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RUTTING PREDICTION OF HOT MIX ASPHALT MIXTURES REINFORCED BY CERAMIC FIBERS

Ahmed Ashor Al-Saad*, Mohammed Qadir Ismael

Department of Civil Engineering, University of Baghdad, Baghdad, Iraq

**ahmed.ashor2001m@coeng.uobaghdad.edu.iq*

One of the most severe problems with flexible asphalt pavements is permanent deformation in the form of rutting. Accordingly, the practice of adding fiber elements to asphalt mix to improve performance under dynamic loading has grown significantly in order to prevent rutting distress and ensure a safe and long-lasting road surface. This paper explores the effects of a combination of ceramic fiber (CF), a low-cost, easily available mineral fiber, and thermal insulator fiber reinforced to enhance the Marshall properties and increase the rutting resistance of asphalt mixes at high temperatures. Asphalt mixtures with 0%, 0.75%, 1.5%, and 2.25% CF content were prepared, and Marshall stability and wheel tracking tests were employed to study the effect of added CF on asphalt mixture performance. Scanning electron microscopy (SEM) and field emission scanning electron microscopy (FESEM) were also used to investigate the morphologies of CF and reinforced asphalt mixtures and to identify the mechanism of improvement .According to the study results, the ideal ceramic fiber content was 1.5%, which yielded an improve in Marshall stability and reduced rut depth by 22.05% and 27.71% at temperatures of 50°C and 60°C, respectively, when compared to asphalt mixtures without CF. Microscopic analyses clearly revealed the surface properties, particle diameter size, and fiber distribution of the reinforced mixture, including the network structure and strength mechanism, which improved the performance of the asphalt mixture by forming a three-dimensional network.

Keywords: rutting resistance, wheel tracking test, scanning electron microscopy (SEM), ceramic fibers (CF)

1 INTRODUCTION

Since asphalt cement is commonly used for road and airport pavements, engineers and developers are continually working to improve the performance of asphalt pavement [1]. Mixing additives, such as polymers and fibers, into asphalt is one current reinforcing strategy. In practical applications, fibers' excellent reinforcing effects and association with simple manufacturing techniques have drawn significant attention to their usefulness as additives in asphalt mixtures [2]. Rutting, a common problem seen in asphalt pavements, is characterized by depressions where vehicular wheels wear paths in the surface layer [3]. Additionally, the sides of the ruts may exhibit raised in high-temperature areas. Besides temperature, other elements that influence asphalt pavement rutting include overloading, low-speed truck traffic, and long, steep slopes [4]. An increase in rut depth in pavements can cause severe problems, including traffic safety hazards and increased repair and maintenance costs. Thus, experts have recognized the rutting phenomenon as the most detrimental structural distress to road surfaces [5]. L. N. Hoang used a wheel tracking device at 60°C and 30,000 cycles to identify the relationship between rutting and aggregate gradation of hot mix asphalt. The study used three aggregate gradations, with maximum aggregate sizes of 9.5 mm, 12.5 mm, and 19 mm. According to the study results, a maximum aggregate size of 19 mm yielded the best rutting resistance [6]. The use of fibers in asphalt mixture has become a more appealing solution for road pavement construction. Several studies have demonstrated that adding fibers to an asphalt mixture improves resistance to permanent deformation, fatigue resistance, and flexibility [7]. According to Zhang [8], at 3600 s and 10°C, asphalt mixtures containing 0.1% and 0.2% of basalt fibers reduced deflection by 13.4% and 34.6%, respectively, due to an improvement in the low-temperature behavior of asphalt mortar resulting from matrix action between the asphalt and basalt fibers in the composition. Ismael [9] evaluated the effect on the resistance to rutting of adding carbon nanotubes (CNT) to two bitumen grades (40/50 and 60/70) of asphalt pavement. The research findings revealed that bitumen with greater viscosity required fewer CNT and demonstrated the best Marshall stability and rutting performance. In a comparison of the two conditions, the 40/50 grade produced a 61.0% increase in rutting resistance and a 35.0% increase in stability at 1.5% CNT, while the 60/70 grade required 2.0% of CNT to achieve similar results. Mawat and Ismael [10] prepared an asphalt mixture with three levels of carbon-fiber content (0.10%, 0.20%, and 0.30%) and three lengths (1.0, 2.0, and 3.0 cm) of fiber. The authors remarked that the indirect tensile strength ratio increased by 11.23%, and the index of retained strength increased by 12.52%, which was achieved by including carbon fibers with a length of 2.0 cm and a carbon content of 0.30%. The evaluation of the impact of glass fibers on asphalt mixes, Mahrez and Karim discovered that utilizing these fibers increased the flow rate while decreasing the asphalt mixture's stability. Because the fibers could resist the structural stresses caused by traffic, the asphalt mixture's fatigue life was increased by enhancing its resistance to cracking and permanent deformation [11]. Other research that evaluated the influence of steel fibers on indirect tensile strength (ITS) reported improvement using a mixture modified with 11% steel fiber to reinforce the asphalt mixture. Adding high-fiber content to the asphalt mixture reduced the indirect tensile strength due to the resulting decrease in the thickness of the mastic film, which created poor adhesion between the asphalt mixture materials [12]. Ceramic fiber (CF), primarily composed of $Al2O_3$ and SiO_2, offers various advantages, including dynamic stability, a large specific surface area, and mechanical stress resistance [13]. In an experimental study that used three different percentages of CF (1%, 2%, and 3%), Wan proved that adding CF reduced rutting depth and improved the temperature sensitivity of the modified asphalt binder [14]. Arabani and Shabani highlighted CF as a proper additive to enhance binder and asphalt mixture performance by increasing resistance, thus reducing permanent deformation and rutting. In other words, the use of these fibers in the binder and asphalt mixture improved its high-temperature performance [15]. In another study, Arabani and Shabani reported that CF enhanced the ability of asphalt mixtures to resist fatigue and rutting, demonstrating the usefulness of ceramic fiber as a reinforcing ingredient in asphalt mixtures [16]. Therefore, the current study used ceramic fibers as a reinforcement to improve the Marshall properties of asphalt mixtures and to resist the occurrence of ruts wearing courses in flexible pavement. The study conditions included two temperatures test to predict the rutting depth, and one of the researches aims includes an explanation of the morphologies of CF and asphalt mixtures with and without CF.

