within asphalt mixtures is inversely proportional to the bulk density. Using high proportions of RCA within asphalt mixtures results in an increase in the air voids ratio due to the irregular shape of the RCA, which prevents strong interlocking, thus increasing the presence of voids and reducing the compaction efficiency of the asphalt mixtures (Tahmoorian & Samali, 2018). The air voids ratio in the reference mixture (MR0F0), which was 3.2%, was lower than the air voids ratios in all asphalt mixtures containing RCA, either with or without steel fibers. Furthermore, the addition of corrugated steel fibers to the asphalt mixture composed entirely of natural aggregates significantly reduced the air voids ratio. As a result, mixture MR0F1 achieved the lowest air voids ratio

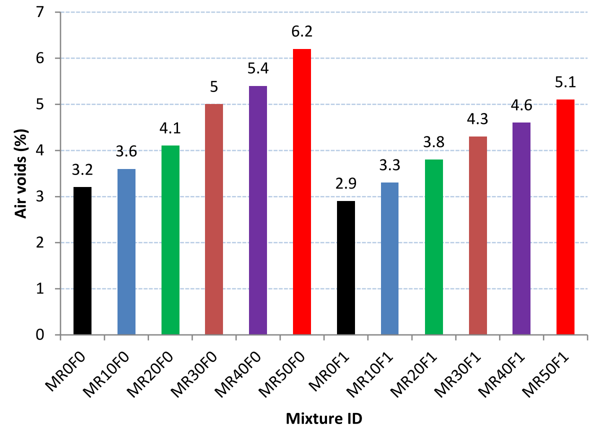


Fig. 10 Effect of RCA ratio and corrugated steel fibers on air voids of asphalt mixtures

among all tested mixtures, with a value of 2.9%. In the first group of mixtures without steel fibers, the incorporation of 10% and 20% RCA resulted in a 13% and 28% increase, respectively, in the air voids ratio within the asphalt mixtures compared to the reference mixture MR0F0. As the percentage of RCA in the asphalt mixtures increased to 30%, 40%, and 50%, the corresponding increase in the air voids ratio was 56%, 69%, and 94%, respectively, compared to mixture MR0F0. The results of the second group, which contains steel fibers, indicate that these fibers can reasonably reduce the air void ratio compared to the reference mixture, as long as the percentage of RCA does not exceed 20%. The air voids ratio of mixtures MR10F1 and MR20F1 was only 3% and 18% higher than that of the MR0F0 mixture, respectively. Although the steel fibers did not significantly reduce the air void ratio within the asphalt mixtures when high percentages of RCA (30–50%) were used, compared to the reference mixture, the air void ratio in those mixtures was still lower compared to their counterparts without steel fibers. The decrease in air void ratio within asphalt mixtures MR30F1, MR40F1, and MR50F1 was 14%, 15%, and 18%, respectively, compared to mixtures MR30F0, MR40F0, and MR50F0, respectively.

3.5 Splitting Tensile Strength

It is essential to produce asphalt mixtures with high tensile strength in order to withstand design loads efficiently over the expected lifespan, without generating cracks that negatively affect the efficiency of the asphalt mixture. Fig. 11 illustrates the effect of using RCA, with or without the addition of corrugated steel fibers, on the splitting tensile strength of asphalt mixtures. Asphalt mixtures fully cast using natural aggregates exhibited higher splitting tensile strengths compared to their counterparts cast

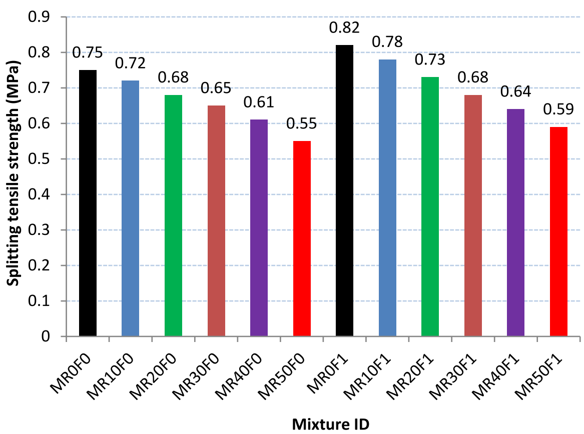


Fig. 11 Effect of RCA ratio and corrugated steel fibers on splitting tensile strength of asphalt mixtures

with varying proportions of RCA. The splitting tensile strength for reference mixture MR0F0 was 0.75 MPa. The use of RCA within asphalt mixtures resulted in the formation of cracks at lower loads, and these cracks propagated faster within the asphalt mixture around the voids between the aggregate particles. Consequently, the splitting tensile strength is negatively affected compared to the reference mixture that did not contain RCA. The incorporation of small proportions of RCA (ranging from 10 to 20%) did not cause a significant decrease in the splitting tensile strength of the asphalt mixtures. Specifically, the splitting tensile strength of mixtures MR10F0 and MR20F0 was only 4% and 9% lower, respectively, compared to the splitting tensile strength of the reference mixture MR0F0. In contrast, the splitting tensile strength of the asphalt mixtures experienced a significant decrease when the proportion of RCA exceeded 20%, attributed to the weakness of the RCA itself and the poor bond between the aggregate particles. Specifically, the decrease in splitting tensile strength for mixtures with RCA proportions of 30%, 40%, and 50% was 13%, 19%, and 27%, respectively, compared to mixture MR0F0. According to Exteberria et al. (2007) and McNeil et al. (2013), the decrease in the splitting strength of asphalt mixtures is due to the increased absorption of the mortar attached to the recycled aggregate, which leads to a poor bond between aggregate and the asphalt. Additionally, this residual mortar creates a weakened area where cracks are likely to initiate.

