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Laboratory study on the asphalt mixture performance by nano-$CaCO_3$ and basalt fiber

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ABSTRACT

Due to rapid changes in weather conditions and increased traffic loads, asphalt pavements have become more susceptible to distress such as rutting, fatigue cracks, and potholes. Therefore, significant attention has been focused on improving the performance of these pavements through various modifications. The objectives of this study are to enhance the overall performance of the asphalt mixture and improve its ability to resist traffic loads at both low and high temperatures simultaneously by using double additives from basalt fiber and nano-$CaCO_3$. The study applied Marshall Stability, Wheel Track Test (WTT), Indirect Tensile Strength (ITS), and Marshall Immersion (MI) tests to assess the performance of the modified mixes. Additionally, the physical properties were examined using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) analysis. Four asphalt mixtures were tested: the first was a control asphalt mix (CAM) to determine the optimum bitumen content (OBC); the second was nano-$CaCO_3$ modified asphalt mix (NCAM) with 2 %, 4 %, 6 %, and 8 % of the bitumen weight; the third was basalt fiber modified asphalt mix (BFAM) with 0.25 %, 0.5 %, 0.75 %, and 1 % of the asphalt mix weight; and the fourth mixture contained 5.5 % bitumen and optimum ratios of nano-$CaCO_3$ and basalt fibers (NCBFAM). The results showed that the addition of 8 % nano-$CaCO_3$ led to significant improvements of 53.97 % in rutting resistance, 22.7 % in low temperature, and 12.5 % in durability (RMS) compared to the control mix (CAM). The addition of 0.5 % basalt fibers improved rutting resistance by 32.54 %, ITS by 7.62 %, and durability by 6.3 %. However, the combination of 8 % nano-$CaCO_3$ and 0.5 % basalt fibers (NCBFAM) resulted in the most substantial improvements, with increases of 46.83 % in rutting resistance, 18.94 % in low temperature, and 10.26 % in durability compared to the conventional mix. These findings demonstrate that the combined addition of nano-$CaCO_3$ and basalt fibers significantly enhances the Marshall properties, high and low temperature, and durability of the asphalt mix.

1. Introduction

Highway is one of the most vital means of transportation in any place, serving as the lifeline through providing roads that offer easy driving, optimal stability, and water resistance. The asphalt mixture was mainly composed of a mixture of heavy petroleum-based substances, mineral aggregate, and air voids.

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Although flexible pavement offers many benefits, such as flexibility, load-bearing capacity, and ease of maintenance, it also has several disadvantages that affect its performance and lifespan. Some of the most notable drawbacks that appear due to climate change and heavy traffic loads include cracking, moisture damage, thermal cracking, rutting, and shoving caused by pressure. In order to mitigate these disadvantages, improvements by adding modifiers, controlling material proportions, improving maintenance techniques, and ensuring construction quality are typically implemented.

There are several additives that enhance the performance of pavements. However, in recent decades, researchers have focused on fibers due to their ability to improve the asphalt mix and provide good performance. Initially, certain types of fiber were used to reduce cracking issues in pavements before the 1990s. However, after that, various other fibers were employed, such as polyester fibers [34], glass fibers [13], nylon fibers [18], carbon fibers [28], and Lignin Fiber [19,36] and others, to improve mechanical properties and extend the service life of asphalt. By 2015, the use of these fibers had expanded. Recently, basalt fibers have attracted significant attention from researchers due to their superior properties compared to other fibers of the same kind.

Researchers have been paying more and more attention to basalt fiber, a novel form of fiber that has emerged quickly in recent years. Using the spinneret process, basalt fiber is produced from natural basalt rocks [9]. First, the basalt rocks are melted at between 1450 and 1500 °C in a furnace. In order to make fiber, the molten material is then wiredrawn via a platinum-rhodium wiredrawing plate. The fibers are then promptly covered with an infiltration agent to prevent a brittle break. Because effluent, waste residue, and waste gas are not released during the production process, basalt fiber is considered environmentally benign [31].

Previous researches and studies have confirmed this, showing that asphalt mixtures reinforced with basalt fibers exhibit significantly better performance in terms of water stability, resistance to both low and high temperatures, and fatigue resistance [12,15,21,23,33,6].

According to ([8]; Li et a l. 2021), basalt fiber was considered one of the most commonly used mineral types in asphalt mixtures. It is much better than glass fibers and less expensive than carbon fiber. Also, [27] found that the use of basalt fibers in asphalt mixtures has a significant impact on Marshall's stability.

Through the conducted Marshall stability and wheel tracking tests, it was confirmed that the addition of basalt fiber significantly improves the high-temperature properties of asphalt mixtures. The inclusion of basalt fiber enhanced key performance indices such as rutting resistance and stability, suggesting that basalt fiber is an effective modifier for asphalt, particularly in regions prone to extreme temperature variations [15].

Another study conducted by [27] investigated the effect of basalt fibers on asphalt mixtures at various ratios (0–0.25–0.5–0.75–1.0–1.5–2.0 %) by weight of the asphalt mixture. The results indicated that increasing the basalt fiber content increases the Marshall stability strength up to 0.5 % with an optimum bitumen content of 5 %. "Furthermore, Fucheng [10] conducted a study on asphalt mixtures modified with 0.4 % basalt fiber content, and the results demonstrated a significant improvement in resistance to water damage.