2 MATERIALS AND METHODS

2.1 Materials

2.1.1 Asphalt

The asphalt cement utilized in this study with a penetration grade of 40-50 and was prepared by Al–Daurah Refinery. The test results meet the requirements of the State Commission on Roads and Bridges (SCRB) [17].

2.1.2 Aggregates

Crushed coarse aggregate (between 4.75 and 19 mm sieve) and fine aggregate (particle size between No. 4 and No. 200) for wearing course were brought from a local source (Al-Obaidi Complex for the Production of Asphalt Paving). The laboratory evaluation defined the aggregate's basic properties. The results of the tests concerning the specification limitations were established by (SCRB, 2003) [17].

2.1.3 Mineral Filler

The asphalt concrete mixture was made with limestone dust. The filler was a non-plastic substance that passed the No. 200 filter (0.075 mm). The filler was sourced from a lime plant in Karbala, Iraq.

2.1.4 Ceramic Fibers

Ceramic fibers were added to the asphalt mixture at levels of 0.75%, 1.5%, and 2.25% per total weight of the mixture. Due to its high thermal conductivity and tensile strength properties, it was chosen for this experiment. Table 1 illustrates the properties of the ceramic fibers, while Figure 2 shows the appearance of the ceramic fibers used in this study.

2.2 Designed Aggregate Gradation

The aggregate and filler gradations were chosen following the (SCRB, 2003) specification, with a Nominal maximum size of 12.5 (mm) (wearing course type III A). Figure 1 illustrates the design aggregate gradation.

Table 1. Basic Properties of Ceramic Fibers.

Average length (mm)	Average diameter (µm)	Density (kg/m^3)	Melting Point (°C)	Tensile strength (kPa)
2.0	7.0	128	1600	83

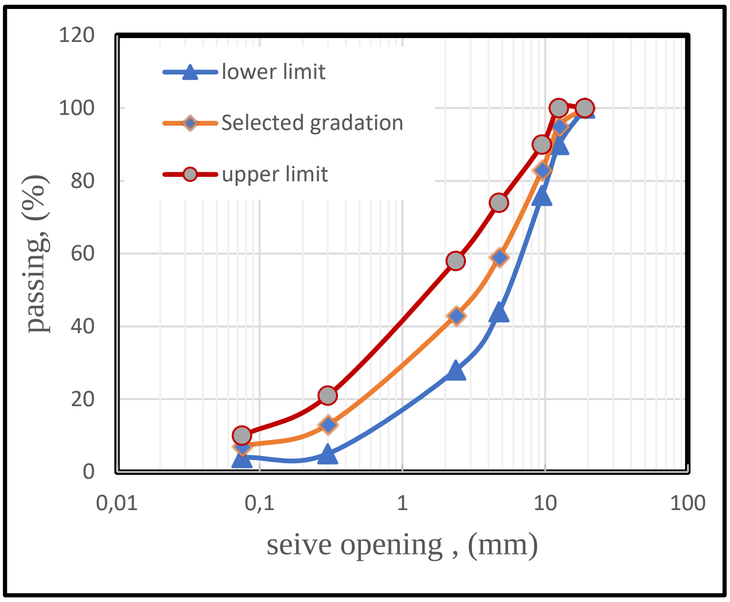

Figure 1. Design aggregate gradation

Figure 2. The appearance of ceramic fiber

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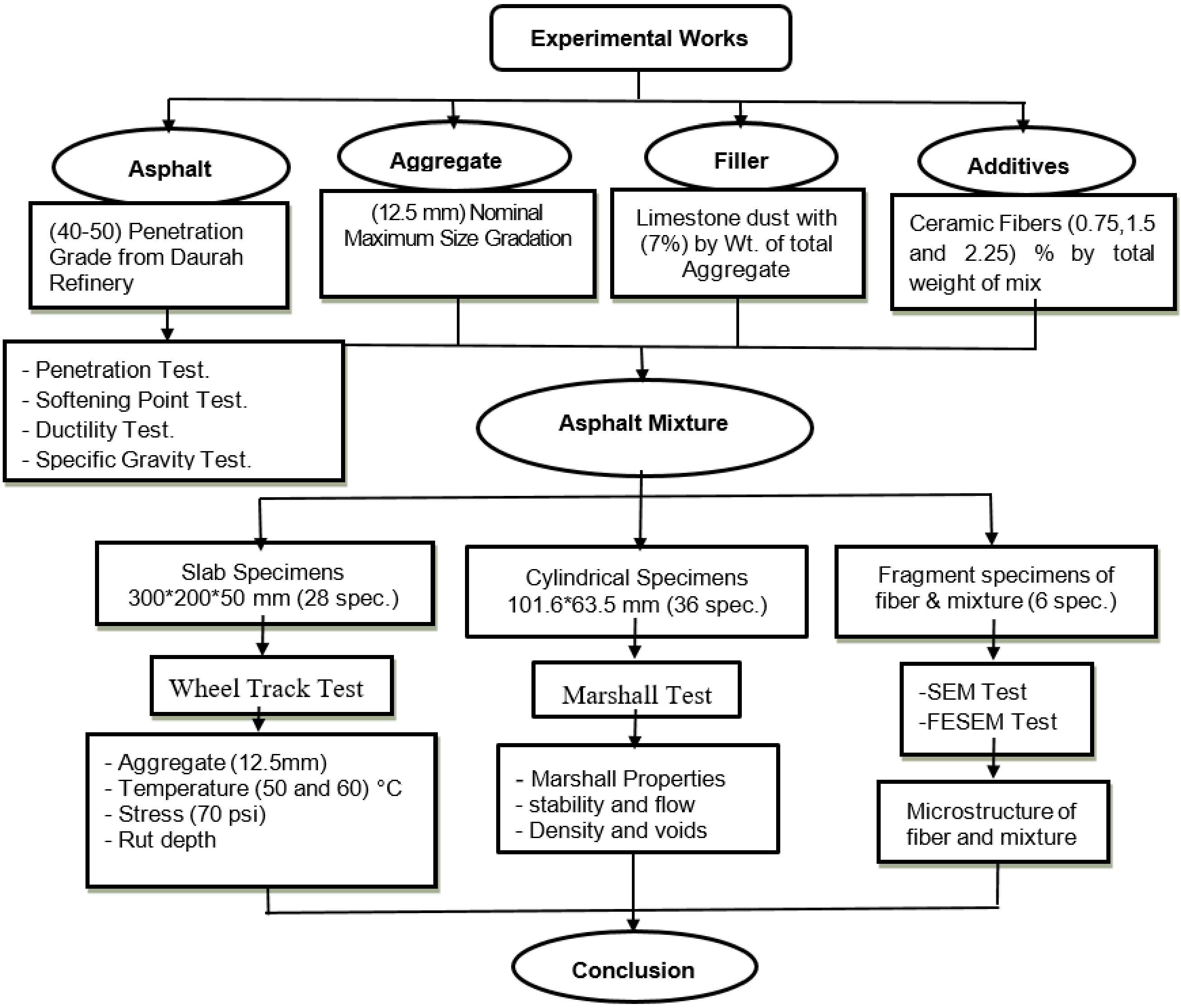