Steel fibers possess a high capability to intercept the path of formed cracks, preventing their continuity and limiting their spread within asphalt mixtures. This positive effect is reflected in the increased splitting tensile strength of asphalt mixtures compared to those without corrugated steel fibers. Mixture MR0F1 achieved the highest splitting tensile strength among all tested asphalt mixtures, attributed to the addition of steel fibers, without any RCA present in that mixture, with a value of 0.82 MPa. The addition of steel fibers to the asphalt mixture containing 10% RCA (MR10F1) resulted in a 4% improvement in the splitting tensile strength compared to the reference mixture without steel fibers (MR0F0). The steel fibers were able to restore a significant portion of the splitting tensile strength of the asphalt mixture containing 20% RCA. The splitting tensile strength of mixture MR20F1 was only 2% lower than that of mixture MR0F0. The steel fibers added at a volume fraction of 1% were unable to prevent the significant decrease in splitting tensile strength of the asphalt mixtures that utilized high proportions of RCA. The splitting tensile strength of the mixtures containing RCA at proportions of 30%, 40%, and 50%, with steel fibers, was lower than that of the reference mixture by 9%, 15%, and 21%, respectively.

3.6 Comparison with Other Studies

For a deeper analysis of the influence of the RCA ratio and the addition of steel fibers on the behavior of asphalt mixtures in terms of stability, flow, density, and air void ratio, the experimental results of the current research were compared with the findings of previous studies, as illustrated in Table 3. Generally, the comparison revealed the need for further experimental studies focusing on the behavior of asphalt mixtures incorporating RCA with the addition of steel fibers. Most available studies either examine the effect of RCA ratio or steel fiber content individually on the mechanical characteristics of asphalt mixtures. Specifically, Albayati et al. (2023) and Lee et al. (2012) explained that increasing the ratio of RCA within the asphalt mixture is not accompanied by a consistent effect, whether increasing or decreasing, on the stability behavior of asphalt mixtures. For instance, results from Albayati et al. (2023) indicated that the stability of asphalt mixtures cast with 10% RCA was higher than the reference mixture by 66%. However, as the percentage of RCA within the asphalt mixtures increased to 20%, 30%, and 40%, the stability of the asphalt mixtures decreased compared to the mixture with only 10% RCA. The stability of mixtures containing RCA at 20%, 30%, and 40% was higher than that of the reference mixture by 43%, 36%, and 25%, respectively. Furthermore, with an increase in the percentage of RCA within the asphalt mixture to 50%, the stability of the mixture showed improvement once again, 61% higher than that of the reference mixture. On the contrary, the results of Lee et al. (2012) align with the findings of the current study in that an increase in the ratio of RCA within the asphalt mixtures negatively impacts the Marshall stability. When using RCA within the asphalt mixtures at ratios of 25%, 50%, 75%,

Table 3 Comparison of current research results with previous studies

Study	Mix ID	% Replacement ratio of RCA	Steel fiber volume fraction	Stability (kN)	Flow (mm)	Bulk density (kg/m^3)	% Air voids	Splitting tensile strength (MPa)
The current study	MR0F0	0	–	12.5	2.9	2354	3.2	0.75
	MR10F0	10	–	11.6	3.1	2349	3.6	0.72
	MR20F0	20	–	10.9	3.2	2343	4.1	0.68
	MR30F0	30	–	10.3	3.4	2331	5.0	0.65
	MR40F0	40	–	9.6	3.5	2323	5.4	0.61
	MR50F0	50	–	8.9	3.7	2305	6.2	0.55
	MR0F1	0	1%	13.6	2.4	2363	2.9	0.82
	MR10F1	10	1%	12.4	2.6	2357	3.3	0.78
	MR20F1	20	1%	11.7	2.8	2350	3.8	0.73
	MR30F1	30	1%	11.2	3.1	2340	4.3	0.68
	MR40F1	40	1%	10.7	3.2	2328	4.6	0.64
	MR50F1	50	1%	9.4	3.4	2312	5.1	0.59
Albayati et al., (2023)	RAP50	0	–	7.9	3.4	2395	3.5	0.9
	RAP40	10	–	13.1	3.5	2361	3.6	1.1
	RAP30	20	–	11.3	3.0	2343	3.9	1.3
	RAP20	30	–	10.8	2.8	2335	4.3	1.2
	RAP10	40	–	9.9	2.7	2277	5.1	1.1
	RAP0	50	–	12.7	2.5	2255	5.6	1.4
Lee et al., (2012)	CS	0	–	14.9	4.1	–	4.0	0.60
	P-25	25	–	13.4	3.3	–	4.0	0.68
	P-50	50	–	14.3	3.8	–	4.0	0.70
	P-75	75	–	11.9	4.3	–	4.0	0.71
	P-100	100	–	11.7	4.1	–	4.0	0.75
AL-Ridha et al., (2021)	-	0	0	9.6	4.3	–	–	0.92
	-	0	0.1%	11.5	4.2	–	–	1.00
	-	0	0.2%	12.3	4.3	–	–	1.14
	-	0	0.3%	10.7	4.4	–	–	1.01
	-	0	0.4%	8.5	4.5	–	–	0.85
Serin et al., (2012)	Control	0	0	8.8	–	–	–	–
	SFAC1	0	0.25%	9.0	11.6	–	4.7	–
	SFAC2	0	0.50%	9.1	11.0	–	4.8	–
	SFAC3	0	0.75%	11.1	11.6	–	4.8	–
	SFAC4	0	1.00%	10.4	11.1	–	4.5	–
	SFAC5	0	1.50%	9.2	11.2	–	5.2	–
	SFAC6	0	2.00%	7.2	–	–	-	–
	SFAC7	0	2.50%	7.1	–	–	-	–

and 100%, the stability of the mixtures decreased by 3.6%, 2.9%, 14.4%, and 15.8%, respectively, compared to the reference mixture.