Nanomaterials are considered recent additions that have gained significant attention in the field of asphalt technology, thanks to their properties such as good homogeneity, uniform distribution, and large surface area that interact effectively with asphalt particles [26]. The pavement sector has seen significant developments as a result of nanotechnology's rapid advancement in a number of civil engineering fields [32]. The use of various nanomaterials has significantly increased, such as nano-silica, Nano-titanium, Nano-carbon, Nano-fibers, Nano-clay, and Nano-zinc oxide, among others, according to research presented by both [16,20]. Recently, there has been increased focus on nano-$CaCO_3$ from researchers to improve asphalt properties. According to previous studies, nano-$CaCO_3$ is added to the asphalt binder in percentages from 0 % to 10 % to evaluate the performance of the modified mixture using nanoparticles. For example, [26] used percentages from 1 % to 7 %, while [14] used percentages from 0 % to 6 %. However, the percentages of calcium carbonate used from 2 % to 10 % according to [24]. The results indicated that with the increase in the nano-$CaCO_3$ ratios, creep resistance, flexural resistance, and moisture resistance increased according to [14]. Regarding the adhesion strength between the asphalt binder and the aggregate, [26] added nanoparticles to the asphalt mixture and conducted Marshall stability and adhesion strength tests, The results showed that addition of 5 % nano-$CaCO_3$ improved the Marshall stability, and enhanced the adhesion strength, which contributed to increased resistance of the mixture to deformations during the high summer temperatures in Iraq .

From the previous studies mentioned, nano-$CaCO_3$ has many properties, such as physical characteristics, increased surface area, reactivity, and increased asphalt viscosity. These properties make asphalt more resistant to permanent deformation and environmental impacts such as high temperatures and moisture, as well as its resistance to wear and aging. This has made it the focus of this research alongside the other material, basalt fiber.

Previous studies have indicated that using basalt fibers or nano-$CaCO_3$ as single additives to improve the performance of the asphalt mixture does not have the ability to enhance the overall performance of the mixture at the same time. Therefore, replacing single additives with double additives to potentially improve the overall performance of the asphalt mixture at low and high temperature.

So, in the current study, the goal is to use double additives from basalt fibers and nano-$CaCO_3$ to enhance the overall performance of the asphalt mixture and improve its ability to resist the traffic loads at low and high temperatures at the same time. The impact of adding both basalt fibers and nano-$CaCO_3$ on the properties of asphalt mixtures will be explored through conducting various tests for control and modified asphalt mixtures, such as WTT, ITS, RMS, SEM, and the EDEX test.

2. Materials and test methods

2.1. Raw materials

2.1.1. Aggregates

The aggregate selected in this study were coarse and fine aggregates of limestone, and it was obtained from the ATAKA quarry, Suze distinct, Egypt. Based on Fig. 1, the selected gradation of mix design (3B) wearing course surface. The main properties of aggregates were introduced in Table 1, according to Egyptian specifications. Crushed limestone was used as the powder filler, with an apparent specific gravity of 2.58.

2.1.2. Bitumen

The base asphalt with 60/70 was used in the experimental program, it was obtained from Suez Refinery, Egypt. Based on the Egyptian specifications, the physical indexes of virgin asphalt are summarized in Table 2.

2.1.3. Basalt fiber

Basalt fiber was fabricated from (basaltic rocks, especially those with a highly vesicular texture or scoria), which are subsequently processed into a continuous fiber at a temperature of (1450–1500) °C, and Obtained from the National Housing and Building Research Center in EGYT. Its mechanical characteristics are mentioned in Table 3. The length that was used is 6 mm, as shown in Fig. 2a.

2.1.4. Nano-$CaCO_3$

Nano-$CaCO_3$ is a white powder as shown in Fig. 2b, it was used as additive to modify the asphalt mixture. nano-$CaCO_3$ was manufactured by the National Housing and Building Research Center in EGYT. The mechanical and chemical properties of it were listed in Tables 4 and 5 respectively.

2.2. Methodology

2.2.1. Experimental plan

In the current study, the sequence diagram for conducting laboratory tests consist of four steps as listed in Fig. 3.

- Qualification tests were conducted on virgin aggregate and bitumen according to Egyptian specification in the first step. Then the mix degradation was selected (3B) wearing surface asphalt mix.
- The second step represented in preparation of control asphalt mix (CAM), according to the Egyptian code [35], five different percentages of asphalt binder (4 %, 4.5 %, 5 %, 5.5 %, and 6 %) were added and examined by Marshall Stability Test, determining OBC which would be constant in all specimens.
- The third step contained optimum content of basalt fibers and nano-$CaCO_3$ optimization separately, by conducting a Marshall stability test for basalt fibers modified asphalt mix (BFAM) with (0.25 %- 0.5 %- 0.75 % and 1.0 %) basalt fibers of asphalt mix weight and nano-$CaCO_3$ modified asphalt mix (NCAM) with (2 %-4 %- 6 %-8 % and 10 %) nano-$CaCO_3$ of bitumen weight. Then, preparation and examination in the Marshall Stability Test of a novel combined modified asphalt mix (BFNCAM) that contains

