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Improvement of Moisture Susceptibility for Asphalt Mixture with Ceramic Fiber

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ABSTRACT

Moisture damage is one of the most significant troubles that destroy asphaltic pavement and reduces road serviceability. Recently, academics have noticed a trend to utilize fibers to enhance the efficiency of asphalt pavement. This research explores the effect of low-cost ceramic fiber, which has high tensile strength and a very high thermal insulation coefficient, on the asphalt mixture's characteristics by adding three different proportions (0.75%, 1.5%, and 2.25%). The Marshall test and the Tensile Strength Ratio Test (TSR) were utilized to describe the impact of ceramic fiber on the characteristics of Marshall and the moisture susceptibility of the hot mix asphalt mixture. The Field Emission Scanning Electron Microscopy (FE-SEM) analysis was used to investigate ceramic fibers' microscopic structure and clarify the mechanics of their improved behavior and their distribution within the asphalt concrete mixture. The results showed that the incorporation of ceramic fibers improved the Marshall properties and the asphalt mixture's susceptibility to moisture damage with an optimum fiber content equal to 1.5%, where Marshall stability increased by 39.04%, and the TSR increased by 11.06% at this content compared with the control asphalt mixture.

Keywords: Ceramic Fiber (CF), Moisture damage, Tensile Strength Ratio Test (TSR), Field Emission Scanning Electron Microscopy test (FE-SEM).

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تحسين حساسية الرطوبة لخليط الأسفلت بألياف السيراميك

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الخلاصة

يعد التلف الناتج عن الرطوبة أحد أكبر المشكلات التي تدمر الرصيف الإسفلتي وتقلل من خدمية الطرق. في الآونة الأخيرة ، لاحظ الأكاديميون وجود اتجاه لاستخدام الألياف لتعزيز كفاءة رصف الأسفلت. يستكشف هذا البحث تأثير ألياف السيراميك منخفضة التكلفة ، والتي تتمتع بقوة شد عالية ومعامل عزل حراري مرتفع للغاية ، على خصائص خليط الأسفلت بإضافة ثلاث نسب مختلفة (0.75٪ ، 1.5٪ ، 2.25٪). تم إجراء اختبار مارشال واختبار نسبة مقاومة الشد لتوضيح تأثير ألياف السيراميك على خصائص مارشال وحساسية الرطوبة لخليط الأسفلت الساخن. بالإضافة إلى ذلك ، تم استخدام تحليل المجهر الإلكتروني لمسح الانبعاث الميداني لتقييم التركيب المجهري لألياف السيراميك ولتوضيح آليات سلوكها المحسن وطريقة توزيعها داخل خليط الإسفلت. وفقًا للنتائج ، أدت إضافة ألياف السيراميك إلى تحسين خصائص مارشال و حساسية الخليط الإسفلت للتلف الناتج عن الرطوبة بمحتوى ألياف مثالي يساوي 1.5٪ ، حيث زاد ثبات مارشال بنسبة 39.04٪ وزاد معدل نسبة مقاومة الشد بمقدار 11.06٪ في هذا المحتوى مقارنة مع خليط الأسفلت الخالي من الالياف.

الكلمات الرئيسية: ألياف السيراميك ، تلف الرطوبة ، اختبار نسبة قوة الشد ، اختبار المجهر الإلكتروني لمسح الانبعاث الميداني.