The flow results of asphalt mixtures without steel fibers in the current research, ranging from 2.9 to 3.7 mm, were consistent with those of Albayati et al. (2023), which ranged from 2.5 to 3.4 mm. Results of Lee et al. (2012) showed that the flow values for the asphalt mixtures ranged from 3.3 to 4.3 mm due to the utilization of a higher range of RCA ratios within the asphalt mixtures. Regarding bulk density, conclusions of Albayati et al. (2023) align with the findings of the current study in terms of values and behavior. In the current research, bulk density decreased from 2354 kg/m^3 to 2305 kg/m^3 due to an increase in the ratio of RCA within the asphalt mixture from zero to 50%. On the other hand, in the study of Albayati et al. (2023), for the same RCA replacement ratio, the bulk density decreased from 2395 to 2255 kg/m^3.

Regarding air voids ratio within the asphalt mixtures, results of Lee et al. (2012) were inconsistent with both the results of the current study and Albayati et al. (2023). The air voids ratio within the asphalt mixtures ranged from 3.2% to 6.2% when using RCA within the asphalt mixtures at ratios ranging from 0 to 50%. On the other hand, in Albayati et al. (2023), the air voids ratio within the asphalt mixtures ranged from 3.5% to 5.6% at the same replacement ratios used in the current study. In contrast to the two aforementioned studies, Lee et al. (2012) indicated that the air voids ratio within the asphalt mixtures remained constant at 4% even with changes in the proportions of RCA within the asphalt mixtures from 0 to 100%.

The current study indicated that the splitting tensile strength of asphalt mixtures decreased with an increase in the ratio of RCA within the asphalt mixtures. On the other hand, Albayati et al. (2023) showed that splitting tensile strength increased with an increase in the ratio of RCA within the mixture up to 20% compared to the reference mixture. However, with an increase in the ratio of RCA to 30% and 40%, the splitting tensile strength decreased compared to mixtures with lower ratios of RCA. Again, with a further increase in the ratio of RCA to 50%, the splitting tensile strength of the asphalt mixture increased. As for Lee et al. (2012), it showed that as the ratio of RCA within the asphalt mixture increased, the splitting tensile strength of the asphalt mixture improved. Splitting tensile strength increased by 25% when fully replacing natural aggregate within the asphalt mixture with RCA.

Table 3 also compares the results of previous studies conducted by AL-Ridha et al. (2021) and Serin et al. (2012), which examined the effect of using different volume fractions of steel fibers on the behavior of fully manufactured asphalt mixtures with natural aggregates. AL-Ridha et al. (2021) clarified that as the percentage of steel fibers increased up to 0.3% within the asphalt mixtures, the stability of the mixture improved compared to the reference mixture. The stability improvement for the mixture containing 0.3% volume fraction of steel fibers reached 11.5% compared to the reference mixture. On the other hand, increasing the volume fraction of steel fibers to 0.4% resulted in a decrease in the stability of the reference mixture from 9.6 kN to 8.5 kN. Conversely, Serin et al. (2012) indicated that the use of steel fibers improved the stability of asphalt mixtures as long as the fiber content did not exceed 1.5%. The use of steel fibers at a volume fraction of 0.75% recorded the highest stability improvement of asphalt mixture at 26% compared to the reference mixture. Also, as the fraction of steel fibers reached 2% and 2.5%, the stability of the asphalt mixture decreased by 18% and 19%, respectively, compared to the reference mixture.

AL-Ridha et al. (2021) and Serin et al. (2012) agreed that increasing the volume fractions of steel fibers did not have a significant effect on the flow value of asphalt mixtures. AL-Ridha et al. (2021) showed that the flow values of asphalt mixtures ranged from 4.2 to 4.5 mm when the fractions of steel fibers changed from 0.1% to 0.4%. Similarly, Serin et al. (2012) demonstrated that using steel fibers at volume fractions ranging from 0.25% to 1.5% resulted in flow values of asphalt mixtures ranging from 11.0 to 11.6 mm. Serin et al. (2012) also showed that using steel fibers at a volume fraction of 1.0% reduced the air voids ratio within the asphalt mixture to 4.5%, compared to 4.7% and 4.8% with steel fiber fractions of 0.25% and 0.5%, respectively. However, the air voids ratio increased to 5.2% as the volume of steel fibers in the mixtures reached 1.5%.

The results of AL-Ridha et al. (2021) are consistent with the findings of the current study, showing that the use of steel fibers enhances the splitting tensile strength of asphalt mixtures. AL-Ridha et al. (2021) illustrated that the splitting tensile strength of asphalt mixtures improved by 8.6%, 23.9%, and 9.8% when using steel fibers at volume fractions of 0.1%, 0.2%, and 0.3%, respectively. Nevertheless, further increasing the fraction of steel fibers beyond 0.3% resulted in a decrease in the splitting tensile strength of the asphalt mixtures. Specifically, the splitting tensile strength of the asphalt mixture employing 0.4% steel fibers decreased by 7.6% compared to the reference mixture devoid of steel fibers.