Figure 3. The work program flow chart.

2.3 Asphalt Mixture Test

2.3.1 Marshall Stability and Flow

As per ASTM D2726-08 [18], cylindrical samples having a diameter of 10.16 cm and a height of 6.35 cm were used in the Marshall stability and flow tests. At a temperature of 60°C, the loading rate was 50.8 mm/min for this experiment.

2.3.2 Wheel Tracking Test

A wheel tracking device estimates the depths of the rut for specific projects by using the laboratory wheel track's rut depth. In addition, simulation tests that evaluated HMA properties were performed by repeatedly rolling a smaller weighted wheel device through a prepared HMA specimen.

The Dynamic Pneumatic Roller Compactor was used in this work, which was performed at the National Center for Construction Laboratories and Research/Laboratory Baghdad (NCCLR). This modern device compresses asphalt mixture slabs of (300*400) mm, 25 to 100 mm thick, under controlled conditions that simulate in-situ compaction. The goal density (2.3 gm/cm^3) was obtained in this study. The specimens were cooled for 24 hours in the mold and then extracted.

After the specimen was fixed into a wheel tracker machine, it was then subjected to a load repetition of 5000 cycles (10,000 passes), according to [19]. The wheel tracker was adjusted using a temperature-controlled cabinet at two temperatures, 50°C and 60°C. The wheel load under stress was 70 psi (483 kPa). The testing procedure is shown in Figures 4 (a) to (d).

The wheel tracking test evaluated dynamic stability, which represented the number of load cycles for every 1 mm of mixture rutting [2]. The following formula was used to calculate dynamic stability:

$$DS = \frac{(t2-t1)*N}{R2-R1} \quad (1)$$

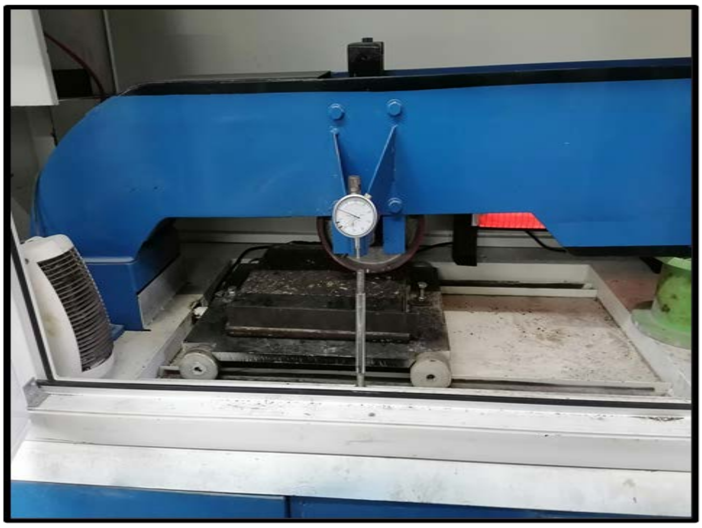
where DS denotes dynamic stability (cycle/mm), t1 is 45 minutes, t2 is 60 minutes, R1 refers to rut depth corresponding to t1 (mm), R2 indicates rut depth corresponding to t2 (mm), and N represents the test wheel's loading speed equal to 52 cycles per minute.

2.3.3 Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) was conducted at the Nanotechnology & Advanced Materials Research Center located at the University of Technology to provide high-resolution close-up illustrations and analyze the microscopic structure of the CF samples. SEM can create three-dimensional images of the surfaces of various materials. In addition, electron microscopy gives extreme magnifications and exact measurements of microscopic features and objects.

(a) Compacting the sample by roller compacter.

(b) Slab specimen after compaction.



(c) Slab inside wheel tracking machine.

(d) Slab after test.

Figure 4. The wheel tracking test procedure.

2.3.4 Field Emission Scanning Electron Microscopy (FESEM)

Following the Marshall tests, small particles were retrieved from the broken surfaces of the asphalt mixtures (with and without CF) and used in this test in Iran to reveal the ceramic fibers' three-dimensional network structure and evaluate the improvement provided by the CF in the different properties of the asphalt mixture. To ensure uniform fiber distribution and create a homogeneous mixture. FESEM microscopes provide images of an object's surface or the distribution of components inside a phase by applying electron radiation to the sample surface under vacuum conditions. Specifically, FESEM delivers topographical and elemental information at magnifications ranging from 10x to 300,000x, with a depth of field that is essentially infinite.

3 RESULT AND DISCUSSION

3.1 Marshall Test

As Figure 5 illustrates, the optimum asphalt content (OAC) of asphalt mixtures with varying CF content of 0, 0.75, 0.15, and 0.225% was 4.9%, 5.05%, 5.35%, and 5.5%, respectively. Due to its wide surface area, CF could absorb some asphalt binder, which increased the optimum asphalt content.

Figure 6 reveals that with increased CF content, Marshall stability increased at first, then declined. The Marshall test indicated that the CF-modified asphalt mixture had greater stability than the control mixture. At level of CF content of 0.75% and 1.5%, the asphalt mixtures' Marshall stability was increased by 26.66% and 37.42%, respectively. Higher stability means a stiffer asphalt mix, proving that the CF dispersed the outside force applied to the asphalt mixture. However, at a CF content of 2.25%, the Marshall stability enhancement declined to 14.28% because the extreme level of CF mandated an extra amount of asphalt, resulting in a softer mixture. In addition, CF in asphalt mixtures may disperse irregularly and congeal as one, causing the three-dimensional network structure of CF to be broken. In another study, Wang [2] was able to obtain the highest increase in Marshall stability of 17.5% by using 0.4% of CF to add reinforcement to an asphalt mixture. According to Arabani and Shabani [16], it was anticipated that increasing the amount of CF in the mixture would have a negative impact on the static characteristics of the asphalt mixes since a mixture featuring 5% added CF had a very low Marshall flow and high Marshall stability when utilized.

