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Assessment of Rutting Resistance for Fiber-Modified Asphalt Mixtures

Nabaa I. Abd[1,*], **Roaa H. Latief** [2]

Department of Civil Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
naba.Abd2101m@coeng.uobaghdad.edu.iq[1], roaa.hamed@coeng.uobaghdad.edu.iq[2]

ABSTRACT

Rutting is one of the most complex and widespread types of distress. The rutting is frequently observed on Iraqi roads, especially at the checkpoints, forming a significant hazard on the asphalt layers. Factors such as heavy loads and high temperatures contribute to this distress. Adding fibers to a hot mix asphalt (HMA) effectively improves performance and extends the lifespan of the flexible pavement. This article used glass, steel, and basalt fibers. The wheel tracking test assessed the fibre-asphalt mixture for rutting resistance and compared it with the mix without adding fibers (control HMA).

Meanwhile, the microscopic structure of fibres and asphalt mixture modified with fibers was examined using the Field Emission Scanning Electron Microscopy (FESEM) technique. Steel, glass, and basalt fibers were incorporated into HMA in proportions of 0.25%, 0.10%, and 0.15%, respectively. The incorporation of fibers in asphalt mixtures implies lower rut depths after 5000 cycles. In comparison to the control HMA, a decrease in the rut depth is observed in fiber-asphalt mixtures, about 22.14%, 15.36%, and 9.64% for basalt, glass, and steel fiber, respectively, which consequently enhances flexible pavement resistance against rutting. The microstructure analysis showed the difference in the mixture's diameters, surface properties, and random fiber dispersion. Therefore, this dispersion contributed to creating a three-dimensional network, which improved the behaviour of HMA.

Keywords: Steel fiber, Glass fiber, Basalt fiber, Rutting, Field Emission Scanning Electron Microscopy (FESEM).

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*Corresponding author
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تقييم مقاومة التخدد لمخاليط الأسفلت المعدلة بالألياف

نبا اسماعيل عبد*، رؤى حامد لطيف

قسم الهندسة المدنية، كلية الهندسة، جامعة بغداد، بغداد، العراق

الخلاصة

يعد التخدد أحد أكثر أنواع التشوه تعقيدًا وانتشارًا. كثيرا ما يتم ملاحظة التخدد على الطرق العراقية ، وخاصة في محطات التوقف ، ويشكل خطرا كبيرا على طبقات الإسفلت. تساهم عدة عوامل في هذا النوع من الضرر ، مثل الأحمال الثقيلة ودرجات الحرارة المرتفعة. تعتبر إضافة الألياف إلى خليط الإسفلت الساخن (HMA) فعالة في تحسين الأداء وإطالة عمر الرصيف المرن. في هذه المقالة ، تم استخدام ثلاثة أنواع من الألياف: الفولاذ والزجاج والبازلت. تم تقييم مقاومة التخدد لخليط الألياف الإسفلتية ومقارنتها مع تلك الموجودة في الخليط دون أي إضافة ألياف (الخلطة الاسفلتية الحارة المرجعية) باستخدام اختبار العجلة. وفي الوقت نفسه ، تم إجراء تقنية الفحص المجهري الإلكتروني لمسح الانبعاث الميداني (FESEM) لفحص البنية المجهرية للألياف وخليط الإسفلت المعدل بالألياف. تمت إضافة ألياف الصلب والزجاج والبازلت إلى HMA بنسب 0.25٪ و 0.10٪ و 0.15٪ على التوالي. إن دمج الألياف في خلائط الإسفلت يعني وجود أعماق تخدد منخفضة بعد 5000 دورة. بالمقارنة مع الخلطة الاسفلتية الحارة المرجعية، لوحظ انخفاض في عمق التخدد في خلائط الألياف الإسفلتية ، حوالي 22.14٪ ، 15.36٪ ، و 9.64٪ لألياف البازلت والزجاج والصلب ، على التوالي ، مما يعزز مقاومة الرصيف المرنة ضد التخدد. أظهرت نتائج تحليل البنية المجهرية الاختلاف في الأقطار وخصائص السطح والتشتت العشوائي للألياف في الخليط ، لذلك ساهم هذا التشتت في تكوين شبكة ثلاثية الأبعاد أدت إلى تحسين سلوك الخلطة الاسفلتية الحارة.

الكلمات المفتاحية: الألياف الفولاذية، الألياف الزجاجية، ألياف البازلت، التخدد، المجهر الإلكتروني لمسح الانبعاث الميداني.