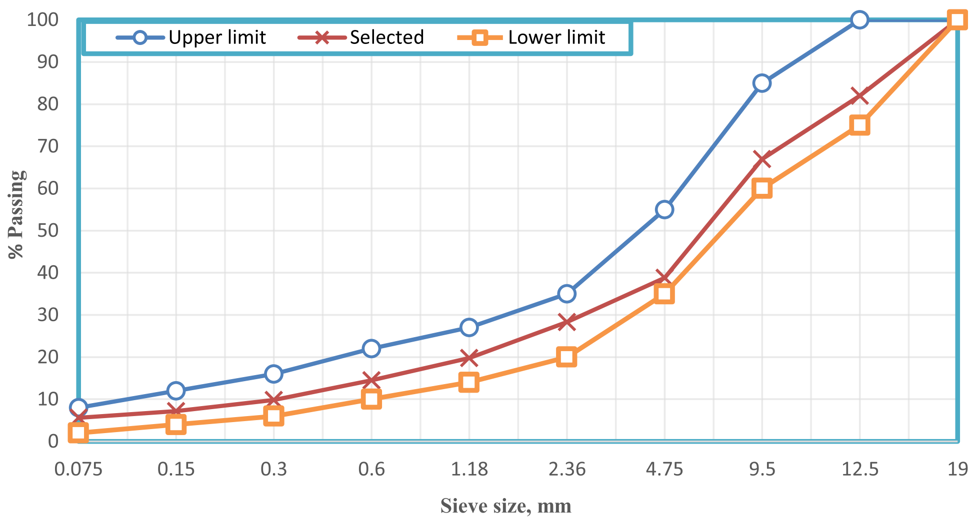

Fig. 1. Aggregate mix gradation curve for (3B) wearing surface.

Table 1
Physical properties of aggregate.

Test	Coarse Aggregate		Fine Aggregate	Designation No	Specification Limits
	Grade 1	Grade 2			
Los Angeles abrasion test	27.9 %	33.3 %	–	AASHTO-T96	≤ 40 %
Specific Gravity	2.624	2.622	2.531	AASHTO-T85	N/A
Apparent Specific Gravity	2.65	2.705	2.603	(For coarse aggregate)	N/A
Absorption %	1.4	2.04	1.4	AASHTO-T84 (For fine aggregate)	< 5 %

Table 2
Basic physical characteristics of the asphalt.

Characteristic	Standard Value	Measured Values	Spec. Limits
Penetration (at 25 °C, 5 sec.), 0.1 mm	ASTM-D5	62	60–70
Ductility (at 25 °C, 5 cm/min), cm	ASTM-D113	100	≥ 95
Softening Point (ring and ball), °C	ASTM-D36	45.4	45–55
Kinematic viscosity (at 135 °C), C.st	ASTM-D 4402	376	≥ 320
Flash point, °C	ASTM-D92	255	≥ 250
Density in 15 °C, g/cm3	ASTM-D 70	1.01	–

Table 3
Basic properties of basalt fiber.

Item	Sustained Operating Temperature	Melting Temperature	Fiber Diameter	Density	Tensile Strength	Elastic Modulus
Value	269 ~ 650 °C	1050 °C	7 ~ 15um	2.63 ~ 2.65 g/cm3	2000 ~ 3000 MPa	89 GPa

Fig. 2. View of (a) basalt fiber; (b) Nano-$CaCO_3$.

Table 4
Properties of nano-$CaCO_3$.

Item	Brightness	Specific Surface Area	Hardness	PH	Bulk Density	Melting point	Moisture Content
Value	96 %	2.7 g/cm2	3	9	0.45–0.95 g/cm3	800 ℃	0.2 %

Table 5
Chemical components of nano-$CaCO_3$.

Item	$CaCO_3$	Cao	MgO	Fe_2O_3	Al_2O_3	SiO_2	L.O.I
Value %	99.4	55.58	0.18	0.01	0.02	0.3	43.67

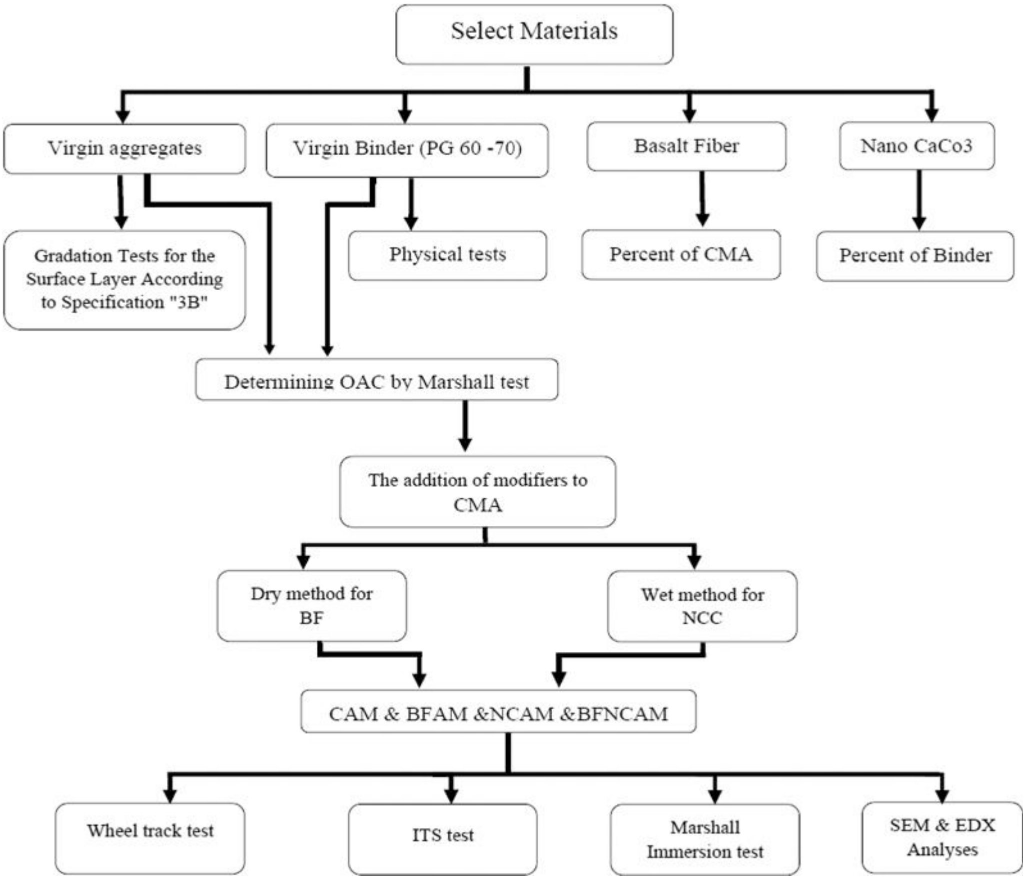

Fig. 3. Sequence diagram for conducting laboratory tests.