The comparison results demonstrate that the stability and strength of asphalt mixtures are not solely dependent on the proportions of RCA. They also depend on factors such as the source of the aggregate (the structural element from which the aggregate is extracted), the age of the structural element, loading conditions, and the environmental conditions experienced by the structural element prior to the recycling process. Similarly, the impact of using steel fibers on the stability, flow, internal air voids ratio, and splitting tensile strength of asphalt mixtures varies from one study to another due to differences in the diameter, surface shape, and tensile strength of the fibers used. Therefore, there is still a critical and urgent need for more experimental studies to investigate the properties of asphalt mixtures manufactured with RCA, while considering the age of the aggregate, the loading conditions, and the type of structural element from which the RCA was extracted. Furthermore, future studies should focus on comparing the effects of using steel fibers with different diameters, surface shapes, and tensile strengths on the behavior of asphalt mixtures made with RCA.

4 The Impact Performance of Asphalt Slabs Containing Different Ratios of RCA

4.1 Modes of Failure and Penetration Depth

Fig. 12 depicts the effect of using RCA with different proportions, with or without corrugated steel fibers, on the failure patterns of all tested asphalt slabs. In general, all the pavement slabs subjected to impact loading exhibited the same failure pattern, forming a crater in the middle of the slab within the loading area. The size of the crater varied in terms of front and back diameters, depending on the proportions of RCA within the slabs, and was also affected by the presence of corrugated steel fibers. In the first group of slabs that do not contain steel fibers, it was observed that only the main crater formed in the middle of the slab within the impact area for the asphalt slab cast entirely with natural aggregate (SR0F0). The same pattern was observed when using small proportions of RCA in the asphalt mixtures at values of 10% and 20% for slabs SR10F0 and SR20F0, respectively. As the proportion of RCA, which has lower shear and bond resistances

Fig. 12 Failure patterns of asphalt slabs subjected to impact loads

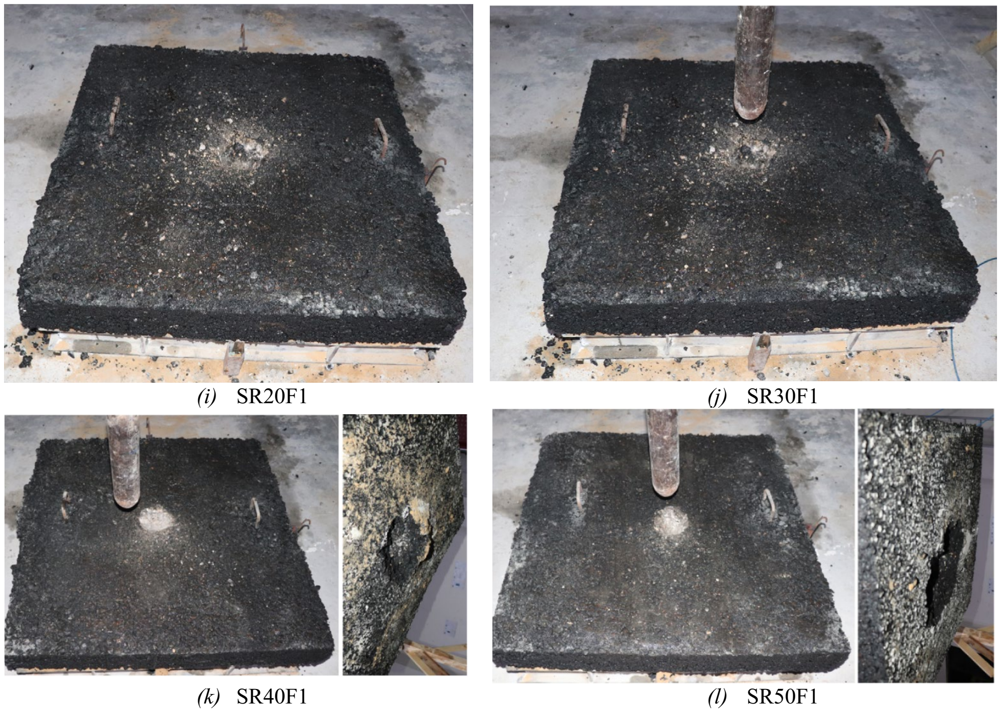


Fig. 12 continued

compared to natural aggregate, increased in the asphalt mixture, superficial cracks initiated around the corners of the main crater in the middle of the slab and propagated outward towards the external perimeter. This pattern, along with the formation of the crater in the middle of the slab, as shown in Fig. 13, was observed in the case of slabs SR30F0, SR40F0, and SR50F0, where 30%, 40%, and 50% RCA was utilized, respectively. The incorporation of corrugated steel fibers in the mixtures of the second group increased the tensile strength of the asphalt slabs within that group compared to the corresponding specimens without steel fibers. Consequently, the failure pattern observed for slabs in the second group consisted solely of the formation of a main crater at the impact zone. Notably, no superficial cracks were observed on the surface of the slabs reinforced with steel fibers, even when high proportions of RCA were used.