1. INTRODUCTION

The asphalt mixture components (aggregate and asphalt) are sensitive materials, especially to repeated loads and temperature **(Al-bayati and Lateif, 2017; Köfteci, 2018; Latief, 2019),** and with the increase in traffic volume intensity through large tyre pressures and heavy truck axles, in addition to the effects of environmental conditions and construction errors **(Sengoz and Topal, 2005)**, it will lead to some undesirable distress including fatigue cracking, low-temperature cracking, and rutting. These defects would reduce ride quality, shorten the service life of road pavements, and require maintenance at a high cost **(Huang, 2004; Chen and Xu, 2010; Xu and Solaimanian, 2008; Liu et al., 2014; Samor and Sarsam, 2021).** Rutting, which is essentially permanent deformation, is one of the most prevalent damages that impact flexible pavement performance **(Arshadi, 2013; Faruk et al., 2015; Domingos and Faxina, 2016; Al-Azawee and Latief, 2020)** and is caused by both horizontal and vertical forces **(Abiola et al., 2014)**. Rutting appears along the sides of the pavement in the wheel path in the form of a longitudinal surface depression **(Miller and Bellinger, 2003)**. This crucial failure in flexible pavements is induced primarily by the path of repeated wheel loadings due to the permanent deformation accumulation on the road pavement surface **(Fang, 2004)** and, therefore, will induce progressive movement for materials **(Tarefder et al., 2003)**. Furthermore, rutting is dangerous to pavement safety because water accumulates in these depressions, impeding efficient drainage from the wearing layer and perhaps leading to early failure. Also, rutting happens at intersections, highways, and bus stations due to friction between the tyre and pavement when applying vehicle braking because of the horizontal loading and accelerating processes that also significantly increase the shear strain and stress in the pavement layers **(Hammoum et al., 2010; Wang and Al-Qadi, 2010; Li et al., 2013).** Environmental factors, slow traffic at high temperatures, traffic volume, repeated heavy vehicle loading, tyre pressure **(Morea et al., 2011)**, material properties, and bituminous layer thickness **(Fang, 2004)** are some variables that affect rutting behaviour. Additionally, the poor quality of the materials for pavement and construction methods **(Zhang et al., 2017a; Zhang et al., 2017b)**, the age of the surface, and the classification of the highway are all significant contributors to the development of ruts **(Abdullah Nur et al., 2013)**. As a result, this increases maintenance and road user costs and shortens the pavement service life. Particually rutting is the main problem with flexible pavements in countries where high temperatures are usual **(Arabani et al., 2014)**. One current method of reinforcing asphalt involves the integration of various additives, involving polymers and fibers, into the mixture. In practical applications, fibers have garnered considerable attention for their benifit as asphalt mixture additives because their compatibility with simple manufacturing procedures and superior reinforcing impacts **(Slebi-Acevedo et al., 2019).** Using fibers in asphalt mixtures has become more desirable for constructing road pavements. Several studies have illustrated that incorporating fibers into an asphalt mixture improves fatigue resistance, permanent deformation, and resistance to flexibility **(Wang et al., 2021)**. Moreover, adding fibers into HMA successfully improves the asphalt mixture's mechanical and functional characteristics. It also rise the lifespan of the road pavement **(Abtahi et al., 2010; Ting et al., 2018; Hainin et al., 2018; Haryati et al., 2019; Norhidayah et al., 2019; Zhang et al., 2019)**. Providing additional tensile strength is the mainly purpose of fibers as reinforcing materials, which may increase the amount of strain energy that can be absorbed throughout the process of fracture and fatigue (Mahrez et al., 2003). Fibers improve mechanical characteristics such as dynamic modulus, reflective cracking, viscoelasticity, and rutting resistance, in addition to changing the asphalt binder to prevent draining in asphalt mixtures **(Lee et al., 2005; Putman and Amirkhanian, 2004)**. Many researchers have evaluated the impact of fiber modefining of asphalt mixtures on rutting resistance. As Pratico and Celauro studied the effect of utilizing basalt fiber with the inclusion of 0.3% by weight of aggregates on HMA mixtures by wheel tracking test, the fibers were added by the dry method. Comparing asphalt mixtures rainforced with basalt fiber with control mixture, Celauro and Pratico obtained that the modified HMA had higher rutting resistance **(Celauro and Pratico, 2018)**. **(Al-Kaissi et al., 2017)** investegated that the dynamic stability of HMA was improved by around 6.4% when 0.2% steel fibers were added compared with the coventional mixture. Mahrez and coworkers demonstrated that utlizing glass fiber will improve some of the main flexible pavement properties. Adding fibers in asphalt mixtures impacts their properties by rising the voids and the flow value and decreasing their stability in the mixture. The findings of incorporating fiber showed their ability to resist structural distress from rised traffic loads on road surfaces by improving the rutting resistance and cracking, therfore enhancing fatigue life **(Mahrez et al., 2005)**.