1. INTRODUCTION

Transportation is important in a country's economic prosperity and long-term development. Engineers and researchers are continuously trying to enhance the performance of pavement materials **(Arabani et al.,2019).** One of the main reasons asphalt concrete mixes fail too early is moisture damage. This form of damage is the gradual degradation of asphalt mixtures caused by adhesive failure (trying to strip the asphalt layer away from the aggregate surface), cohesive failure (reduction in the hardness of the mixture mainly due to water action), or both **(Vargas et al., 2016).** The moisture damage may appear as peeling or raveling of the top layer of the asphalt mixture. Early raveling damage might develop into more wearing severe surface disintegration very quickly, resulting in potholes that have a high effect on the safety of the road pavement **(Kringos, 2008).** Moisture damage is considered that has various effects on the community. Economically, maintaining and repairing the roadways harmed by moisture degradation cost millions of dollars **(Hussein et al., 2020).** Fibers have become increasingly used in hot mix asphalt (HMA) to develop asphalt pavement. Numerous types of research have shown that adding fibers to the mixture enhanced stiffness, resistance against moisture damage, permanent deformation, and resistance to fatigue **(Slebi et al., 2019). (Xu et al., 2010)** investigated the effect of various reinforced fibers on the characteristic of asphalt mixture underwater effect. According to the results of this study, fibers considerably increased asphalt mixture toughness, fatigue life, and rutting resistance. The split indirect tensile strength (SITS) at low temperature, ultimate flexural strength, and flexural strength have been improved **(Al-taher, 2015).** The effect of Polyester Fibers in different lengths was explored to enhance the resistance to flexural bending and fatigue of asphalt mixture by adding three percent of this fiber (0.25 %, 0.50 %, and 0.75 %) by the total weight of the asphalt mixture. As a result, for the 0.50% of 12.70 mm fibers length, the repetitions to failure increase by 9.40%, and fatigue cracking resistance is enhanced by polyester fibers. Marshall stability and indirect tensile strength were reduced by 11.70 and 6.00 percent by 0.75 percent of 12.70 mm fibers, respectively, both parameters suffer from small reductions in their values. **(Jamal et al., 2013)** investigated carbon nano-fiber characterization to improve asphalt mixture by using varying percentages of this fiber. This research discovered that carbon nano-fiber has a unique ability to enhance the performance of HMA mixes. The concept of carbon nano-fiber behavior and its effects on the general mechanical properties and laboratory performance of HMA mixes are also presented. **(Morea, 2018)** investigated the usage of glass macrofibres to improve asphalt mixture performance. Macrofibres improved residual stress capacity and initial peak fracture stress. Significantly improved fracture behavior at cold to warm temperatures. Additionally, adding fibers greatly improved the rutting behavior, with a reduction in permanent deformation of up to 50% compared to the control mix. **(Sarsam et al., 2015)** studied the resistance of recycled asphalt mixture after aging to damage from moisture. With the aid of a recycling agent, the recycled mixture was made from old asphalt concrete (soft asphalt cement mixed with silica fumes). The result of this study pointed out that the moisture damage enhances by 76.17% compared with the control mix, and ITS was lower for unconditioned samples for aged after-recycling process mixtures than a reference by 67.1% and was lower for aged before recycling process mixtures by 64.1%.

(Ismael et al., 2019) investigated asphalt mixtures' susceptibility to moisture modified by hydrated lime with three percent (1.0%, 1.5%, and 2.0%) by using the saturated surface dry method, the result shows that tensile strength ratio values for AC (40-50) and AC (60-70) improved by 24.50% and 29.16%, respectively, while the index of maintained strength values for both asphalt grades improved by 14.28% and 17.50%. According to (**Wan et al., 2016)** Al2O3 and SiO2 are the main ingredients of ceramic fiber, which has the characteristics of becoming stable at relatively high temperatures, having a high specific surface area, and resisting mechanical vibration from outside sources. It might increase moisture and rutting resistance **(Arabani et al., 2019).** They used three percent ceramic fiber (1%, 3%, and 5%) for the modified asphalt binder. After the experimental test, the result shows that the resistance of the asphalt binder at low temperatures is decreased by adding ceramic fibers. In comparison, it kept the binder's ability to resist cracking and enhanced its effectiveness at high temperatures. These fibers may be considered appropriate additions to enhance the performance of binder and asphalt mixes, with an optimum content of 3%. **(Wang et al., 2021)** studied the effect of ceramic fiber on improving asphalt mixture by using 5 % of this fiber (0%, 0.1%, 0.2%, 0.3%, 0.4%, and 0.5%). The results showed that adding ceramic fiber to asphalt mixtures might increase moisture resistance and their mechanical characteristics, both low-temperature cracking resistance and high-temperature stability, with 0.4% being the ideal CF concentrate. **(Qin et al., 2018)** used Scanning electron microscopy (SEM) analysis to evaluate the microstructure and shape of asphalt mastics and basalt fiber. It was discovered that basalt fibers improved the characteristics of asphalt mastics, particularly their fracture resistance. Due to its biggest contact area with asphalt mastic, basalt fiber with a 6 mm diameter performed better in asphalt absorption and strength than fibers with a 9 mm or 15 mm diameter.

This study tries to look into the impact of ceramic fibers as suitable and cost-effective additives as a reinforcement on moisture susceptibility and Marshall properties of asphalt mixture to extend the lifespan of asphalt pavements of wearing course in flexible pavement and also explain the microscopic structure and mechanism of improvement of asphalt mixture by ceramic fiber.

2. MATERIALS AND EXPERIMENTAL WORK

2.1. Materials

2.1.1. Asphalt.

This study employed one type of asphalt cement with a penetration grade of (40–50) made by Al-Daurah Refinery. The asphalt cement's physical characteristics in this research satisfy the State Commission on Roads and Bridges requirements. (SCRB). **Table 1** shows the physical properties of asphalt cement.

Table 1. Asphalt cement physical properties

Test	Units	Results	SCRB 2003 Specification Limits	ASTM Specification No
Penetration (25 °C, 100g, 5 sec)	1/10 mm	44	40-50	D-5
Ductility, (25°C, 5 cm/min)	cm	168	≥100	D-133
Kinematics viscosity, at 135 °C	cSt	410	--	D-2170
Softening point (Ring & Ball)	°C	51	--	D-36
Flashpoint (Cleveland open cup)	°C	272	232 min	D-92
Specific gravity, at 25 °C	--	1.046	--	D-70
After Thin-Film Oven Test (ASTM D 1754)				
Retained Penetration of Residue, (25 °C, 100 gm, 5 sec)	%	60	55 (Min)	D-5
Ductility, (25 °C, 5 cm/min)	Cm	84	> 25	D-113

2.1.2. Coarse Aggregates.

The crushed coarse material came from the Al-Nibaee Quarry: the sieve size (19mm) and the sieve (4.75 mm). **Table 2.** Shows the results per the specified limit (SCRB, 2003).