From Figure 7, it can be seen that the flow decreased as the CF content rose. The observed decline in the flow value can be attributed to the increased stiffness that the added CF provided to the asphalt mixture.

Figure 8 illustrates the bulk specific gravity of asphalt mixtures with various percentages of CF content, having a bulk specific gravity range of 2.32 to 2.341. Because the density of CF was generally lower than that of the aggregates and asphalt, the bulk specific gravity dropped in proportion to the rise in CF content. Furthermore, increasing the CF and OAC reduced the asphalt mixture's density when compacted at the same pressure.

As displayed in Figure 9, the air void percentage increased as the CF content increased. This phenomenon occurred because asphalt mixtures containing CF were more challenging to compress than asphalt mixtures without CF due to the high elastic modulus of CF.

Due to the decrease in bulk specific gravity, the VMA increased as the CF content increased, as shown in Figure 10.

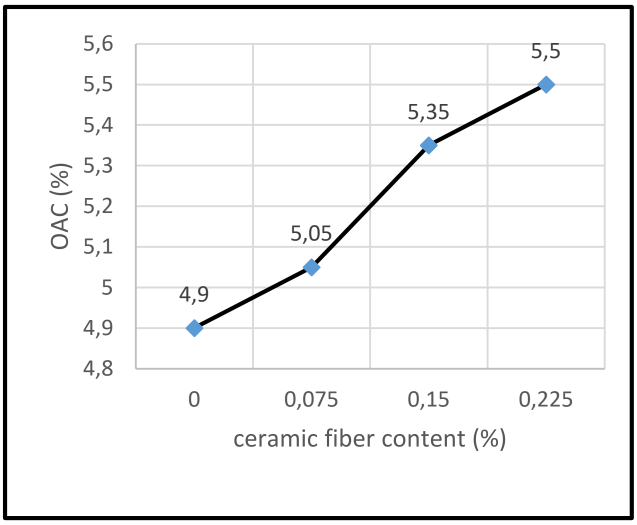


Figure 5. OAC and CF content relationship

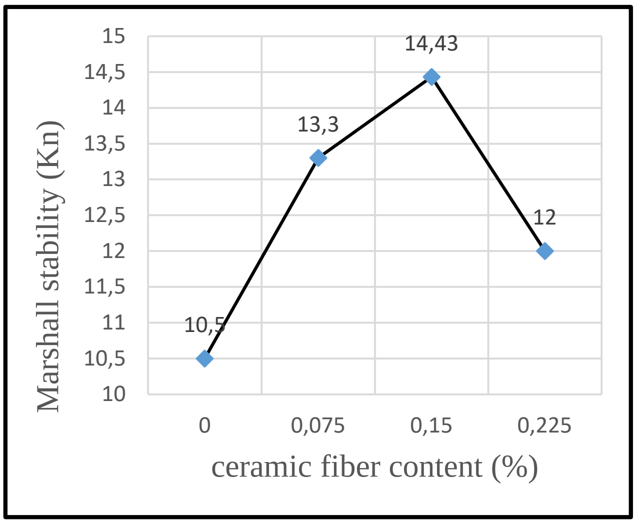


Figure 6. Marshall stability and CF content relationship

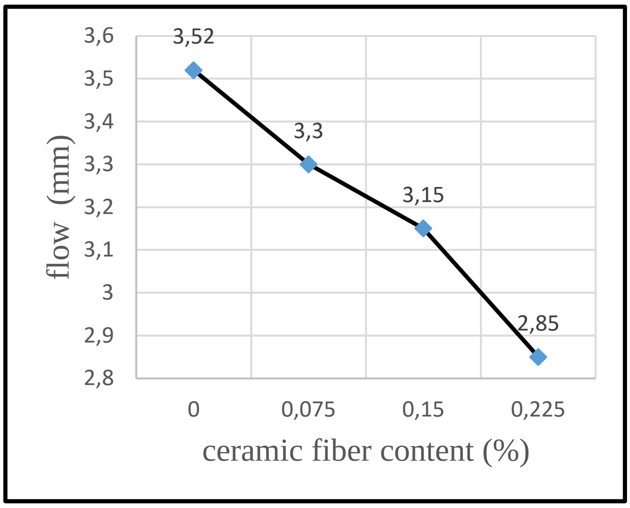


Figure 7. Flow and CF content relationship

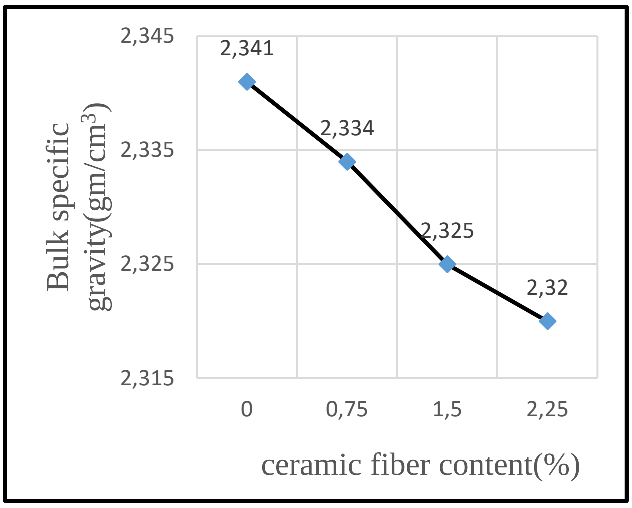


Figure 8. Bulk specific gravity and CF content relationship

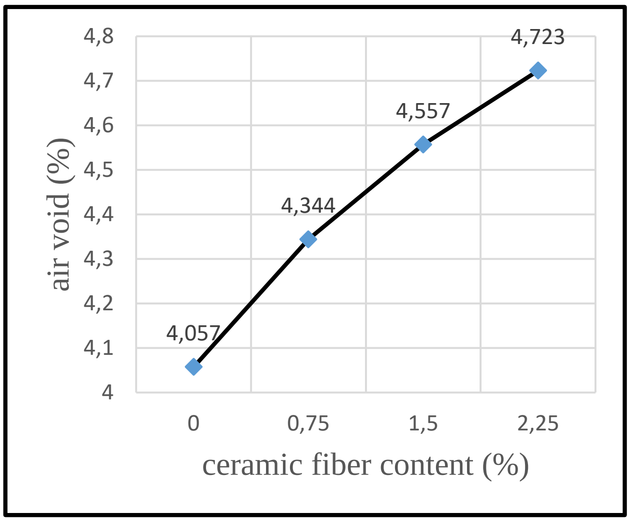


Figure 9. Air void and CF content relationship

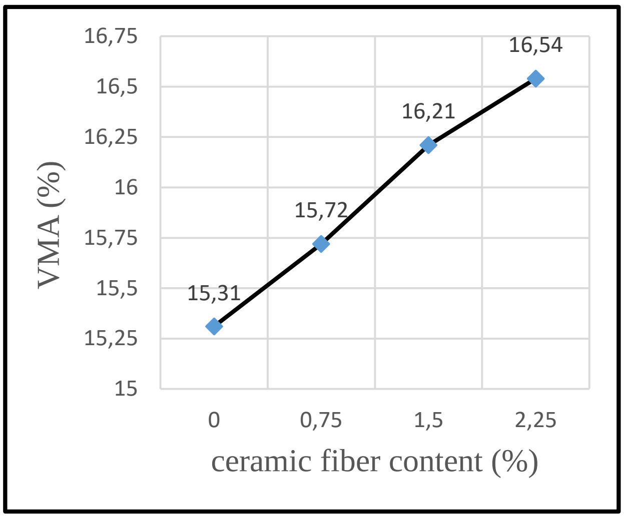


Figure 10. VMA and CF content relationship

3.2 Tracking Test

Figures 11 and 12 and Table 2 present the wheel tracking test results. As can be observed in Figures 10 and 11, the rut depth decreased while dynamic stability increased with increasing CF content under varying temperature conditions. At 50°C, when comparing mixtures with CF content of 0.75%, 1.5%, and 2.25% to asphalt compositions that did not contain fibers, the asphalt mixture's best high-temperature performance was achieved, with decreases in rut depth of 11.76%, 22.05%, and 33.82%, respectively, and enhancement of dynamic stability by 8.33%, 32.6%, and 40.00%, respectively. At a temperature of 