This study investigates the impact of three types of fibers (glass, steel, and basalt), which are cost-effective and approprite additives to expand the life service of asphalt pavements, on the rutting resistance of asphalt mixtures. Furthermore, the research objectives to exceplain the mechanism and microscopic structure by which glass, steel, and basalt fibers improve the asphalt mixtures performance.

2. MATERIALS SELECTION

2.1 Asphalt Cement

The asphalt cement type "AC (40–50)" in this study, provided from Al-Dora refinery in Baghdad city, was utilised to prepare the conventional and modified-asphalt mixtures. The physical characteristics of asphalt cement, like specific gravity, fire point, ductility, softening point, flash point, and penetration are significant and must be verfied before utilising them in asphalt mixtures. Consequently, the physical properties of AC (40–50) are examined, and the findings of these properties are compared with the Iraqi specifications limits for bridges and roads **(SCRB/R9, 2003)**. All the results are within the limits.

2.2 Fine and Coarse Aggregates

The aggregates (fine and coarse) used in this research are from the Al-Nibaie quarry. The physical properties of fine and coarse aggregates were tested and identified through laboratory tests. The physical properties of aggregates included the following: bulk-specific gravity, wear, water absorption, flat and elongated particles, and angularity. Finally, the test results are compared with the specification requirements **(SCRB/R9, 2003),** all within the limits.

2.3 Mineral Filler

Limestone filler was imported from Hit City in Al-Anbar province, located in the western region of Iraq, to be used in this study. It was passed through sieve No. 200 (0.075 mm), about 94% of the total weight. Also, the specific gravity was 2.76.

2.4 Fibers

In this research, three different kinds of fibers were utilized. The first type is a glass fiber (GF) with a length of roughly 12 mm. Glass fiber, an eco-friendly and inorganic fiber material, is highly resistant to chemical change with a specific gravity of 2.68. This fiber becomes soft at 860 °C but will not burn. The second type is basalt fiber (BF), which has a length of about 16 ±1.2 mm and a diameter of about 13.0 µm. The natural basalt stone is the source of basalt fiber created by rapidly drawing molten basalt lava at 1400–1500 °C **(Slebi-Acevedo et al., 2019).** The third type is steel fiber (SF), which has a length of 13 ±1.2 mm and is around 0.20 ±0.02 mm in diameter. These fibers were obtained from a local source in Baghdad. **Fig. 1** illustrates the appearance of the fibers utilized in this work.

The length of fibers in this study was chosen based on the past literature of other researchers. The impact of adding fibers to asphalt concrete might vary significantly depending on the properties of the fibers. For instance, if the fibers are excessively long, they might cause a phenomenon known as "balling", where some fibers clump together. This can result in a poor blending of the fibers with the asphalt concrete. On the contrary, the fibers may act like "extra filler" in the asphalt mixture without having any reinforcing effect if they are too short **(Mahrez et al., 2003).**

(a) Glass fiber

(c) Steel fiber

Figure 1. Fiber Images: (a) GF, (b) BF, (c) SF.

3. GRADATION SELECTION

Based on the specification requirements **(SCRB/R9, 2003)**, the coarse aggregate sizes range from 19 to 4.75 mm, and the fine aggregate sizes are between 4.75 and 0.075 mm. In this research, gradation Type IIIA for the wearing layer was chosen within the specification limits **(SCRB/R9, 2003)**. The nominal maximum size for the selected gradation was 12.5 mm. **Fig. 2** illustrates the desired gradation and the specification limits (minimum and maximum).