2.1.3. Fine Aggregate**.**

The same supply of coarse aggregate provided the crushed fine aggregate, which has a sieve size between 4.75 mm and 0.075 mm.

Table 2. Physical Properties of Coarse Aggregate.

Property	ASTM Specification	Result	SCRB Specification
Bulk Specific Gravity	C-127	2.58	----
Apparent Specific Gravity	C-127	2.605	----
Percent Water Absorption	C-127	0.57	----
Percent Wear (loss Angel’s abrasion)	C-131	15.26	30 Max

It comprises hard, firm grains clear of harmful amounts of clay, silt, or other substances. The fine aggregate's physical characteristics meet the State Commission on Roads and Bridges (SCRB, 2003), as given in **Table 3.**

Table 3. Physical Properties of Fine Aggregate

Property	ASTM Specification	Result	SCRB Specification
Bulk Specific Gravity	C-128	2.63	---
Apparent Specific Gravity	C-128	2.621	---
Percent Water Absorption	C-128	0.731	---

2.1.4. Mineral Filler.

In this study, limestone dust was utilized to prepare the asphalt-concrete mixture. The filler goes through the sieves opening (0.075 mm) and is obtained from the Karbala, Iraqi lime factory.

2.1.5. Ceramic Fibers.

In Iraq, the usage of ceramic fibers as asphalt concrete reinforcement is restricted. Ceramic fiber is considered one of the cheap fibers derived from commercial sources without looking for private items, with a high thermal insulation coefficient and high tensile strength. As a result, it was employed in this research to enhance the performance of the asphalt mixture and its resistance to moisture damage by three percent content (0.75%, 1.5%, and 2.25%) of the total weight of the asphalt mixture. The main properties for ceramic fibers' are presented in **Table 4 (Hussein et al., 2020).** The appearance of this fiber is shown in **Fig. 1**.

Table 4. Primary characteristics of ceramic fibers.

Average length (mm)	Average diameter (10^{-3} mm)	Density (kg/m^3)	Melting Point (°C)	Tensile strength (kPa)
3.0	4	130	1650	84

2.2. Designed aggregate gradation.

The aggregate and filler gradation were selected in guidelines with **(SCRB, 2003)** requirements, with a nominal maximum size of 12.5 millimeters (mm) (wearing course type IIIA). **Fig. 2** shows the gradation of selected aggregates.

Figure 1. The appearance of CF.

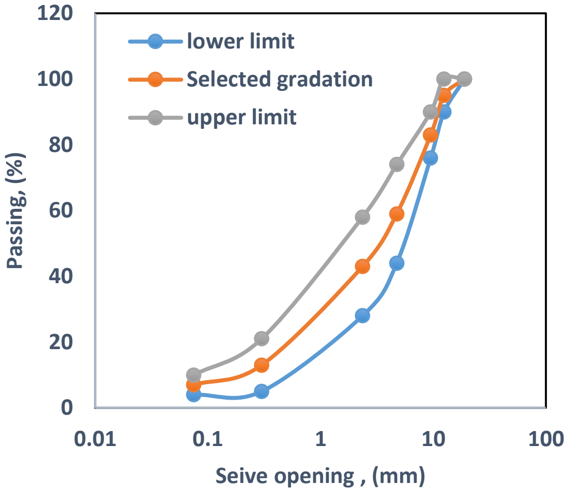


Figure 2. Design aggregate gradation.

2.3 Asphalt Mixture Test

2.3.1. Marshall test

According to (ASTM D2726-08), The OAC for conventional and modified asphalt mixes with five principal asphalt concentrations between 4 and 6 % (by the total weight of mixture) with an increase of 0.5% was determined by analyzing a series of Marshall tests (stability, density, and air voids). Three samples were made and evaluated utilizing aggregate in each mixture (12.5 mm nominal maximum size gradation). The average value (Max stability, Max bulk density, and 4% Air voids) was taken to accept the OAC for the wearing course layer. The Marshall test obtained the Marshall parameters using Marshall samples formed in a Marshall compactor under 75 blows per side, measuring 2.5 inches in height and 4 inches in diameter. These parameters included the optimal ratios of asphalt, bulk specific gravity, air void volume, aggregate mineral voids, Marshall stability, and flow value. This test was conducted in a water bath at 60 °C for 60 minutes using a loading rate of 50.8 mm/min. **Fig. 3** shows the procedure of the Marshall test.