60°C, comparing the same percentages of CF content as in the earlier test to asphalt compositions that did not contain fiber yielded the following results. The rut depth for a CF content of 0.75% decreased by 15.66%, while dynamic stability improved by 12.11%. When the CF content was 1.5%, rut depth decreased by 27.71%, and dynamic stability improved by 33.15%. Lastly, in the samples with a CF content of 2.25%, rut depth decreased by 37.34%, while dynamic stability was improved by 42.86%. The asphalt binder's thermodynamic constants changed due to the ceramic fiber's thermal insulating action. As a consequence, the asphalt mixture was less susceptible to temperature increases. This finding indicates that the high-temperature stability of asphalt mixtures can be greatly improved with the addition of CF, providing a greater level of improvement with increasing test temperature. The causes of this behavior can be divided into two areas of interest: reinforcement and temperature insulation. Notably, the fiber had a significant impact on the asphalt mixture's reinforcing capabilities, making it stronger and allowing the asphalt to exhibit less strain under the same stress. CF in an asphalt mixture can alter asphalt's absorption of light particles as well as vary the composition of asphalt from free to structured, thus reducing the material's susceptibility to temperature and increasing its stiffness. The addition of CF to asphalt mixtures has also been shown to produce a three-dimensional network structure that helps to limit aggregate slippage and improve the asphalt mixture's deformation resistance. compare with Wan, [14] study result When CF was utilized to modify the asphalt binder, the results revealed a considerable improvement in the rutting resistance between 30°C and 50°C. The impact of extra CF was minimal, however, at temperatures over 50°C.

Table 2. Summary of the wheel tracking test results.

Variables	Temperature, (˚C)	Rut depth, (mm)	Percent of change, (%)
Conventional	50	6.8	-11.76
0.75% CF		6	
1.5% CF		5.3	-22.05
2.25% CF		4.5	-33.82
Conventional	60	8.3	-15.66
0.75% CF		7	
1.5% CF		6	-27.71
2.25% CF		5.2	-37.34

* Negative signal (-) indicates a decrease in rut depth.