optimum content of basalt fiber and nano-$CaCO_3$ and a constant ratio of bitumen, which was previously determined in the second step.

- The final step before analysis and conclusion was applying several tests, such as Marshall Immersion, Indirect Tensile Strength, Wheel tracking tests, and SEM and EDX analysis.

2.2.2. Specimens preparation

There are different methods to prepare the asphalt mixes: dry method, wet method, and the third one contains wet and dry

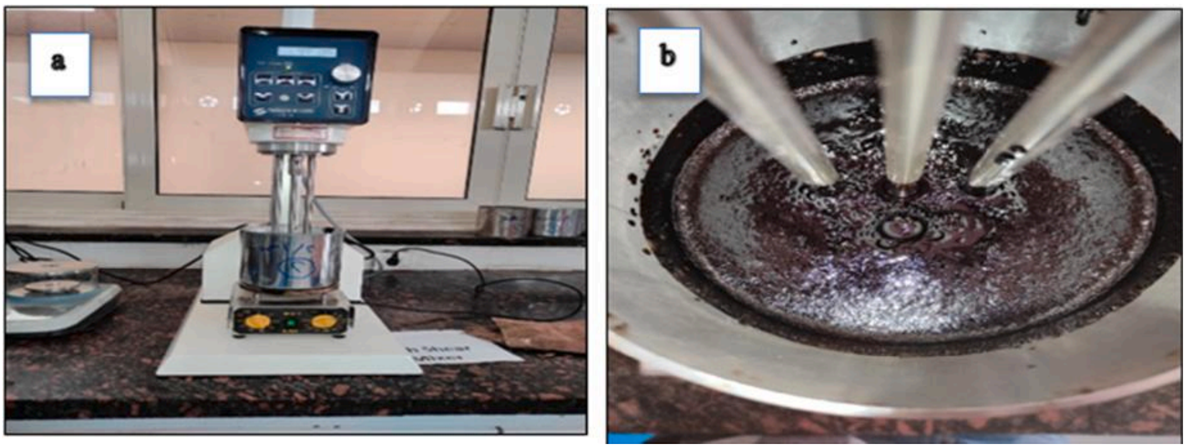

Fig. 4. Mixing of nano-$CaCO_3$ with bitumen in high shear mixer, (a) high sheer mixture; (b) asphalt binder after mixing with nano-$CaCO_3$.

methods. The control asphalt mixture (CAM), basalt fiber modified asphalt (BFAM), nano-$CaCO_3$ modified asphalt (NCAM), and combined basalt fiber and nano-$CaCO_3$ modified asphalt (BFNCAM) mixes were prepared as follows:

In control asphalt mixture CAM preparation, each of the aggregates and bitumen were heated to a temperature about 165 °C separately before mixing them for 90 s in an asphalt mixing pot.

The main issues or drawbacks associated with the use of basalt fibers is their ability to absorb moisture, which causes the fibers to clump together, reducing their dispersion in the asphalt and consequently affecting the durability of the mixture. The results showed that basalt fibers are less moisture-absorbent compared to other types of fibers [33]. The dry condition was used for adding basalt fiber. First, basalt fibers were mixed with the heated aggregates; the asphalt binder was added to the mixture after good distribution of fibers in the aggregate. The mixture was then mixed for 5 min in an asphalt mixer while the bowl was being heated. If the distribution is not deemed sufficient, the mixing period can be extended by an additional minute.

Another method of mixing was the wet condition; it's used to blend the nano-$CaCO_3$ with asphalt binder. Despite the advantages that nanomaterials offer to asphalt mixtures, they require a specific mixing approach due to the potential agglomeration that may occur during addition, which is one of the major drawbacks. The wet method is a preferred technique for blending nanomaterials with the binder to prevent or minimize agglomeration[30]. A mixer at a minimum rate of 4000 RPM was used for this purpose. Nano-particles are characterized by their large surface area, which necessitates sufficient mixing with the asphalt binder to ensure proper distribution of the nanoparticles and prevent agglomeration. This process is essential to achieve a homogeneous mixture of nano-CaCO3 with the asphalt binder. The chosen number of revolutions is based on previous studies conducted on the same type of asphalt binder with nano particles [3]. nano-$CaCO_3$ and bitumen were separately heated to 135 °C for 4 h, then they were mixed in the mixture for 60 min [3] as shown in Fig. 4. Finally, the mix of nano-$CaCO_3$ with asphalt binder was added to mix with the heated aggregates. Basalt fibers were added to the asphalt mixture by the direct method, while Nano-$CaCO_3$ was added to the asphalt mixture by the indirect method. Both direct and indirect methods were used in adding the modifier materials to the asphalt mixture.