2.3.2. Tensile Strength Ratio Test (TSR).

The TSR test involves preparing and analyzing samples of asphalt mixture to identify how moisture affects tensile strength. For further details, see ASTM D-4867, which provides a detailed explanation of this test. Using the correct number of blows (45, 55, 65, 75), the samples in this test had the number of strikes that resulted in 7±1% air voids.

(a) Preparing Mixture and Putting in Mold (b) Group of Samples Following Mold Extraction

(c) Specimens in Water Bath (d) Test Running

Figure 3. Marshall test procedure.

As illustrated in **Fig. 4**, 51 blows were applied to achieve this percentage. After calculating the number of blows, the Marshall samples were divided into six groups of two sets, each with three samples. The first set lasted 30 minutes in a water bath at 25 °C (unconditioned samples), then the ITS value was computed for each sample, and the average was obtained. To remove air, the second set was put in clean water under a vacuum at 25°C. After that, samples were frozen at 18 °C for 16 hours. To finish the thawing process, the samples were put in a water bath at 60 °C for 24 hours following the freezing phase (conditioned samples). These samples were placed in a separate water bath at 25 °C for an hour before the measured ITS. The ASTM D-6931-12 methodology is utilized for the ITS calculations. The loading device held the sample, and the loading strips were placed parallel to and in the center of the parallel diametric level. The loading strips' length has surpassed the specimen's thickness. A diametrical load of 50.8mm/min (2in/min) was applied until the specimens failed. **Fig. 5** shows the procedure of this test.

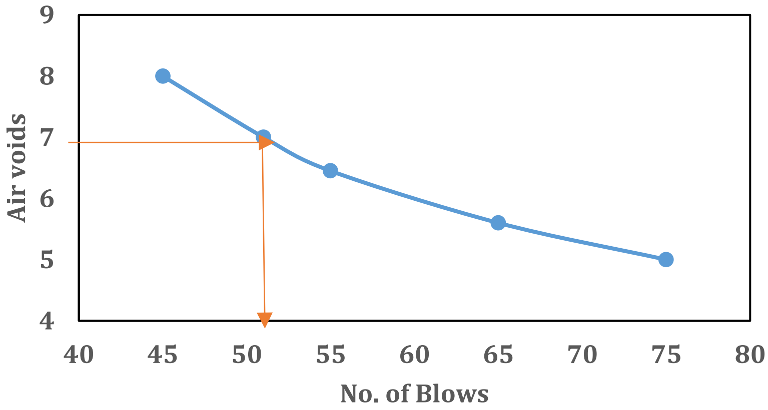
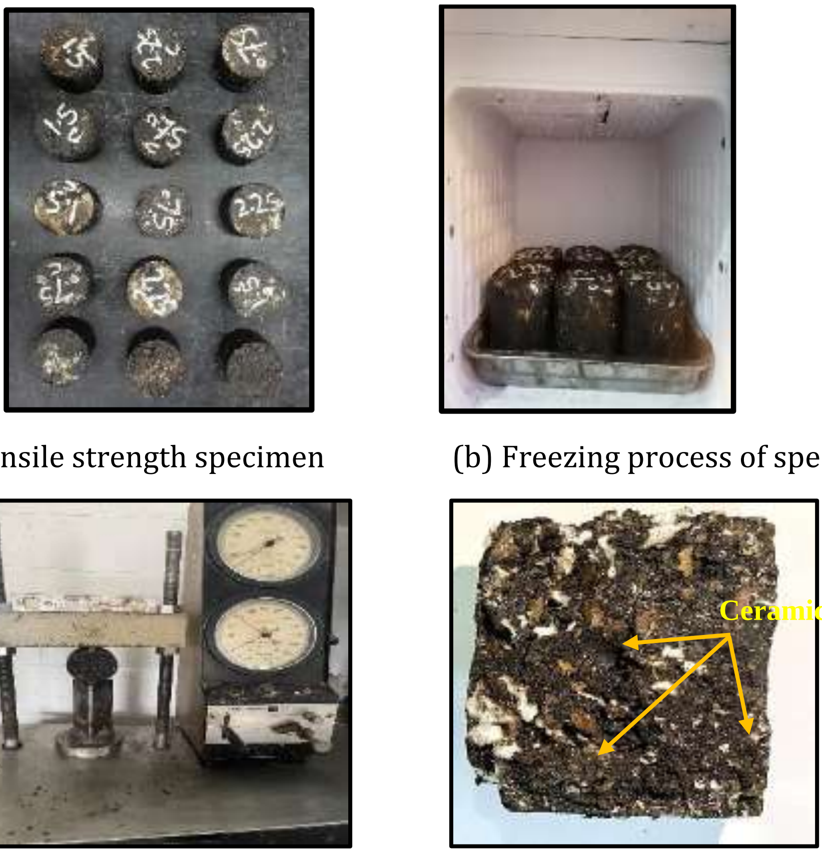


Figure 4. The relationship between the number of blows and the percentage of air voids.