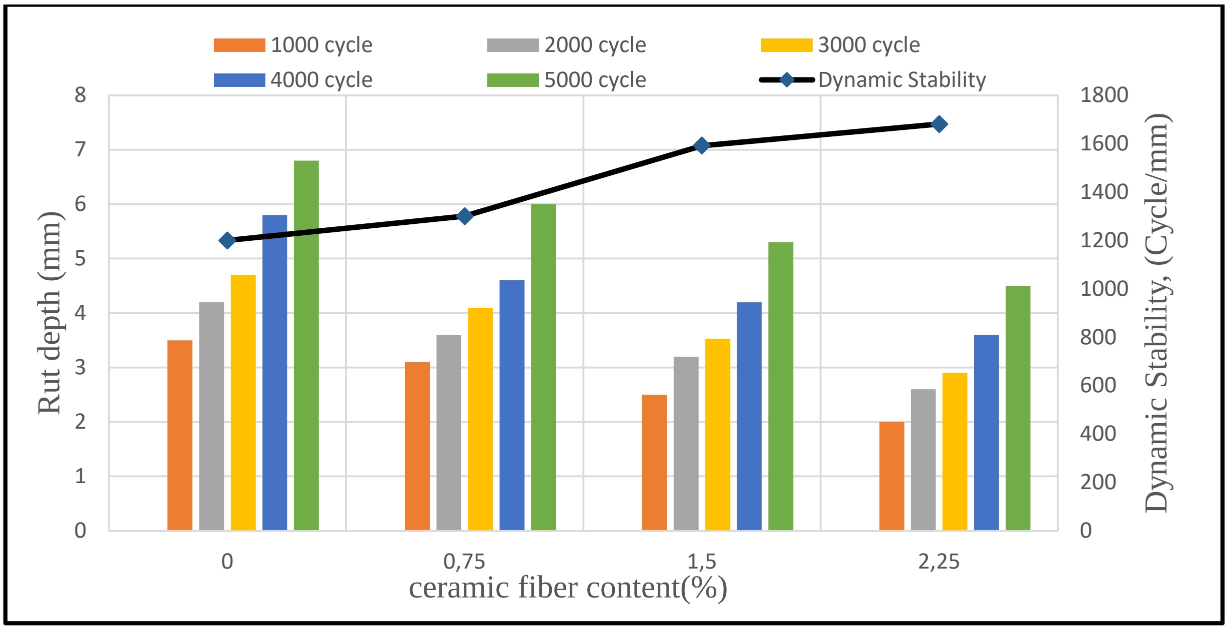


Figure 11. Relation between (Rut depth, Dynamic stability) and CF content at 50°C.

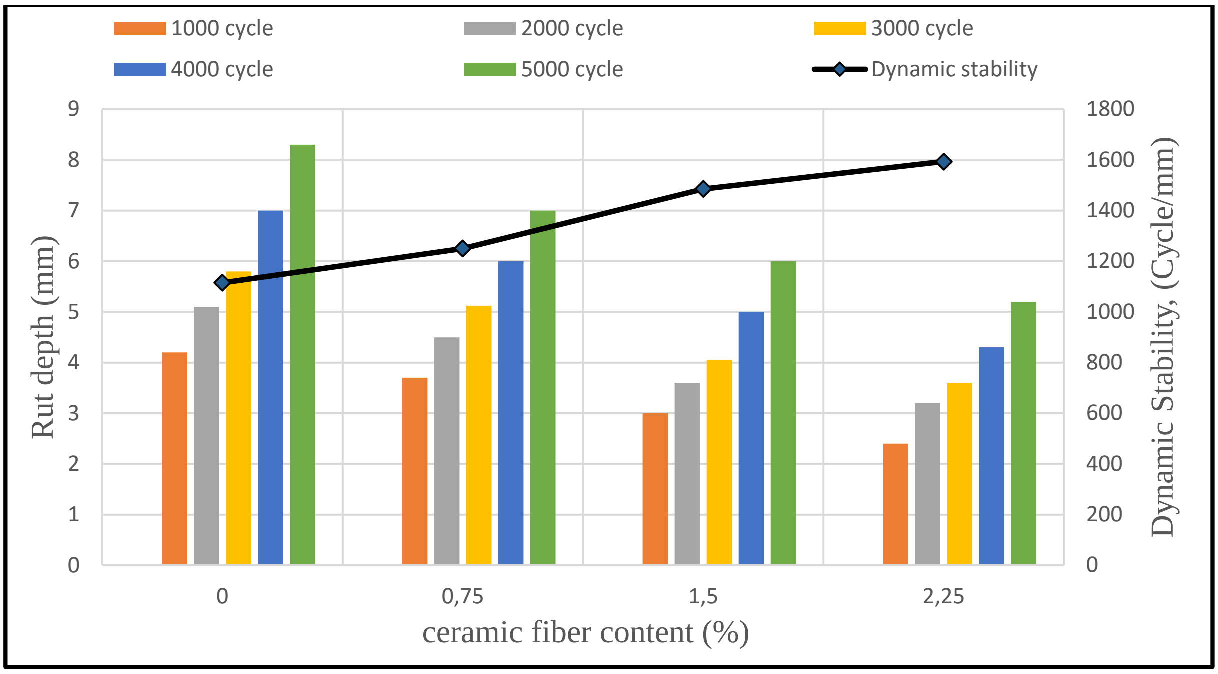


Figure 12. Relation between (Rut depth, Dynamic stability) and CF content at 60°C.

3.3 Scanning Electron Microscopy (SEM) Test

Figure 13 illustrates the current study's test results in the form of different magnified images showing the texture and orientation of ceramic fiber atoms with microstructure distribution in high definition. Measuring the diameters of some atoms revealed that they ranged from 4.5 µm to 10.93 µm. Some of the pictures reveal the presence of some spherical and irregular-shaped particles overlapping in the cylindrical fiber structure.

3.4 Field Emission Scanning Electron Microscopy (FESEM) Test

The different morphology of the CF-reinforced asphalt mixture observed with the use of FESEM is displayed in Figure 14. Figure 14 (a) reveals the microstructure of the asphalt mixture without CF (control mix). Notably, as shown in Figures 14 (b) and (c), the CF was distributed randomly in the asphalt mixture, reinforcing the asphalt mixture by creating a stable three-dimensional network that could also withstand extreme temperatures by forming a grid of interconnecting fibers between the aggregate and binder. This network of fibers encouraged the creation of a thick mastic layer without allowing asphalt to drain down. When external forces were applied to the asphalt mixture, CF was able to transfer and disperse forces coming from different directions, thus reducing stress cracking. As shown in Figure 15, the CF had an irregular shape and a conventional cylindrical shape, indicating a large specific surface area that absorbed additional asphalt and generated a thick layer of asphalt film. As can be seen in Figure 15 (b), the fiber threads absorbed drops of asphalt, whose diameter was several times the diameter of the ceramic fibers. Converting asphalt from free to structured was done by CF adsorption, improving the viscosity, strength, and stability of the mixture at high temperatures. CF roots can be seen in Figure 15 (c); these were strongly connected to the asphalt in terms of intersecting, demonstrating high adhesion properties between the CF and the asphalt.