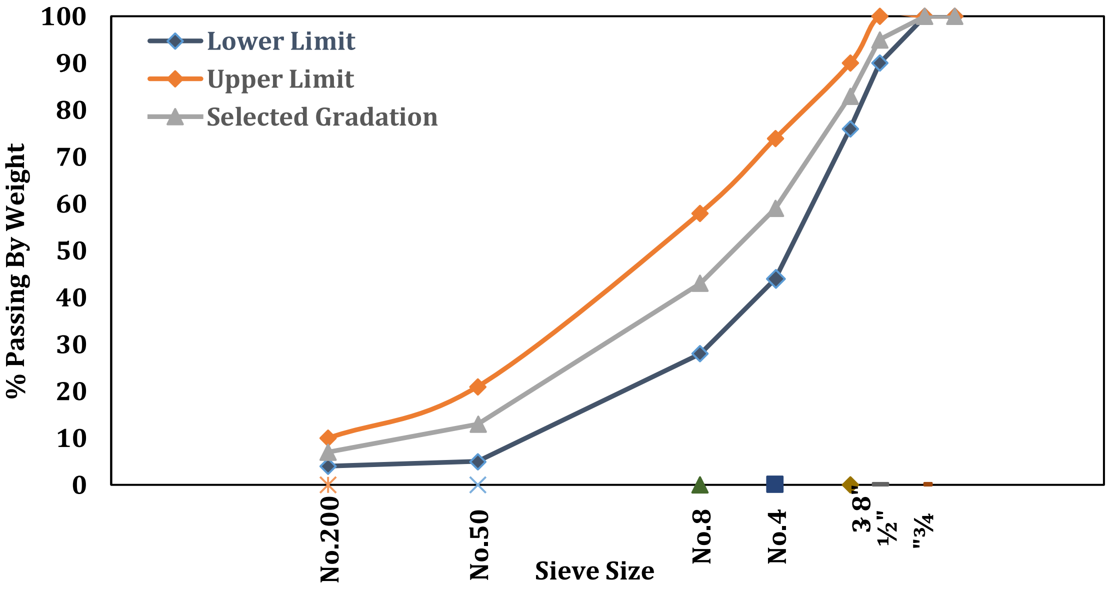


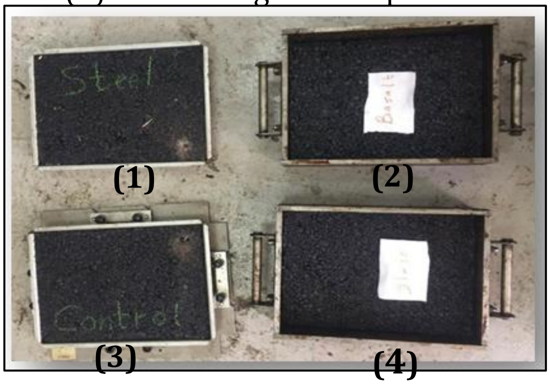
Figure 2. Gradation of Aggregates for Wearing Layer.

4. EXPERIMENTAL WORK

4.1 Wheel Tracking Test

The wheel tracking test was used to measure the depth of the ruts produced by repeatedly passing a loaded wheel at high temperatures to assess the ability to resist rutting for asphalt mixtures utilizing a wheel-tracking machine in the lab. The Marshall design method determined that 5% of the AC (40–50) was the optimal asphalt content (OAC) for traditional and fiber-asphalt mixtures. After conducting the Marshall test and tensile strength ratio (TSR) test for asphalt mixtures modified with fibers, the maximum Marshall stability values and the highest TSR values were found at 0.25% SF, 0.10% GF, and 0.15% BF. Furthermore, these ratios exhibited acceptable values for volumetric properties in accordance with specification limits **(SCRB/R9, 2003).** Therefore, these percentages were used in the wheel tracking test. In this study, a dry mixing technique was carried out in which, after heating the aggregate, the fibers were added all at once and mixed with the aggregate for 15–25 seconds. Then, the asphalt is weighed to the specified quantity, added to the mixture (aggregate and fibers), and blended for around 3 minutes until all aggregates and fibre particles are well coated with asphalt. The four asphalt mixtures, namely control, GF-mixture, SF-mixture, and BF-mixture, were compacted at dimensions (300 × 400 x 50) mm by employing the Dyna Compact Pneumatic Roller Compactor to achieve the desired density of 2.34 gm/cm^3 for this study. Then, the slabs were extracted from the mold after being left to cool for 24 hours, as illustrated in **Fig. 3**.

(b) Slab during the compaction



(a)Dyna-Compact Roller

(c) Compacted Slabs (1) SF, (2) BF, (3) Control Mix, (4) GF

Figure 3. The Compaction Process (a) Dyna-Compact Roller, (b) Slab during the compaction, (c) Compacted Slabs.

Finally, the slabs are subjected to 5000 cycles of load repetition in the wheel tracking device, based on as the rubber wheel moved across the specimen surface forward and backwards. The stressed wheel load was 70 psi at 50 °C temperature. **Fig. 4** shows the wheel tracking device and the compacted slabs for mixtures with and without fibers after the wheel test.