2.3. Experimental procedures

In this research, the Marshall stability test was used to determine the optimum content of bitumen in the control asphalt mix, which represents the constant ratio in the modified mixes. After adding each of the basalt fibers and nano-$CaCO_3$ with selected proportions, the optimum ratio of them was determined based their impact on the Marshall stability of the asphalt mixture. Furthermore, several tests, including wheel tracking, indirect tensile strength, Marshall immersion tests, and SEM and EDX analyses, were performed to examine the effect of the optimum ratio of these additives on the performance of the asphalt mixture.

2.3.1. Marshall test

The main objective of Marshall testing was to determine the optimum asphalt content for all mixtures according to the control mixture by preparing three sets of samples with different asphalt content ratios according to AASHTO-T245 as shown in Fig. 5. The

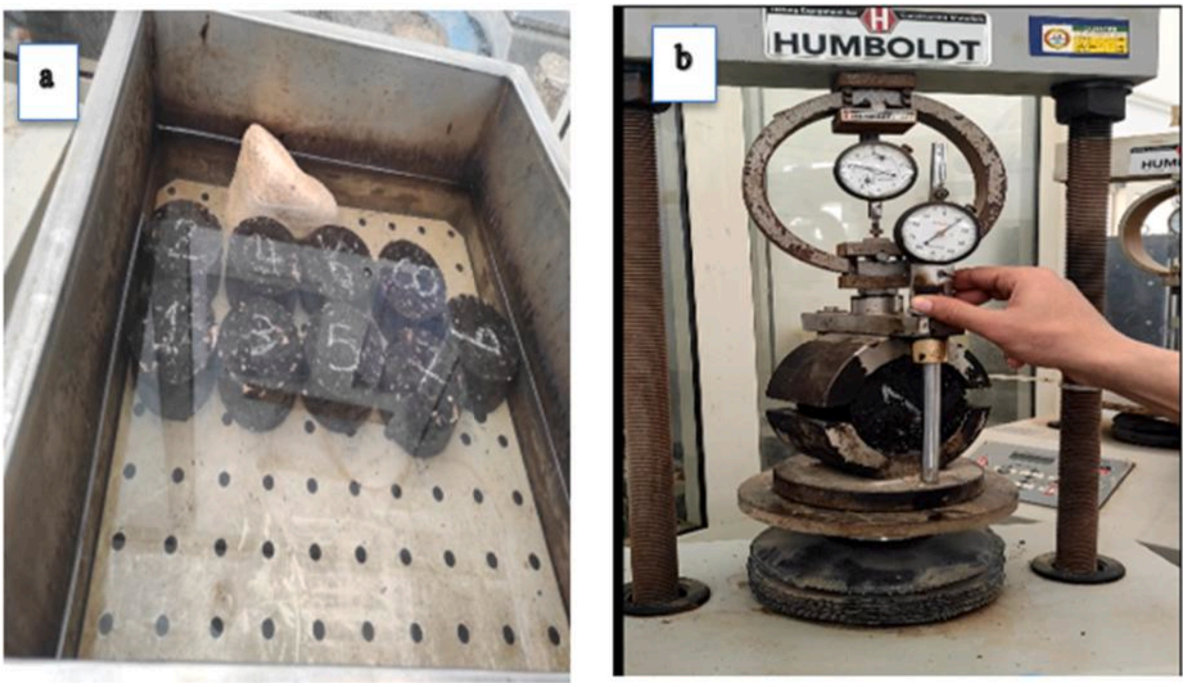

Fig. 5. Some stages of testing samples using the marshall method, (a) samples inside the water bath; (b) marshall apparatus.

dimensions of these specimens were 101.6 mm in diameter and 63 ± 0.5 mm in height. These ratios included 4 %, 4.5 %, 5 %, 5.5 %, and 6 % of asphalt content. Also, Marshall stability test was used to determine the optimal fiber content and the different percentages of nano-$CaCO_3$ in asphalt mixtures. According to the high-temperature rheological parameters, the optimal content of nano-CaCO3 composite was determined. The volumetric and mechanical properties of each sample were analyzed to determine the most efficient mix [29].

2.3.2. Wheel tracking test

The Wheel Tracking Test (WTT) is commonly used to evaluate the rutting resistance of asphalt pavement, specifically its ability to resist permanent deformations under high temperatures and concentrated moving loads. The test follows the procedure outlined in AASHTO T324–14, a standard by the American Association of State Highway and Transportation Officials ([1].

This test measures the rutting of HMA samples modified with nano-$CaCO_3$ and basalt fiber. The asphalt mixture's deformation was used to measure the rutting test [37].

The asphalt mixtures were compacted using the Superpave Gyratory Compactor to obtain the required percentage of air voids inside the cylindrical mold with a diameter of 150 mm and a height of 120 mm. Then, the mold was cut in half after 24 h, with each half having a height of 50 mm. After that, it was heated to 60 °C for at least five hours before the test as shown in Fig. 6.

2.3.3. Indirect tensile strength test

In this test, a direct tensile test is used to determine the tensile strength of asphalt mixtures at low temperatures. The test is conducted according to AASHTO T-283 [2], which specifies that the sample diameter should be 100 mm and the height 63.5 ± 2.5 mm, and that the samples should be placed at a temperature of −5 °C. The loading is applied in a strip and perpendicular to the surface of the sample at a rate of 1 mm/min, [7] as shown in Fig. 7.

Samples are prepared according to Section 2.2.2, with a minimum of three samples for each type of asphalt mixture. After preparation, the samples are tested under a load applied at a rate of 1 mm/min, and the average results for these samples are calculated to obtain the final tensile strength value for each mixture type [7].