(a) Indirect tensile strength specimen

(b) Freezing process of specimens.

(c) Test Running.

(d) Specimen after Test.

Figure 5. The Steps of TSR Test

2.3.3. Field Emission Scanning Electron Microscopy (FE-SEM)

A field-emission scanning electron microscope (FE-SEM) imaging process was used with small size segments collected from the asphalt's fractured surfaces mixture (with and without ceramic fiber). This test was done to investigate the ceramic fiber's microscopic structure, ensure that the fibers in the mixture were distributed well, and create a homogeneous mixture. The sample surface is put under electron radiation in a vacuum to provide an image of the surface or its portion distribution. In order to do this, cylindrical samples of ceramic fiber having a diameter of 50 mm and a thickness of 15 mm were immersed in liquid nitrogen to reach a brittle condition. The cylindrical sample was then broken apart from its center for scanning **(Arabani et al., 2019).**

3. Results and Discussion

3.1. Marshall Test Result.

As shown in **Fig. 6** for ceramic fibers, the stability increased by about (23.81, 39.04, and 17.14 %) for ceramic fiber content (0.75, 1.5, and 2.25 %), respectively. Adding ceramic fibers enhanced all of the asphalt concrete's properties, with the maximum increase in stability achieved at 1.5% of the total mixture's weight. This is probably because the ceramic fibers were evenly distributed throughout the mixture, building a three-dimensional network structure that firmly prevents any structure movement and is very resistant to shear displacement. Marshall stability first improved, then decreased. This result is expected as the amount of fiber has become relatively large due to its high density, leading to some weakening of the asphalt mixture. The cause for this is that the fibers may not be distributed uniformly throughout Marshall samples. The increased number of fibers in the mix results in low contact points between the aggregates and reduced stability since fibers cause clustering in the mixture, causing weakening the asphalt mixture and fracturing the three-dimensional network structure of CF.

Fig. 7 clearly shows the link between CF content and Marshall flow. Analyzing flow values showed that it reduced as fiber content increased. This indicates that when the fiber quantity was increased, the mixture's flexibility decreased because of the fibers' stiffness. However, flow levels between the necessary specification ranges of 2 to 4 mm were recorded.

Fig. 8 shows that the density decreased when CF content increased. The maximum decrease in bulk density occurred for ceramic fiber at 2.25%. With higher fiber and OAC concentrations, compressing the mixes becomes harder as bulk density values decrease. This means the mixture needs more compaction to reach a higher density because ceramic fibers have a much lower density than asphalt and aggregates.

As seen in **Fig. 9,** increasing the ceramic fiber content resulted in higher air void values. Due to the high elastic modulus of ceramic fibers, a rise in the air void values makes compressing the mixtures harder as the fiber content increases.

Fig. 10 shows that as the amount of fibers in the mixtures increased, the amount of voids filled with bitumen reduced because the fibers caused clustering in the mixture, preventing the asphalt from filling all the spaces. With less effective asphalt film thickness between aggregates due to the decline in VFA, the asphalt mixture will be less durable and break less often.

As shown in **Fig. 11,** the void in the mineral aggregate, which includes air voids and voids filled with effective asphalt, is calculated as a percentage of the total volume and places in the compressed asphalt mix between the aggregate increases with the increase of ceramic fiber content. This increase in VMA can be attributed to the decrease in bulk-specific gravity.

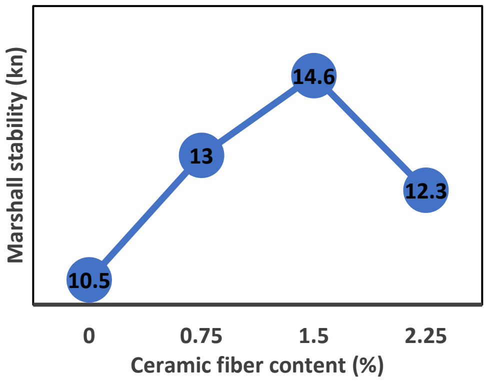


Figure 6. Effect of CF on Marshall Stability.

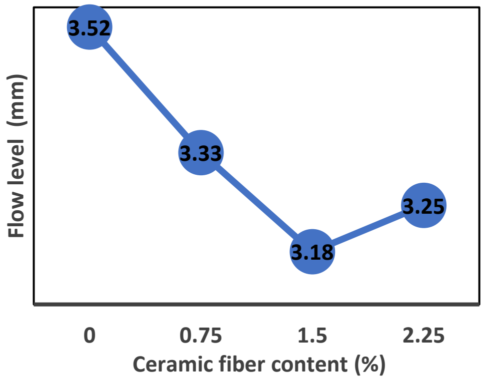


Figure 7. Effect of CF on Marshall Flow.