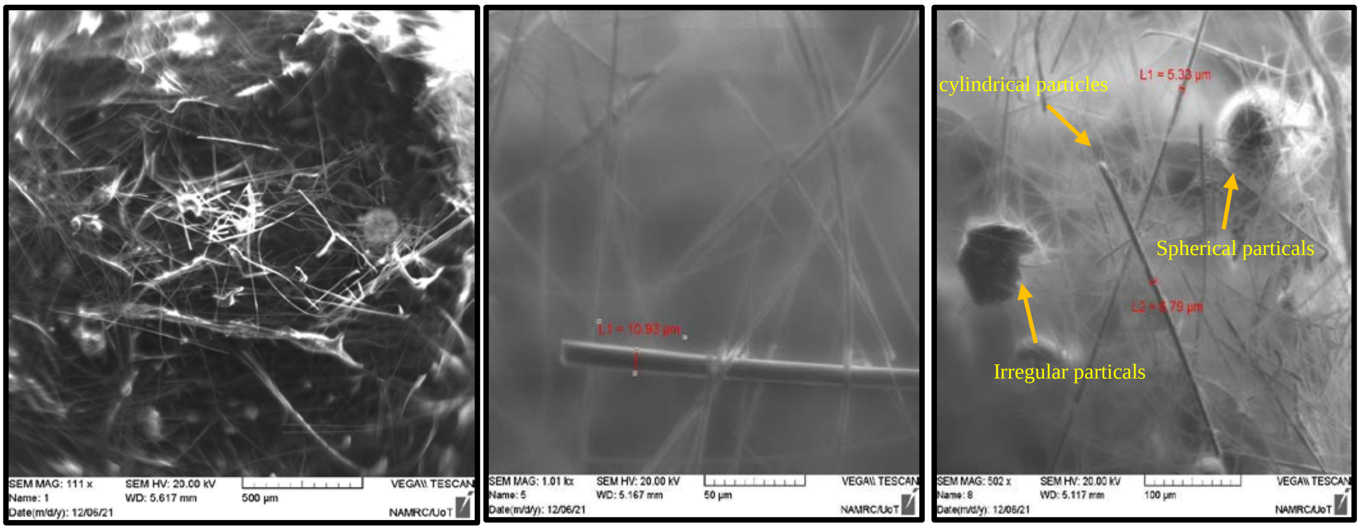
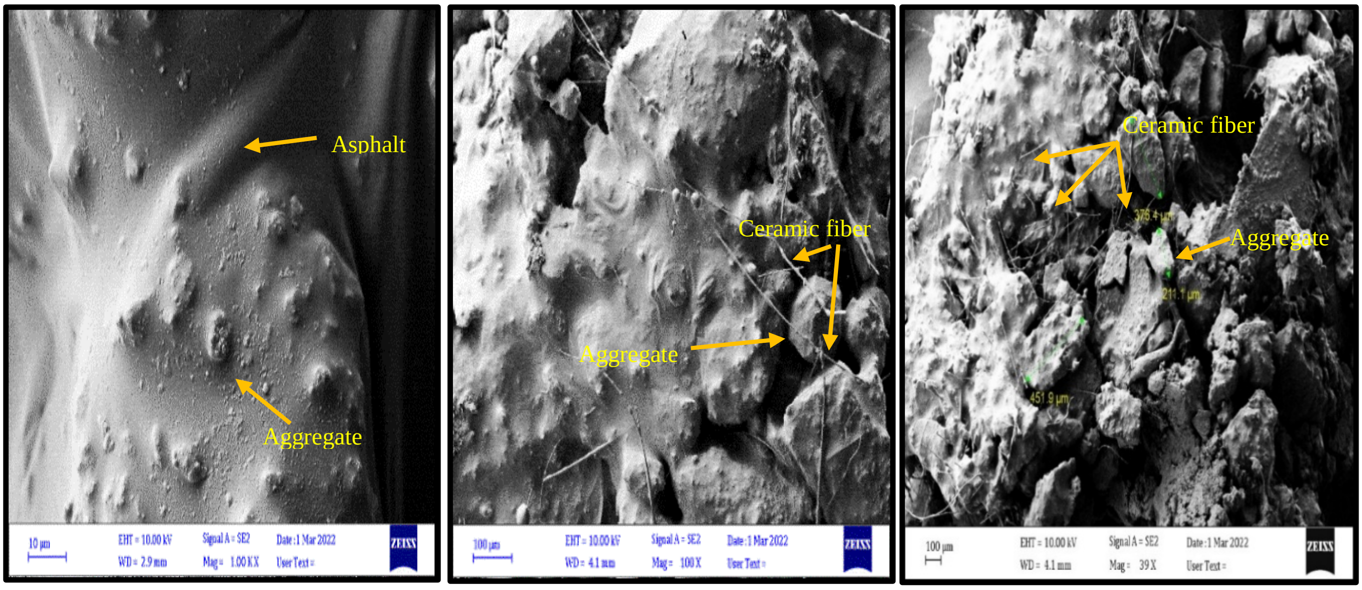
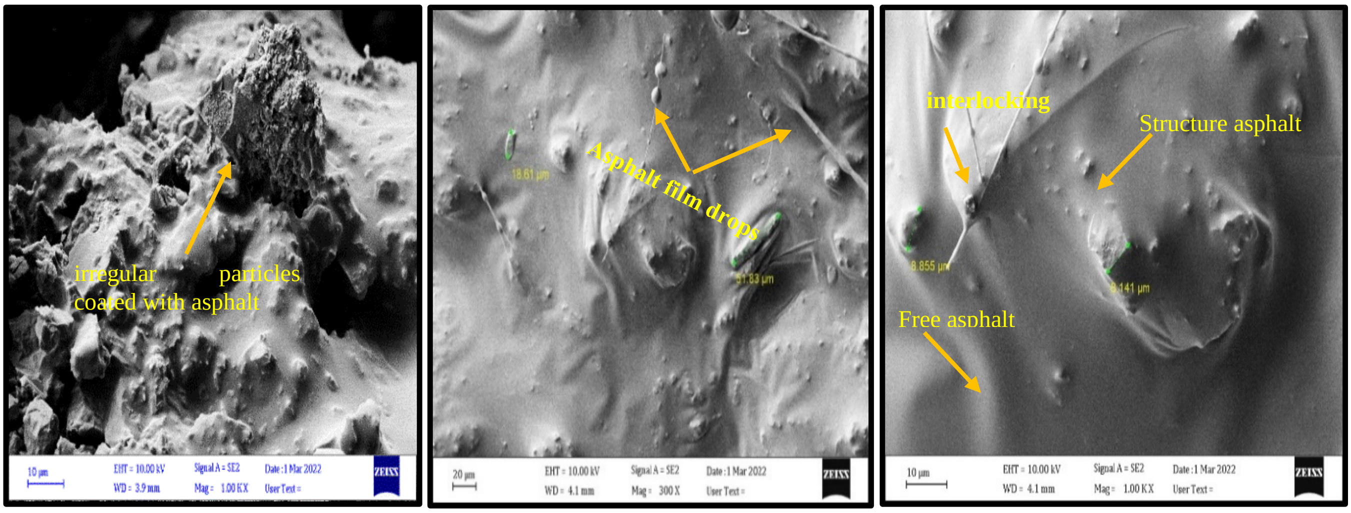


Figure 13. Some micrographs of ceramic fibers



(a) without CF. (b) 1.5% CF. (c) 2.25% CF.