2.3.4. Marshall immersion test

The Marshall immersion test was used to compute the residual Marshall stability ratio. The Marshall immersion test is regarded as one of the most popular techniques for assessing an asphalt mix's resistance to moisture susceptibility. The samples were prepared and tested according to the ASTM (D-1075). According to this test, the samples were divided into two groups, each group consisting of sixteen identical specimens with a diameter of 101.6 mm and varying heights, with eight specimens in each group. The first group (A) was heated to a temperature of 25 ± 1 °C by placing them in a temperature-controlled air bath for no less than 4 h. After that, measure the Marshall stability of the specimens according to the approved test method, while the second group (B) was immersed in water at a temperature of 60 ± 1 °C for 24 h according to [3]. After that, measure the Marshall stability of the specimens in accordance with the standards specified in Test Method [5]. The Marshall Stability test was performed on each group, and the residual Marshall Stability ratio (RMS) was calculated using the Eq. (1).

$$RMS = \frac{MS2}{MS1}x100 \tag{1}$$

Where RMS represents residual Marshall stability, MS1 is Marshall stability for group A (4 h and 60 °C), and MS2 is Marshall stability for group B (24 h and 60 °C).

2.3.5. Scanning electron microscope and energy dispersive X-rays

The electron microscope is an advanced device used to make highly detailed observations by magnifying particles or objects to sizes larger than those visible with a standard optical microscope. This type of microscope is used to analyze materials at the molecular level,

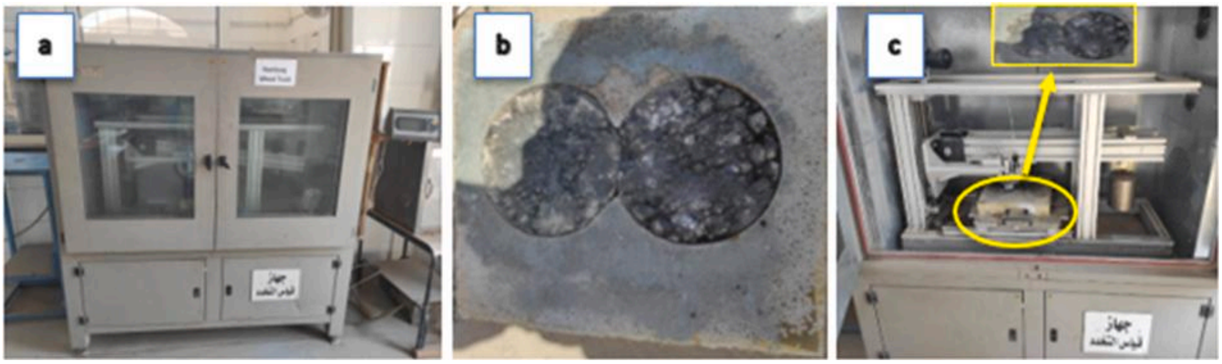

Fig. 6. (a) Wheel tracking test machine, (b) preparing the Mold;(c) placing the mold inside the device to apply the test.

Fig. 7. The device was used in ITS test, (a) gyratory compactor; (b) sample in freezer; (c) sample in ITS machine.

including asphalt materials and many other substances, allowing for the study of fine details that are essential for understanding the properties and structure of materials [25].

For the asphalt materials or asphalt mix to be analyzed using the Scanning Electron Microscope (SEM) and Energy Dispersive X-rays (EDX). SEM was used to examine the sample's morphology and clarify its fine components and how these materials are interrelated. As for the sample size used in the test, it does not exceed one centimeter, provided that this sample contains a mixture with all the components to ensure that these components are examined.

The large samples were cut into smaller pieces so that they could fit into the designated space inside the device, as shown in Fig. 8. There is no specific size requirement. After that, the device is operated and various magnification factors ranging from 500 to 5000 times are used to understand the microstructure and morphology of each mix individually.

EDX was produced when electrons are ejected from the sample's atomic shells [11]. The elemental composition of each blend was determined using EDX. Elemental analysis is performed at specific locations using an EDX detector after SEM images are acquired. Based on the collected energy spectra, the EDX system can ascertain the chemical composition of the materials and generate elemental composition charts.

3. Result and analysis

3.1. Marshall test

3.1.1. Marshall results for CAM

The OAC was calculated as the average of three asphalt content levels that achieved peak stability, maximum density, and a target air voids percentage (AV) of 4 %. Based on the test results, it was found that the optimal asphalt binder according to Egyptian code was 5.5 %. The results of the Marshall tests for each mix are summarized in Table 6. These results are consistent with the specifications of the Egyptian code and [4,8].

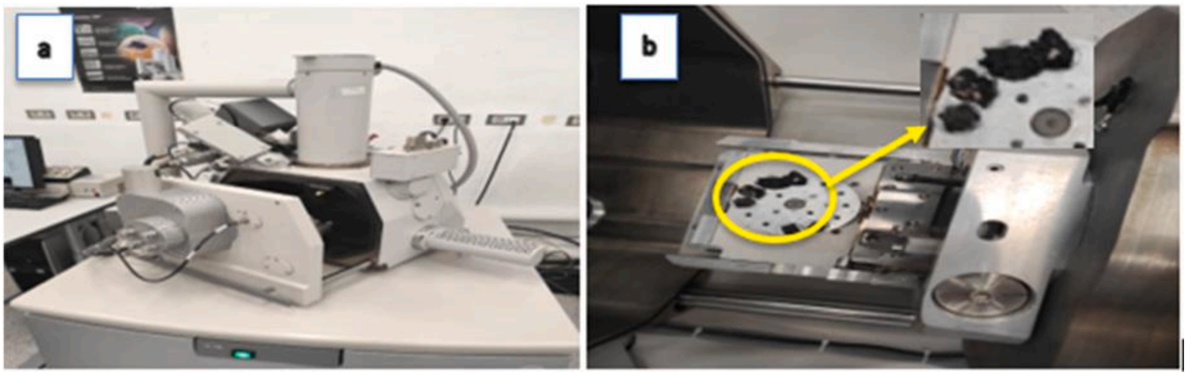

Fig. 8. Sample preparation for SEM testing; (a) SEM device; (b) placing samples inside the device.