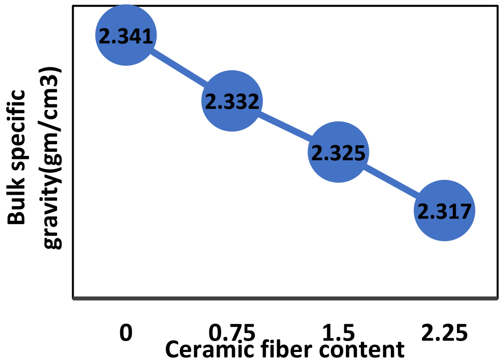


Figure 8. Effect of CF on Bulk Density.

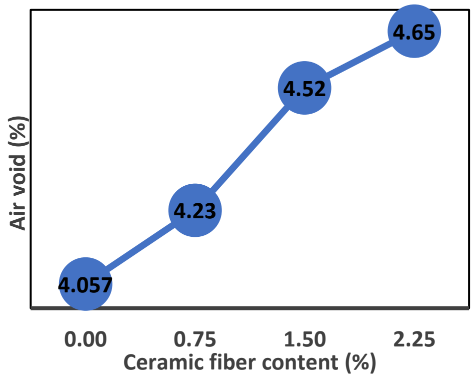


Figure 9. Effect of CF on Air Voids.

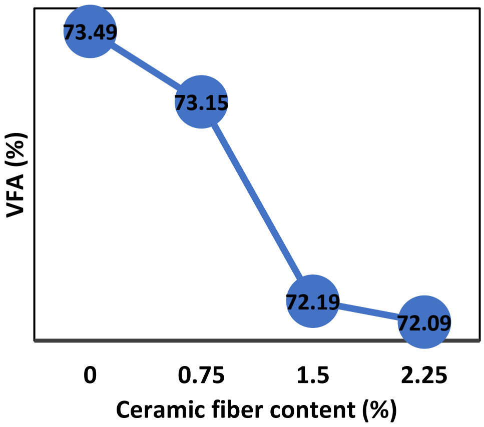


Figure 10. Effect of CF on VFA.

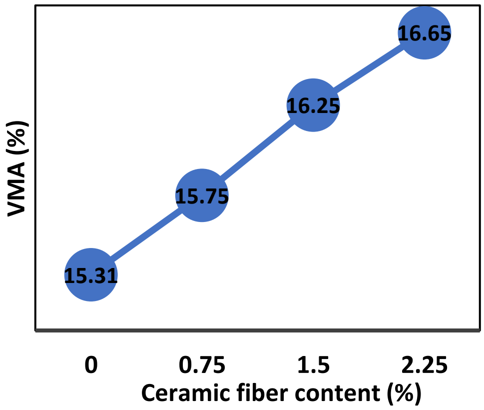


Figure 11. Effect of CF on VMA.

3.2 Indirect Tensile Strength Ratio Test Result (TSR)

The indirect tensile strength test was utilized in the asphalt mixture to determine the asphalt concrete's tensile characteristics and for the moisture susceptibility estimation. The asphalt mixture's susceptibility to moisture may be forecasted using the tensile strength ratio (TSR) test. The high values of the TSR reference the higher moisture resistance level in the asphalt mixes. This test showed the effect of CF in different percentages on the indirect tensile strength of the mixtures.

The asphalt mixes modified with ceramic fibers had greater dry ITS, wet ITS, and TSR values than the traditional mixtures. Due to the interlocking phenomena, which improves the strength of the mix when fibers are present, the networking of fibers and bitumen may be used to stop water from entering the mixture. It is essential for improving wet tensile strength because it makes the mixture more resilient to moisture damage. The tensile strength of the asphalt mixture is significantly impacted by using fibers with the right type and content. Due to the fibers' random orientation in different directions, which firmly connects, and increased rigidity of particles inside the matrix, the mixture was stiffer.

Additionally, CF absorption makes the asphalt binder viscous and improves the bond between the aggregate and asphalt. Consequently, increasing the asphalt mixture's water stability and reducing stripping by increasing the adhesive force between the asphalt and the aggregates is possible. This stops stripping caused by moisture. In dry and wet situations, the ITS increased due to the increased adhesive force.

The results show that using adjusted asphalt concrete mixtures with 0.75, 1.5, and 2.25% standard ceramic fibers increased the dry indirect tensile strength by 20.51, 28.17, and 12.82% compared to conventional asphalt mixtures. And using the same percentage of ceramic fibers, as shown in **Fig. 12,** increased the wet indirect tensile strength by (23.43%, 40.62%, and 12.5%). Furthermore, The TSR value grew by (3.71%, 11.06%, and 5.18%) for using reinforced asphalt mixture by (0.75%, 1.5%, and 2.25%) of ceramic, as shown in **Fig. 13.** The values of dry and wet indirect tensile and the TSR percent strength were higher for (1.5%) ceramic fibers than for (0.75, 2.25) % ceramic fibers content.