Figure 14. Three-dimensional network structure of asphalt mixture



(a) (b) (c)

Figure 15. Ceramic fiber absorption

4 CONCLUSIONS

1. Rutting in asphalt pavement can be significantly improved by the addition of CF to the asphalt mixture. In tests that compared various fiber-containing asphalt mixes' resistivity and mechanical properties to asphalt compositions that did not contain CF, Marshall stability and dynamic stability increased by 37.42% and 33.15%, respectively, at a level of 1.5% CF content.
2. In terms of pavement performance and economic benefits, the ideal CF content to increase the performance characteristics of asphalt pavement is 1.5%.
3. When the percentage of CF in the asphalt mixture exceeds 2.25%, the workability of the mixture generally decreases. Furthermore, increasing the percentage of the ceramic addition requires more asphalt content, which leads to increased rutting.
4. During testing, the rate of improvement in rutting resistance increased with increasing temperature. In a mixture comprising 2.25% CF, the rutting depth decreased by 33.82% at 50°C and 37.34% at 60°C in a temperature-based test compared to the traditional asphalt mixture.
5. SEM analysis revealed that CF in the asphalt mixture was effective due to the creation of three-dimensional network structures that increased rutting resistance by improving the temperature susceptibility and hardness of the asphalt mixture.

5 REFERENCES

[1] Mirabdolazimi, S. M. and Shafabakhsh, G. (2017) 'Rutting depth prediction of hot mix asphalts modified with forta fiber using artificial neural networks and genetic programming technique', *Construction and Building Materials*, 148, pp. 666–674. doi: 10.1016/j.conbuildmat.2017.05.088.

[2] Wang, X. et al. (2021) 'Investigation of the Performance of Ceramic Fiber Modified Asphalt Mixture', Advances in Civil Engineering, 2021. doi: 10.1155/2021/8833468.

[3] Abbas, A. and Ismael, M. (2020) 'Assessment Resistance Potential to Moisture Damage and Rutting for HMA Mixtures Reinforced by Steel Fibers', 6(9), pp. 1726–1738.

[4] Ji, X. et al. (2013) 'Application of asphalt mixture shear strength to evaluate pavement rutting with accelerated loading facility (ALF)', Construction and Building Materials, 41, pp. 1–8. doi: 10.1016/j.conbuildmat.2012.11.111.

[5] Kashani Novin, M. (2011) 'The Effects of Bitumen Percentage and Percentage of Air Void on Rutting Potential of HMA by using Dynamic Creep Test', 10th Annual International conference on sustainable construction & pavement, (February). Available at:https://www.researchgate.net/publication/271199882.

[6] Hoang, L. N. (2018) 'Effect of aggregate gradation on rutting of asphalt concrete by using a wheel tracking device in Vietnam Abstract ':, pp. 1–6. doi: 10.1515/jmbm-2018-2007.

[7] Slebi-Acevedo, C. J. et al. (2019) 'Mechanical performance of fibers in hot mix asphalt: A review', Construction and Building Materials, 200, pp. 756–769. doi: 10.1016/j.conbuildmat.2018.12.171.

[8] Zhang, X. et al. (2017) 'Numerical analysis of the rheological behaviors of basalt fiber reinforced asphalt mortar using ABAQUS', Construction and Building Materials, 157, pp. 392–401. doi: 10.1016/j.conbuildmat.2017.09.044.

[9] Ismael, M. Q., Fattah, M. Y., & Jasim, A. F. (2021). Improving the rutting resistance of asphalt pavement modified with the carbon nanotubes additive. Ain Shams Engineering Journal, 12(4), 3619–3627. https://doi.org/10.1016/j.asej.2021.02.038

[10] Mawat, H. Q. and Ismael, M. Q. (2020) 'Assessment of moisture susceptibility for asphalt mixtures modified by carbon fibers', Civil Engineering Journal (Iran), 6(2), pp. 304–317. doi: 10.28991/cej-2020-03091472.

[11] Mahrez, A. and Karim, M. R. (2010) 'Fatigue characteristics of stone mastic asphalt mix reinforced with fiber glass', 5(12), pp. 1840–1847.

[12] Liu, Q. et al. (2010) 'Induction heating of electrically conductive porous asphalt concrete', Construction and Building Materials, 24(7), pp. 1207–1213. doi: 10.1016/j.conbuildmat.2009.12.019

[13] Hussein, S., & Qadir, M. (2020). Improving the Moisture Damage Resistance of HMA by Using Ceramic Fiber and Hydrated Lime. 13, 274–283.

[14] Wan, J. et al. (2016) 'Characteristics of ceramic fiber modified asphalt mortar', Materials, 9(9), pp. 1–12. doi: 10.3390/ma9090788.

[15] Arabani, M. and Shabani, A. (2019) 'Evaluation of the ceramic fiber modified asphalt binder', Construction and Building Materials, 205, pp. 377–386. doi: 10.1016/j.conbuildmat.2019.02.037.

[16] Arabani, M., Shabani, A. and Hamedi, G. H. (2019) 'Experimental Investigation of Effect of Ceramic Fibers on Mechanical Properties of Asphalt Mixtures', Journal of Materials in Civil Engineering, 31(9), p. 04019203. doi: 10.1061/(asce)mt.1943-5533.0002821.

[17] SCRB, (2003), "Standard Specifications for Road and Bridge", Section R/9, HotMix Asphalt Concrete Pavement, Revised Edition. State Corporation of Roads and Bridges, Ministry of Housing and Construction, Republic of Iraq

[18] ASTM, "Road and Paving Materials Vehicle Pavement Systems", Annual Book of ASTM Standards, (2018), Vol. 04 and Vol.05, American Society for Testing and Materials.

[19] Austroads AGPT-T231-06, Deformation Resistance of Asphalt Mixtures by the Wheel Tracking Test, 2006

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