Table 6
The results of marshall method for CAM.

Mix type	OAC%	Stability (Kg)	Flow (mm)	VA%	Density (g/cm3)
CAM	4.0	1351.02	2.75	10.42	2.27
	4.5	1429.45	2.63	7.53	2.33
	5.0	1636.06	3.50	5.93	2.35
	5.5	1475.83	2.91	4.87	2.36
	6.0	1425.24	2.95	3.69	2.37
Standard Value	–	> 1100	2–4	3–5	–

3.1.2. Marshall results for BFAM

The Marshall test results with different percentages of basalt fibers were added present in Table 7. The 0.5 % of basalt fibers is considered optimal, as it has shown considerable effectiveness in enhancing both the stability and flexibility of asphalt mixtures, as per the Marshall method characteristics. This proportion significantly improves the asphalt's stability. This aligns with previous studies [15].

Basalt fibers enhanced the bonding strength between the asphalt binder and the aggregates, also function as a network to bind the components of the mix together. The percentage of air voids decreased according to adding basalt fiber compared to the traditional mix, due to the asphalt binder adhering well to both sides of the well-dispersed basalt fibers in the mix, which reduces voids in the asphalt mixture. The fibers also help reduce the flow of the mix, as basalt fibers minimizes the movement of aggregates during loading due to the network it forms.

3.1.3. Marshall results for NCAM

Alternatively, the Marshall test was carried out on the asphalt mixture modified with various percent of nano-$CaCO_3$. Based on the rheological properties of asphalt at high temperatures, it was found that the optimal percentage of nano-$CaCO_3$ carbonate that improves the stability and flexibility of asphalt is 8 %.The results showed that the Marshall stability was increased with an increase in the percentage of NCAM at 8 % by 35.94 % compared with CAM, where nano-$CaCO_3$ enhances the bonding resistance between the asphalt binder and the aggregates because the nanomaterials improve the physical and chemical interactions, thereby reducing the permanent deformation of the NCAM, The large surface area of the nanomaterial inhibits the exudation of lighter fractions of the asphalt binder, as these fractions are absorbed by the surface of the nanomaterial [24], Thus, the percentage of air voids and flow decreased with the addition of the same percentage of nano-$CaCO_3$ according to CAM, as shown in Table 8. Then, according to the Egyptian specifications for asphalt mixtures, it was found that using 5.5 % bitumen with 8 % nano-$CaCO_3$ provides the best performance for the mixture compared to other percent of nano-$CaCO_3$.

3.1.4. Marshall results for BFNCAM

As for the addition of a mixtures of basalt fiber and nano-$CaCO_3$ to the asphalt mix, the authors found that adding basalt fiber with nano-$CaCO_3$ improved the Marshall stability, air voids, flow, and density according to the CAM as shown in (Figs.9 to 12).

Considering the Marshall stability, it is evident that the addition of nano-$CaCO_3$ to the asphalt mixture, the Marshall stability increased by 36 % and the flow resistance values decreased by 6.6 % as shown in Fig. 9. Consequently, basalt fibers were added to enhance flow resistance; adding basalt fibers at a rate of 0.5 % of the sample weight improved the flow resistance of the asphalt mixture by 4.16 % according to the CAM, as illustrated in Fig. 11. Therefore, the addition of double additives enhances the performance of the asphalt mixture compared to adding a single additive.

The results are evident that the addition of a double additive of improved materials to the asphalt mixture resulted in an improvement in Marshall stability, flow, air voids, and density, although to a lesser extent compared to the mixture containing only nano-$CaCO_3$. Nano-calcium carbonate enhances the physical and chemical properties of the asphalt binder, thereby increasing the bonding strength between the aggregates and the binder. Basalt fibers, on the other hand, function as a network to bind these components together, but they also increase the air void content. However, the surface area of the nano-$CaCO_3$ helps to reduce these voids, leading to an increase in Marshall stability, flow, air voids, and density for the mixture compared to the one containing only nano-$CaCO_3$ carbonate.

Table 7
The results of marshall method for CAM& BFAM.

Mix Type	AC%	BF%	Stability (Kg)	Flow (mm)	VA%	Density (g/cm3)
CAM	5.5	–	1475.83	2.87	4.87	2.36
BFAM		0.25	1614.98	2.87	4.78	2.35
		0.5	1657.15	2.89	4.50	2.35
		0.75	1542.29	3	5.88	2.32
		1.0	1511.67	3.375	7.57	2.28
Standard Value	–	–	> 1100	2–4	3–5	–

Table 8
The results of marshall method for CAM& NCAM.