3.3. Field Emission Scanning Electron Microscopy (FE-SEM) Test Result.

Fig. 14 shows the micrographs of the structural composition of ceramic fibers. Through this test, the diameters of the fibers were measured and found to be approximately 4.5 µm. In addition, it pointed to the shapes of fiber, most of which are cylindrical, including spherical, and a few irregular shapes. It was also clarified how to distribute these fibers overlapping each other in a thorny way, forming a network of strong interconnected fibers. **Fig. 15 (a)** shows a high-resolution microscopic image of a sample of the asphalt mixture, with a width of a test slide equivalent to 2.5 mm, magnified thousands of times. This image shows the mixture's ingredients, including aggregates and asphalt-free from ceramic fibers. While the presence of ceramic fiber, shown in **Fig. 15 (b**), forms a denser layer of asphalt around the aggregate, it acts as a reinforcing link between the aggregate and asphalt. It strengthens the asphalt mixture by establishing a stable three-dimensional network that works to increase the cohesion of the aggregate with the asphalt and the adhesion between the aggregate grains with each other to prevent them from slipping easily. All of these modifications gave the asphalt mixture more strength to withstand the effects of moisture damage and generally made the mixture stiffer.

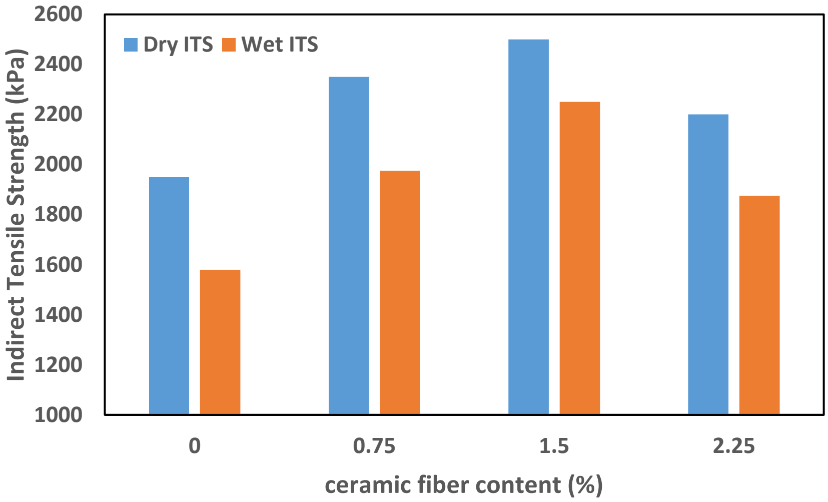


Figure **12.** The effect of ceramic fibers on Dry and Wet ITS.

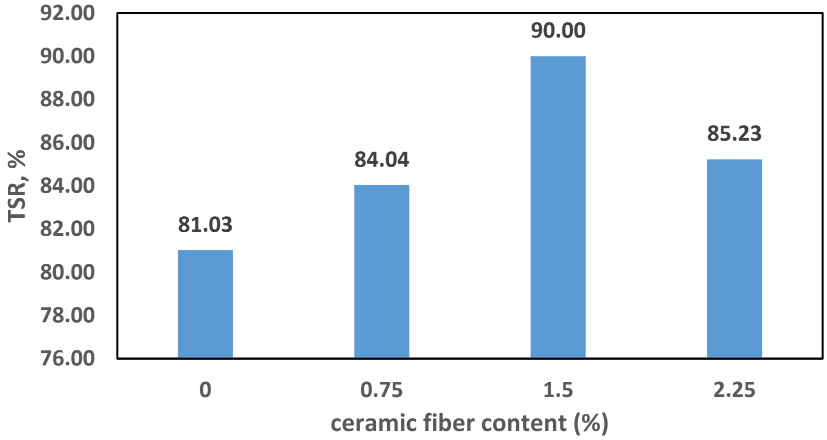


Figure 13. The effect of Ceramic Fibers Content on the TRS.