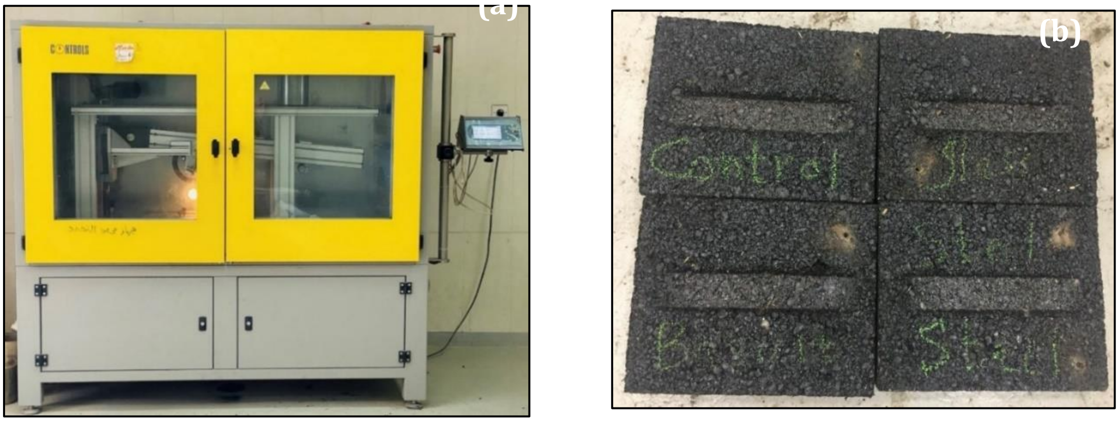


Figure 4. (a) Wheel Tracking Device, (b) Slabs After Wheel Track Test

4.2 Field Emission Scanning Electron Microscopy (FESEM)

The microscopic structure of fibers (steel, glass, and basalt) and asphalt mixtures with and without fibers were studied using FESEM. A small piece was gathered from the mix of fractured asphalt surfaces to confirm that the threads were distributed uniformly throughout the mixture. FESEM delivers an almost infinite depth of focus with elemental data and topography, with zoom extending from 10x to 300,000x. The TESCAN MIRA3 device carried out this test, as shown in **Fig. 5**.

Figure 5. Tescan Mira3 Device

5. RESULTS AND DISCUSSION

5.1 Wheel Tracking Test

A wheel track test was performed to assess the resistance of the fiber-asphalt mixtures to rutting. The test outcomes show that including fibers in asphalt mixtures is efficient because it decreases rut depth and improves the rutting resistance of flexible pavement. **Figs. 6 and 7** show the effect of fibers on rut depth.

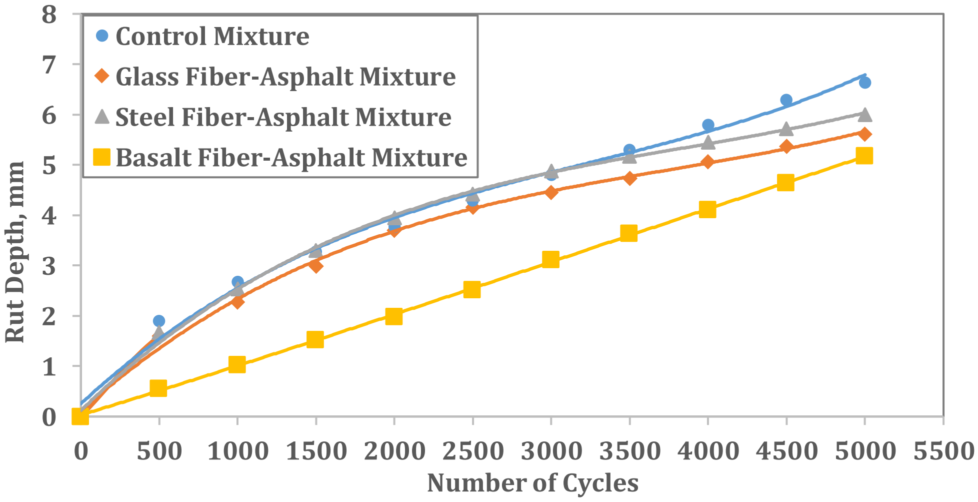


Figure 6. Rut Depth and Cycle Number Relationship.