Table 4 shows the effect of using RCA and corrugated steel fibers on the penetration depth of the asphalt pavement slabs resulting from impact loading. The results of the first group show that the steel mass easily penetrated the thickness of the asphalt slabs unreinforced with steel fibers, especially when the proportion of RCA within the asphalt mixtures exceeded 20%. Among the slabs of the first group, the reference specimen (SR0F0) achieved the lowest penetration depth of 41 mm due to the absence of any RCA in the mixture. With an increase in the proportion of RCA within the asphalt slabs to 10% and 20%, the penetration depth increased compared to the reference sample, reaching 53 mm and 61 mm, representing penetrations of 44% and 51% of the thickness of samples

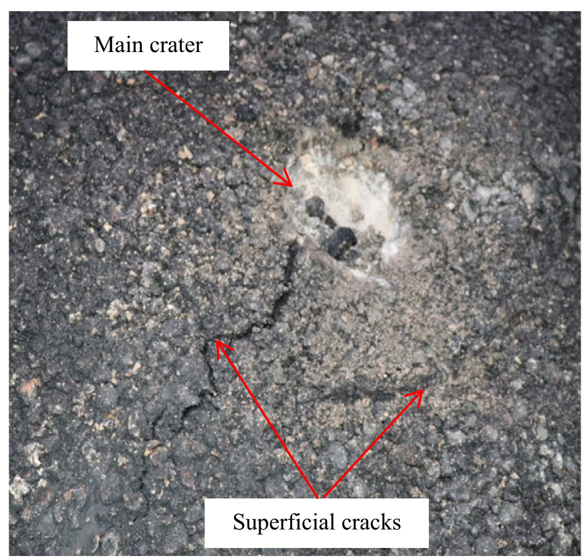


Fig. 13 Superficial cracks initiating along the top surface of SR30F0, SR40F0, and SR50F0 slabs

Table 4 Front and back craters diameter as well as penetration depth in tested asphalt slabs

Group ID	Specimen ID	Mixture	Front crater diameter (mm)	Back crater diameter (mm)	Penetration depth (mm)
Group I	SR0F0	MR0F0	126	176	41
	SR10F0	MR10F0	134	188	53
	SR20F0	MR20F0	146	212	61
	SR30F0	MR30F0	153	218	70
	SR40F0	MR40F0	161	223	76
	SR50F0	MR50F0	174	291	Complete penetration
Group II	SR0F1	MR0F1	120	138	30
	SR10F1	MR10F1	125	144	38
	SR20F1	MR20F1	133	156	44
	SR30F1	MR30F1	139	160	49
	SR40F1	MR40F1	144	184	56
	SR50F1	MR50F1	148	202	67

SR10F0 and SR20F0, respectively. Further increasing the proportion of RCA in the asphalt mixtures to 30% and 40% resulted in penetrations of 58% and 63% of the thickness of samples SR30F0 and SR40F0, respectively. This penetration of a significant portion of the slab thickness negatively affects the mechanical properties and ability of pavement slabs to withstand design loads. With the proportion of RCA reaching 50%, sample SR50F0 was penetrated completely, indicating the fragility of the interlocking between the recycled aggregate particles used. The second group, to which steel fibers were added, showed better penetration resistance than the corresponding slabs in the first group, indicating the effectiveness of steel fibers in improving the bond strength between aggregate particles. No slab thickness was completely penetrated, even when the proportion of RCA within the asphalt slabs reached 50%. Additionally, the penetration depth of all asphalt slabs containing steel fibers was less than that of their counterparts without steel fibers at the same proportion of RCA. Among all the tested asphalt slabs, the reference slab with steel fibers (SR0F1) showed the least penetration depth of 30 mm, representing only 25% of the total slab thickness. Moreover, the penetration depth decreased by 28%, 27%, 30%, and 26% for slabs SR10F1, SR20F1, SR30F1, and SR40F1, respectively, which incorporated 10%, 20%, 30%, and 40% RCA, due to the use of steel fibers compared to specimens SR10F0, SR20F0, SR30F0, and SR40F0, respectively. The importance of adding steel fibers when using high proportions of RCA in asphalt mixtures is clearly evident in slab SR50F1, where the penetration depth was only 67 mm, compared to the complete penetration of the sample thickness observed in slab SR50F0.

4.2 Effect of RCA Ratio and the Presence of Steel Fibers on the Diameter of Front and Back Craters

When asphalt slabs are subjected to impact loads, the front face of the slabs crushes, creating a crater due to compressive stresses. Additionally, a crater forms on the back face of the slabs as a result of being exposed to tensile stresses. In general, the diameter of the crater on the back side of the asphalt slabs is larger than that on the front side due to the lower tensile strengths of the asphalt slabs compared to the compressive strengths. Fig. 14 illustrates the relationship between the utilization of RCA at various proportions, with or without the inclusion of corrugated steel fibers, and the diameter of the crater formed on the front face of the asphalt slabs. The results show that the diameter of the crater on the front face significantly increased with the increase in the proportion of RCA in the asphalt mixture due to the decrease in the mechanical characteristics of the asphalt mixture. However, steel fibers have been successful in controlling the formation of the crater, preventing its diameter from increasing, and impeding the path of resulting cracks, especially with small proportions of RCA (less than 30%). The diameter of the crater formed on the front face of the reference slab (SR0F0) was 126 mm, while it reached 134 mm and 146 mm when using RCA at proportions of 10% and 20%, respectively. When using RCA in the asphalt slabs at proportions of 30% and 40%, the diameter of the crater on the front face of the slabs reached 153 mm and 161 mm, respectively. This represents an increase of 21% and 28% compared to the diameter of the crater formed on the reference asphalt slab (SR0F0). The largest diameter of the crater on the front face was recorded at 174 mm among the samples of the first group when the proportion of RCA reached 50% within the asphalt slab SR50F0. This represents an increase of 38%