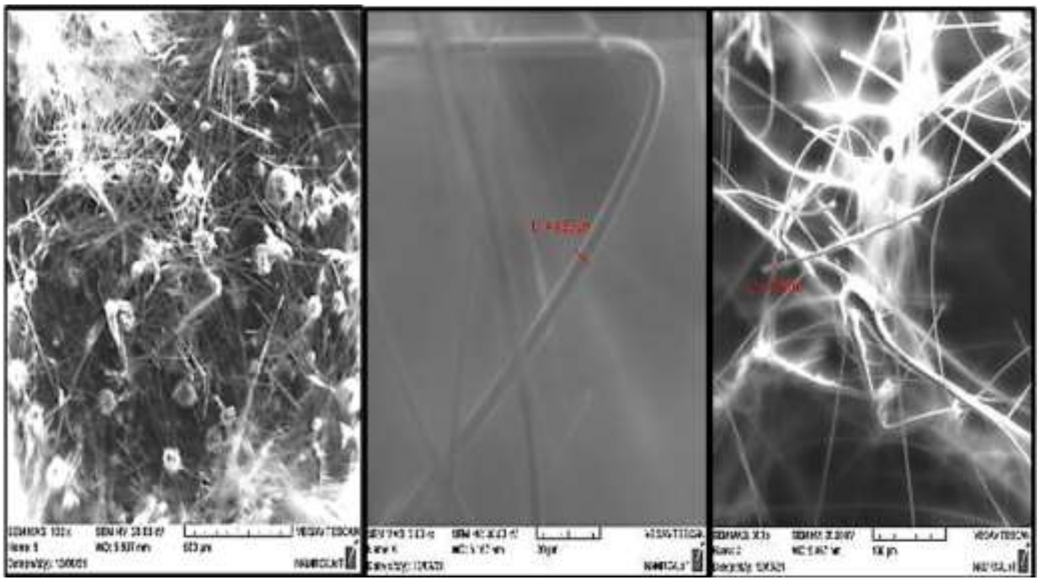


Figure 14. Some microscopic images of ceramic fibers.

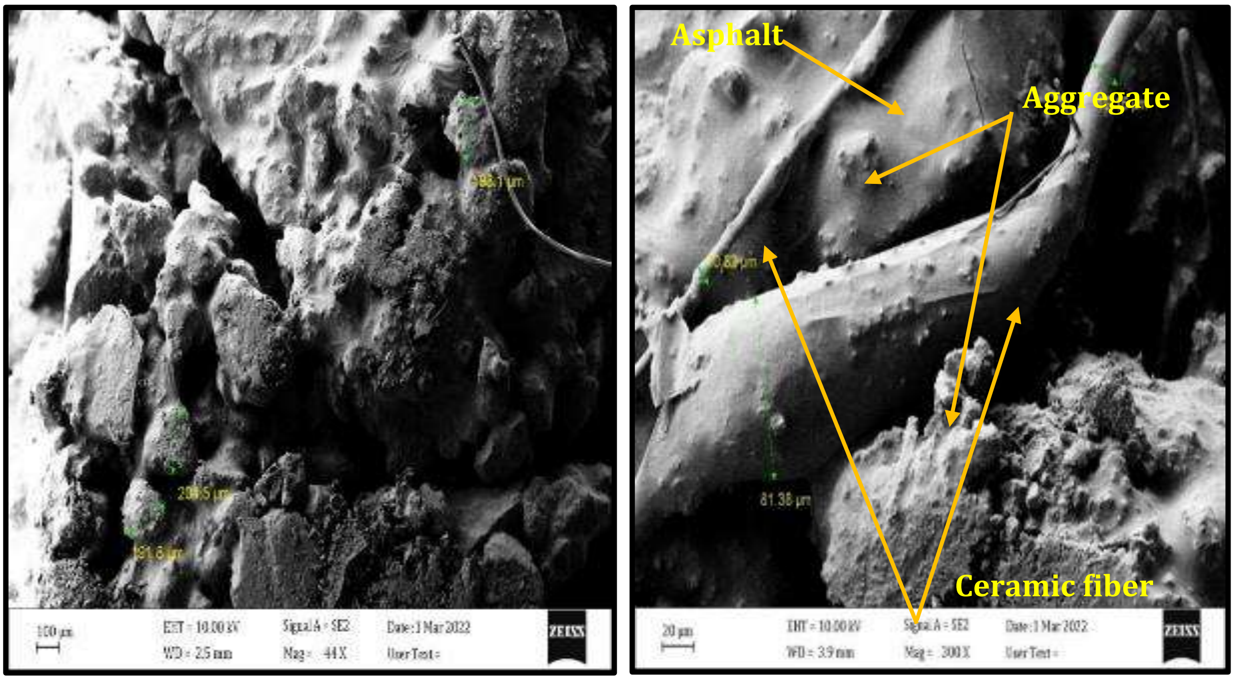


Figure 15. The network structure of the asphalt mixture in three dimensions, a) Without ceramic fiber, (b) Reinforced by ceramic fiber

4. CONCLUSIONS

Based on the limits of the materials and test procedures conducted in this study, the following conclusions are reached:
1. The results show that using (0.75%, 1.5%, and 2.25%) ceramic fiber increased dry indirect tensile strength by 23.07%, 28.21%, and 15.38% compared to conventional asphalt mixture. Wet indirect tensile strength increased by 36.07%, 50.31%, and 23.41% when using the same percent of ceramic fibers.
2. When (0.75%, 1.5%, and 2.25%) ceramic fiber was utilized, the TSR value increased by (10.55%, 17.24%, and 6.96%), respectively, in comparison to the control asphalt mixture.
3. At 1.5% ceramic fibers, stability increased, reaching a peak of 39.04%
4. The behavior of CF in the asphalt mixture enhances the shear displacement resistance and firmly restrains any movement of a structure which enhances the Marshall properties and moisture damage resistance
5. The SEM analysis demonstrated the ceramic fiber interference mechanism within the asphalt mixture to improve the bonding between the aggregate grains or between the aggregate and the asphalt, increasing the asphalt mixture's resistance to moisture degradation.

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