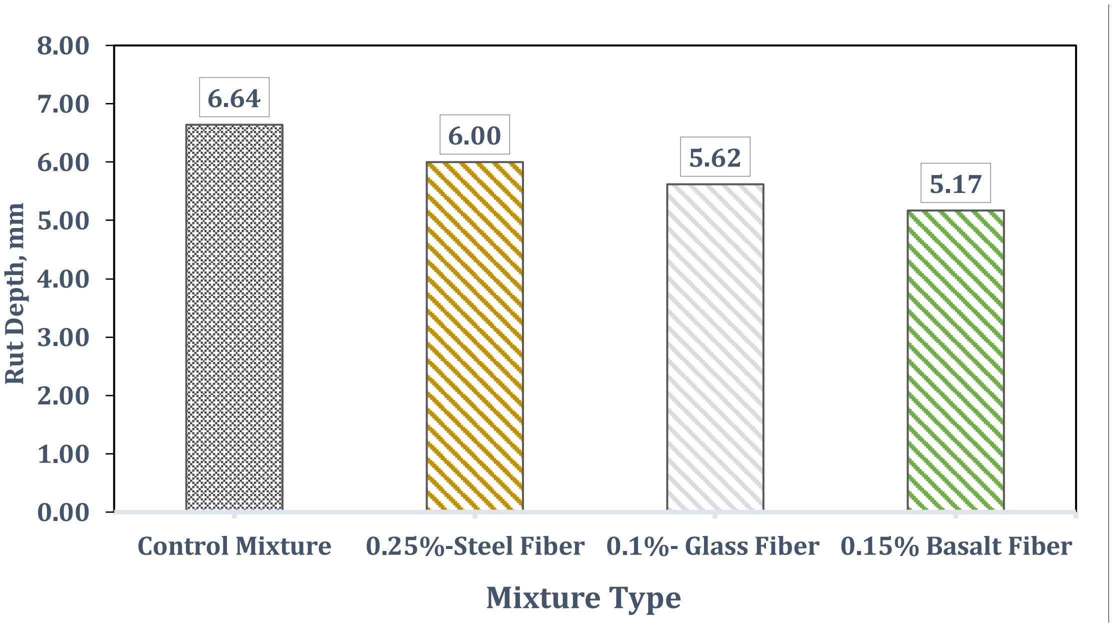


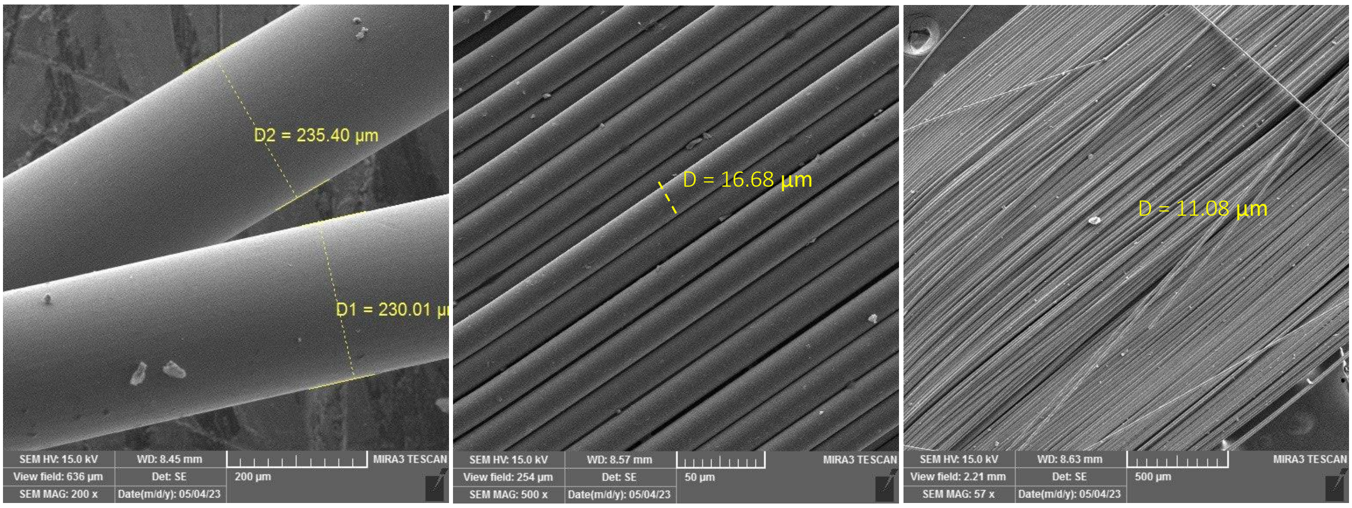
Figure 7. Impact of Fibers on Rut Depth.

As illustrated in **Fig. 6**, all fiber-asphalt mixtures exhibit a reduction in rutting depth compared to traditional mixtures. The wheel track test results revealed that the BF-asphalt mixture showed the most significant decrease in rut depth (22.14%), followed by the GF-asphalt mixture at 15.36%, and finally, the SF-asphalt mixture, which achieved the least reduction at 9.64% compared to other mixtures. This improvement may be due to the excellent dispersion of the fibers within the structure of asphalt mixtures, which produce a three-dimensional mesh that strongly impedes the movement of the aggregate particles and has high resistance to shear displacement, and this is consistent with the results of previous research **(Mahrez and Karim, 2007; Saleem and Ismael, 2020; Cheng et al., 2018)**. Basalt fiber show the highest rutting resistance distress of asphalt mixtures in comparsined to the modified mixtures with steel and glass. This may be due to physical characteristics of basalt fiber directly effect on the HMA performance, for example, high heat resistance, suitable radiation impedance, high tensile strength, eco-friendly, low adsorption rate, and high corrosion resistance **(Yan et al., 2021).**

Furthermore, the chemical composition of basalt fiber is a essential factor in enhancing asphalt and basalt compatibility; such as, Al_2O_3 in basalt fibers important improve the uniform distribution of flaws **(Chen et al., 2020; Xing et al., 2020).** The improvement of asphalt mixtures modefied with glass fiber to rutting resistance is because the high strength of glass fiber and its capability to recover fully elastic. Additionally, glass fiber is an excellent flexible reinforcing agent, giving thermal and chemical stability at temperatures up to 200 °C **(Nguyen et al., 2013)**.