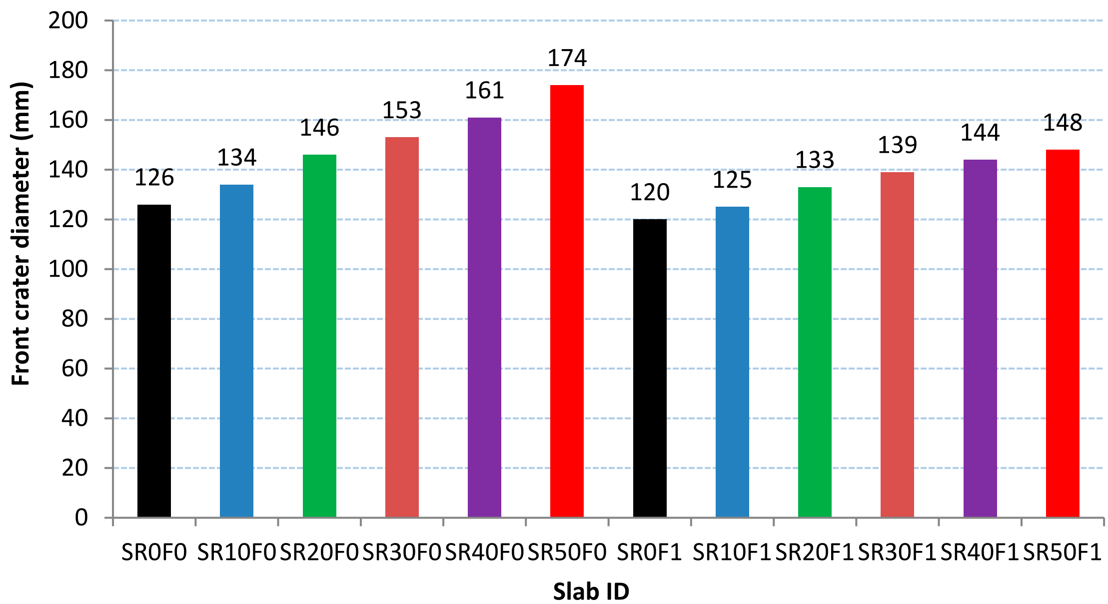


Fig. 14 Effect of RCA ratio and corrugated steel fibers on front crater diameter of asphalt slabs

compared to the diameter of the crater formed on the reference asphalt slab (SR0F0). The diameter of the crater on the front face decreased to 120 mm for the specimen SR10F1 due to the inclusion of steel fibers in the asphalt mixtures. The addition of steel fibers to the asphalt slab containing 10% RCA reduced the diameter of the front crater to 125 mm, representing a 7% decrease compared to the corresponding slab with the same replacement ratio but without steel fibers. Furthermore, the diameter of the front crater of slab SR10F1 was slightly smaller than that of the reference slab. The diameter of the crater on the front face was 8.9%, 9.2%, 10.6%, and 14.9% smaller when using RCA at proportions of 20%, 30%, 40%, and 50%, respectively, compared to the slabs that did not contain steel fibers.

Fig. 15 demonstrates that the diameter of the crater on the back face of the reference asphalt slab was 176 mm. However, when using RCA at proportions of

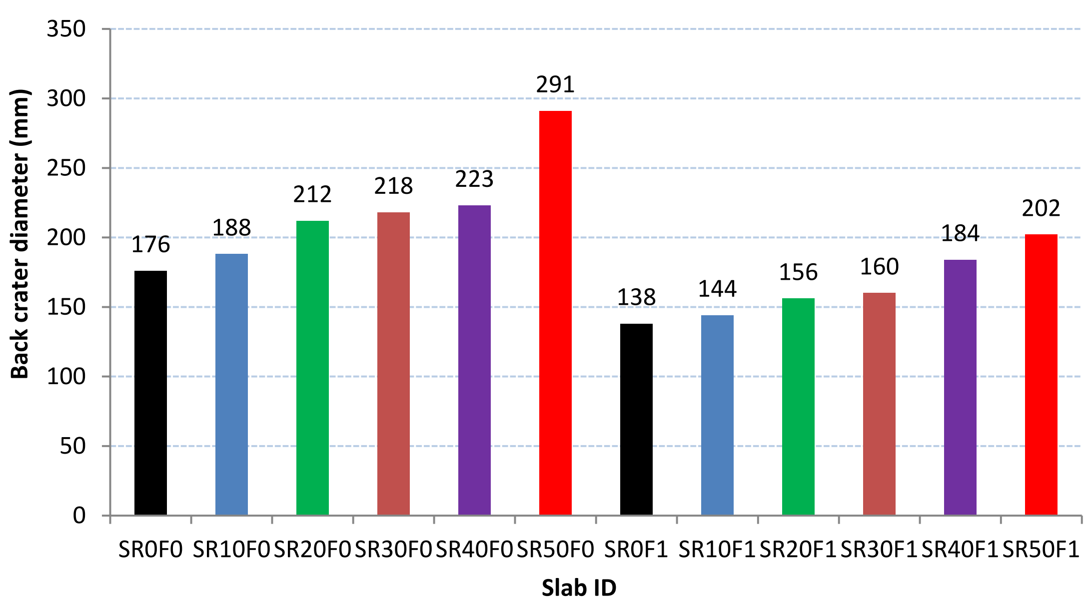


Fig. 15 Effect of RCA ratio and corrugated steel fibers on back crater diameter of asphalt slabs

10%, 20%, 30%, and 40% without steel fibers, the diameter of the back craters increased to 188 mm, 212 mm, 218 mm, and 223 mm, respectively. The increases ratios in the diameter of the back craters for specimens SR10F0, SR20F0, SR30F0, and SR30F0 were 6.8%, 20.5%, 23.8%, and 26.7%, respectively, compared to the reference slab SR0F0. Slab SR50F0 recorded the highest back diameter at 291 mm (65% larger than the reference slab) because this specimen contained the highest proportion of RCA among the tested asphalt slabs at 50%. The presence of steel fibers within the asphalt slabs improved their tensile strength, resulting in a smaller diameter of the back crater compared to slabs without steel fibers. The diameter of the back crater for specimen SR0F1 was 138 mm, which was 21.6% smaller than that of the reference slab. Moreover, the diameter of the back crater for specimens SR10F1, SR20F1, SR30F1, SR40F1, and SR50F1 with RCA ratios of 10%, 20%, 30%, 40%, and 50%, in addition to steel fibers, was smaller than that of the counterpart slabs without steel fibers by 23.4%, 26.4%, 26.6%, 17.5%, and 30.6%, respectively.