5.2 Fiber Surface Morphology

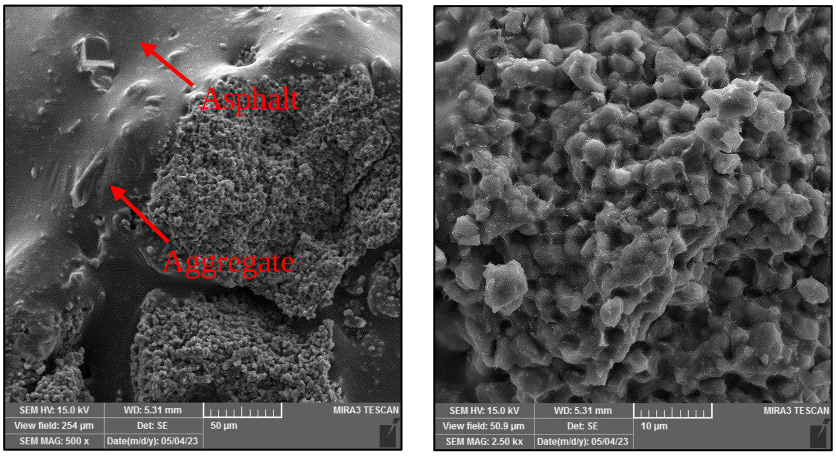
Fig. 8 illustrates the microscopic images of the fibers obtained through FESEM, which showed the microstructure of the fibers in high definition. According to the photos, the utilized fiber had a consistent cylindrical shape with a different diameter for each type.



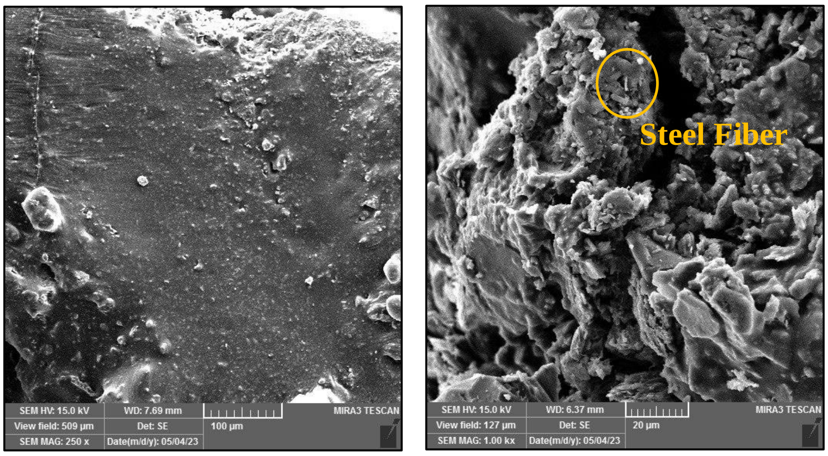
(a) SF (b) GF (c) BF

Figure 8. Fibers micrograph (a) SF, (b) GF, (c) BF.

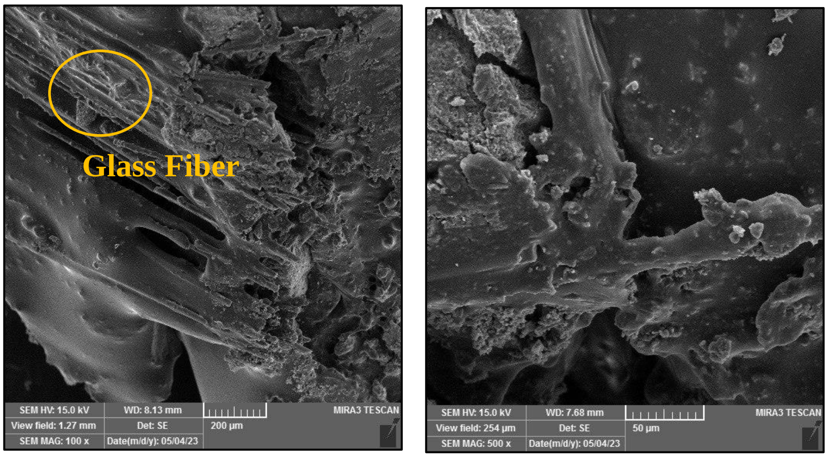
Regarding the microscopic images for the asphalt mixture, **Fig. 9 (a)** displays the microstructure of the control HMA and reveals that it is mostly flat with a certain degree of peeling. The distribution of these fibers that overlap each other to form a network of robust, interconnected fibers was made clear, as shown in **Fig. 9** (b, c, and d) of the fiber-asphalt mixture microstructure; however, the steel fiber is not very visible on the microscopic image in contrast to the glass and basalt fibers, which were both highly visible. The images demonstrated that the fibers were coated with asphalt completely, and thus this indicates strong adhesion between the asphalt and the fibers. As depicted, the inclusion of fibers results in forming a more compact layer of asphalt surrounding the aggregate. It serves as a strengthening connection between the aggregate and asphalt by creating a three-dimensional network that enhances the integrity of the asphalt mixture.



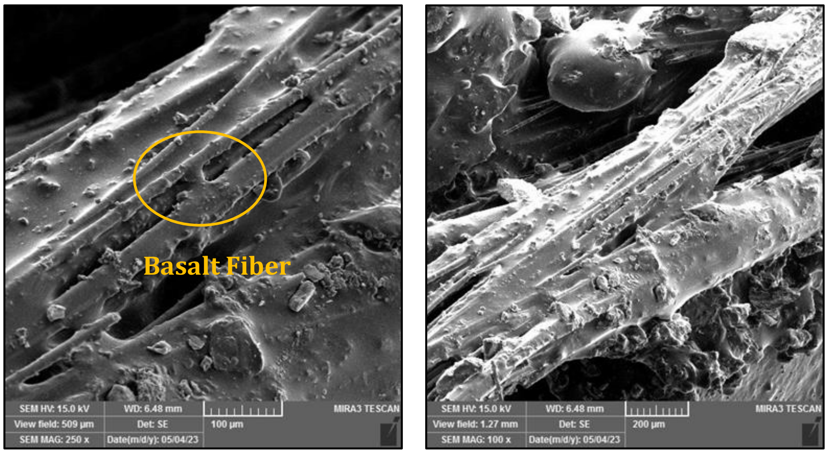
(a) FESEM Images of the Control Mixture at various scales.



(b) FESEM Images of the SF-Mixture at various scales.



(c) FESEM Images of the GF-Mixture at various scales.



(d) FESEM Images of the BF-Mixture at various scales.

Figure 9. Microscopic Pictures of Asphalt Mixtures (a) Control Mixture, (b) Steel Fiber-Asphalt Mixture, (c) Glass Fiber-Asphalt Mixture, (d) Basalt Fiber-Asphalt Mixture.

This mesh helps reduce the movement of aggregates and asphalt and disperse and transfer stress. Consequently, the strength of the asphalt mixture increased. Fibers effectively improve the crack resistance of the HMA and play a bridge role, which delays the crack's development, thus decreasing the crack susceptibility of the asphalt mixture.

6. CONCLUSIONS

The present work investigates the application of steel, glass, and basalt fibers as additives to enhance the HMA performance and assess their influence on rutting resistance. The tensile strength ratio and Marshall tests were conducted to determine the optimum fiber content and use in the rutting test. Then modified asphalt mixtures with fiber of glass, basalt, and steel (0.10%, 0.15%, and 0.25% by weight of total mix) were subjected to wheel tracking test and FESEM test. The findings can be summarized as follows:

- The results of the wheel tracking test showed that using 0.15%, 0.10%, and 0.25% of basalt, glass, and steel fiber led to a decrease in rut depth of about 22.14%, 15.36%, and 9.64%, consecutively. These findings suggest an enhancement in the rutting resistance of the HMA.
- The wheel track test findings indicated that the BF-asphalt mixture exhibited higher rutting resistance, followed by the GF and SF-asphalt mixture. Adding fibers improves the asphalt mixtures, although the improvement varies from type to type based on the characteristics of each kind.
- The FESEM revealed the microscopic structure of the fibers individually and the fibers within the asphalt mixture. Additionally, it showed that fiber particles were distributed randomly throughout the mixture, leading to an improved asphalt mix by forming a three-dimensional mesh.
- The construction cost for fiber-asphalt mixtures may increase due to the additional fiber cost. However, for overall long-term contributions, the maintenance cost will be reduced because of improvements in the rutting resistance of mixtures modified with fibers.

NOMENCLATURE

Symbol	Description	Symbol	Description
AC (40–50)	Asphalt Cement with Penetration Grade (40-50)	HMA	Hot Mix Asphalt
BF	Basalt Fiber	OAC	Optimal Asphalt Content
FESEM	Field Emission Scanning Electron Microscopy	SF	Steel Fiber
GF	Glass Fiber	TSR	Tensile strength ratio

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Credit Authorship Contribution Statement

Nabaa I. Abd: Writing – review & editing, Writing – original draft, Investigation, Experiment, Resources, Review analysis. Roaa H. Latief: Writing – review & editing, Supervision, Methodology, Results analysis, Reviewing & support.

Declaration Of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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