The ratio between the diameter of the crater on the back face to the diameter of the crater on the front face was 1.40 for the reference slab that did not contain RCA or steel fibers (SR0F0). With the addition of steel fibers in the case of slab SR0F1, this ratio decreased to 1.15. The ratio between the diameter of the crater on the back face to the diameter of the crater on the front face for slabs SR10F0, SR20F0, SR30F0, SR40F0, and SR50F0, without the addition of steel fibers, was 1.40, 1.45, 1.42, 1.38, and 1.67, respectively. On the other hand, the ratio between the back and front crater diameters after incorporating steel fibers for specimens SR10F1, SR20F1, SR30F1, SR40F1, and SR50F1 was 1.15, 1.17, 1.15, 1.28, and 1.36, respectively. These ratios were smaller than those of the counterpart slabs without steel fibers by 18%, 19%, 19%, 7%, and 18%, respectively.

5 Analytical Investigation

Previous studies on the theoretical calculation of penetration depth for asphalt slabs subjected to impact loads are scarce, particularly in cases involving RCA or steel fibers. The current research aims to elucidate the available models from previous studies and delineate the variables upon which each model relies, in preparation for comparing the theoretical results of penetration depth with the current experimental findings. The comparison aims to assess the efficiency of existing mathematical models and to develop a precise mathematical model capable of accurately calculating the penetration depth for asphalt pavements containing RCA and steel fibers.

5.1 Petry

The Petry model (1910) is the first mathematical model introduced to predict the depth of penetration in thick walls resulting from impact loading. The penetration depth in the Petry model depends on the mass, diameter, and velocity of the impact projectile as illustrated in Eq. (1):

$$\frac{X}{d} = 3.39x10^{-4}\left(\frac{M}{d^3}\right)\log_{10}\left(1 + \frac{V^2}{19974}\right), \quad (1)$$

where X represents the penetration depth, M stands for the impact mass, d denotes the diameter of the impact projectile, and V is the impact velocity.

5.2 Tolch and Bushkovitch

Tolch and Bushkovitch (1947) conducted numerous experimental tests to derive Eq. (2), which calculates the penetration depth based on the same variables (mass and diameter of the projectile and impact velocity) that Petri used when formulating his model. The novelty in Tolch and Bushkovitch's model is the addition of the coefficient k, which is determined as either 2.7 for hard rocks or 4.7 for soft rocks like concrete:

$$\frac{X}{d} = 2.217x10^{-7}\left(\frac{kMV}{d^{2.83}}\right). \quad (2)$$

5.3 Comparison Between Experimental Findings and Available Models

Table 5 presents the analytical penetration depth results for the slabs calculated according to the mathematical equations of both Petry (1910) and Tolch and Bushkovitch (1947), compared with the experimental records. The results indicate that neither mathematical model accounted for the percentage of RCA or the presence of steel fibers within the asphalt slabs. Consequently, the penetration depth results remained constant for all slabs, failing to accurately reflect the experimental findings. Petry's model yielded a lower penetration depth compared to the experimental values, whereas the Tolch and Bushkovitch model predicted higher values with respect to the experimental results.

5.4 Proposed Equation

It is necessary to develop a mathematical model capable of predicting the penetration depth in asphalt slabs resulting from impact loading, taking into account the percentage of RCA and the presence of steel fibers. A nonlinear regression analysis was conducted based on the mathematical models explained earlier, with appropriate modifications to incorporate the percentage of

Table 5 Comparison of the experimental penetration depth with analytical models in previous studies

Slab ID	*d*(m)	*M*(kg)	*V*(m/s)	*k*	*f*	*R*	Experimental penetration depth (mm)	Analytical penetration depth *X* (mm)			
								Petry (1910)	Tolch and Bushkovitch (1947)	Proposed equation	Proposed/experimental
SR0F0	0.05	10	2.0	4.7	1.0	1.0	41	29.5	95	40	0.98
SR10F0	0.05	10	2.0	4.7	1.0	1.1	53	29.5	95	44	0.83
SR20F0	0.05	10	2.0	4.7	1.0	1.2	61	29.5	95	48	0.79
SR30F0	0.05	10	2.0	4.7	1.0	1.3	70	29.5	95	52	0.74
SR40F0	0.05	10	2.0	4.7	1.0	1.4	76	29.5	95	56	0.74
SR50F0	0.05	10	2.0	4.7	1.0	1.5	120	29.5	95	60	0.50
SR0F1	0.05	10	2.0	4.7	0.85	1.0	30	29.5	95	34	1.13
SR10F1	0.05	10	2.0	4.7	0.85	1.1	38	29.5	95	37.4	0.98
SR20F1	0.05	10	2.0	4.7	0.85	1.2	44	29.5	95	40.8	0.93
SR30F1	0.05	10	2.0	4.7	0.85	1.3	49	29.5	95	44.2	0.90
SR40F1	0.05	10	2.0	4.7	0.85	1.4	56	29.5	95	47.6	0.85
SR50F1	0.05	10	2.0	4.7	0.85	1.5	67	29.5	95	51	0.76
Average											0.84
Standard deviation											0.15
% Coefficient of variation											18.88

RCA and the presence of steel fibers, as illustrated in Eq. (3):

$$\frac{X}{d} = 5x10^{-6}\left(\frac{MV}{d^3}\right) * f * R, \tag{3}$$

where $X, M, d, andV$ represent the penetration depth, the impact mass, the diameter of the impact projectile, and the impact velocity, respectively. The coefficient f represents the presence of steel fibers and is considered as 1.0 when steel fibers are absent or 0.85 when steel fibers are added. The coefficient R represents the presence of RCA within the asphalt slabs, and its value is calculated as (1.0 + recycled aggregate proportion).

Table 5 demonstrates that the modifications made to the mathematical models presented by Petry (1910) and Tolch and Bushkovitch (1947) resulted in a proposed mathematical model capable of accurately predicting the penetration depth in asphalt slabs under impact loading. The proposed mathematical model also incorporates the percentage of RCA and the presence of steel fibers, eliminating the fixed penetration depth values in all asphalt slabs. Instead, each slab now has its own penetration depth determined by the percentage of RCA and the presence or absence of steel fibers. Table 5 also shows that, except for slab SR50F0 which was fully penetrated, the ratio between the penetration depth calculated by the proposed mathematical model and the experimental penetration depth ranged from 0.74 to 1.13. On the other hand, the theoretical penetration depth calculated by the proposed mathematical model was 50% of the experimental penetration depth for specimen SR50F0. However, the average ratio between the theoretical and experimental penetration depths for all tested slabs was 0.84 with a standard deviation and coefficient of variation of 0.15 and 18.88%, respectively.

6 Conclusions

The current research examines the substitution of natural aggregates in asphalt concrete mixtures with recycled concrete aggregates (RCA), aiming to conserve available natural resources and safely dispose of construction industry waste. The study included three main objectives. The first objective was to conduct an experimental study to determine the Marshall stability, flow, bulk density, air void ratio, and splitting tensile strength of 12 asphalt concrete mixtures containing varying proportions of RCA, ranging from 0 to 50%. Six mixtures were cast without steel fibers, while the remaining six mixtures had corrugated steel fibers added at a volume fraction of 1%. The second objective was to cast six asphalt concrete slabs containing RCA ranging from 0 to 50%, along with six slabs containing the same proportions of RCA but with the inclusion of steel fibers at a volume fraction of 1%. These asphalt slabs were tested under the influence of impact loads to assess the effect of the RCA ratio and the presence of steel fibers on the penetration depth and the diameter of the crater on both the front and back surfaces of the slabs. The third objective was to evaluate the efficiency of existing mathematical equations for predicting the penetration depth of asphalt pavements and to improve their accuracy using the proposed model. The proposed mathematical model considers both the percentage of RCA and the presence of steel fibers in asphalt mixtures to address the current gap, which is the lack of an accurate mathematical model for well predicting the penetration depth of asphalt slabs subjected to impact loads. The following points can be inferred from the results of the study:

1. To prevent a significant decrease in the stability and splitting tensile strength of the mixtures compared to the reference mixture, the percentage of RCA in asphalt mixtures should not exceed 20%.
2. Using RCA at a replacement ratio of up to 20% did not significantly reduce the stability of the asphalt mixtures. The stability decreased by 7.2% and 12.8%, respectively, compared to the reference mixture when 10% and 20% RCA were used.
3. The stability of the asphalt mixtures significantly decreased when using RCA at ratios of 30%, 40%, and 50%. Specifically, the recorded decrease in stability of mixtures MR30F0, MR40F0, and MR50F0 was 17.6%, 23.2%, and 28.8%, respectively.
4. The stability of asphalt mixtures containing steel fibers was higher than their counterparts without fibers.
5. The use of RCA at small proportions ranging from 10 to 20% did not significantly change the flow properties of asphalt mixtures. In contrast, the flow values of asphalt mixtures cast using 30%, 40%, and 50% RCA were 17.2%, 20.7%, and 27.6% higher than that of the reference mixture, respectively.
6. The flow values of the asphalt mixtures containing steel fibers and cast using 10% and 20% RCA were 10.3% and 3.4% lower, respectively, than that of the reference mixture. Furthermore, the flow of asphalt mixtures containing 30%, 40%, and 50% RCA, in addition to steel fibers, decreased by 8.8%, 8.5%, and 8.1%, respectively, compared to counterpart mixtures without steel fibers.
7. The incorporation of small proportions of RCA (ranging from 10 to 20%) did not cause a significant decrease in the splitting tensile strength of the asphalt mixtures.
8. The penetration depth decreased by 28%, 27%, 30%, 26%, and 44% for asphalt slabs incorporating 10%, 20%, 30%, 40%, and 50% RCA, respectively, due to the inclusion of steel fibers compared to counterpart specimens without steel fibers.
9. The proposed analytical model accurately predicted the penetration depth in the asphalt slabs considering the RCA ratio and the presence of steel fibers. The average ratio between the theoretical and experimental penetration depths for all tested slabs was 0.84, with a standard deviation of 0.15 and a coefficient of variation of 18.88%.

7 Limitations and Future Recommendations

This study is limited to the use of steel fibers in asphalt mixtures. Additionally, the steel fiber content was kept constant at 1% by volume across all the asphalt mixtures. Therefore, the following points would be valuable extensions of the current research:

1. Investigating the mechanical characteristics of asphalt mixtures reinforced with different types of fibers, such as steel, polypropylene, carbon, and plastic.
2. Examining the effect of varying fiber ratios on the flowability of asphalt mixtures.

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