Mix Type	AC%	NCC %	Stability (Kg)	Flow (mm)	VA%	Density (g/cm^3)
CAM	5.5	–	1475.83	2.87	4.87	2.36
NCAM		2	1620.21	2.80	7.42	2.37
		4	1670.52	2.81	6.57	2.38
		6	1709.85	2.75	4.68	2.38
		8	2006.28	2.73	3.54	2.39
		10	2001.48	2.71	3.11	2.4
Standard Value	–	–	$\geq$ 1100	2–4	3–5	–

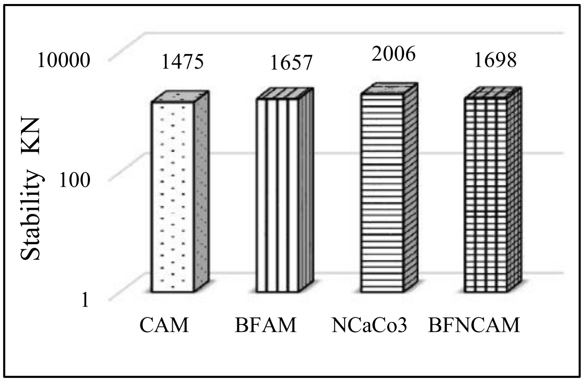

Fig. 9. Stability results for BFNCAM.

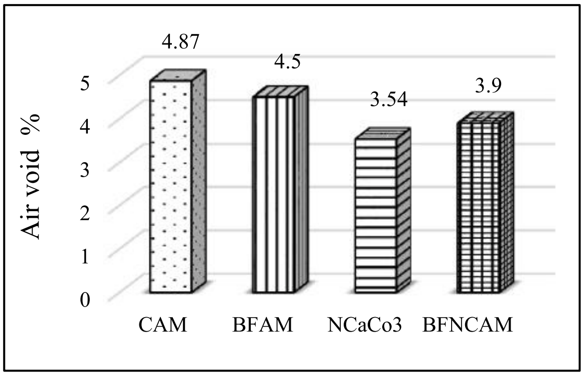

Fig. 10. Air voids results for BFNCAM.

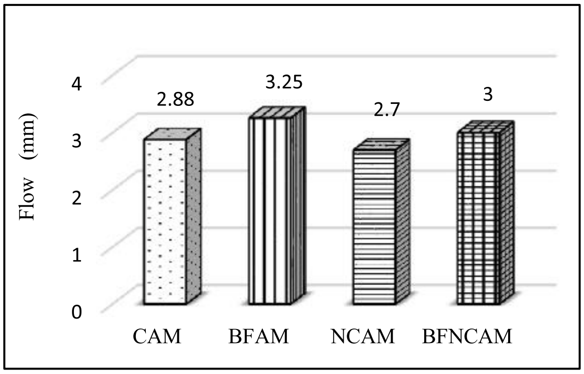

Fig. 11. Flow results of BFAM.

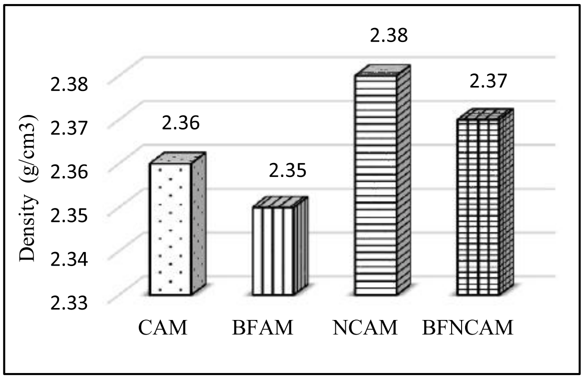

Fig. 12. Density of BFAM.

3.1.5. Wheel tracking results

The Wheel Tracking Test (WTT) was used to determine how well the Nano-$CaCO_3$ and basalt fiber modified Hot Mix Asphalt (HMA) samples performed at high temperatures. The percentage of fiber basalt and nano-$CaCO_3$ that are utilized is 0.5 % and 8 %, respectively.

The rutting values obtained from the Wheel tracking test as shown in Fig. 13, indicating that adding 8 % nano-$CaCO_3$ resulted in a 53.97 % reduction in rutting values compared to the control mix. Samples containing 0.5 % basalt fibers showed a reduction of 32.54 % in rutting compared to the control mix, while samples with a combination of nano-$CaCO_3$ and basalt fibers saw a 46.83 % reduction in rutting.

This improvement is attributed to the high surface area of nano-$CaCO_3$, which enhances bitumen particles and increases their strength, leading to higher bitumen viscosity and improved adhesion with aggregates, thereby reducing rut depth [29]. On the other hand, basalt is only beneficial as an additive in limited amounts; excessive addition yields negative results. Increasing the quantity of basalt fibers gradually expands the distance between bitumen particles, weakening the bond strength between them, causing cohesion and adhesion between particles to break at minimal force, thus diminishing bitumen's adhesion capability [33]. The reason for this can be attributed to the differences in properties between nano-$CaCO_3$ and basalt fibers. nano-$CaCO_3$ has a large surface area, allowing it to disperse effectively with the asphalt binder, which enhances its adhesion to the binder and improves its resistance to rutting. On the other hand, although basalt fibers have strength and flexibility, they do not interact as effectively as nanoparticles due to the nature of the fibers. Additionally, it is more difficult to achieve a homogeneous distribution of basalt fibers within the mixture, unlike nano--$CaCO_3$. As a result, basalt fibers have a lesser effect on improving the rheological properties of the mixture when added with nano-$CaCO_3$ in the same mix.

3.1.6. Indirect tensile strength results

The average results of the indirect tensile strength test for each mixture. When adding basalt fibers at a rate of 0.5 % of the sample

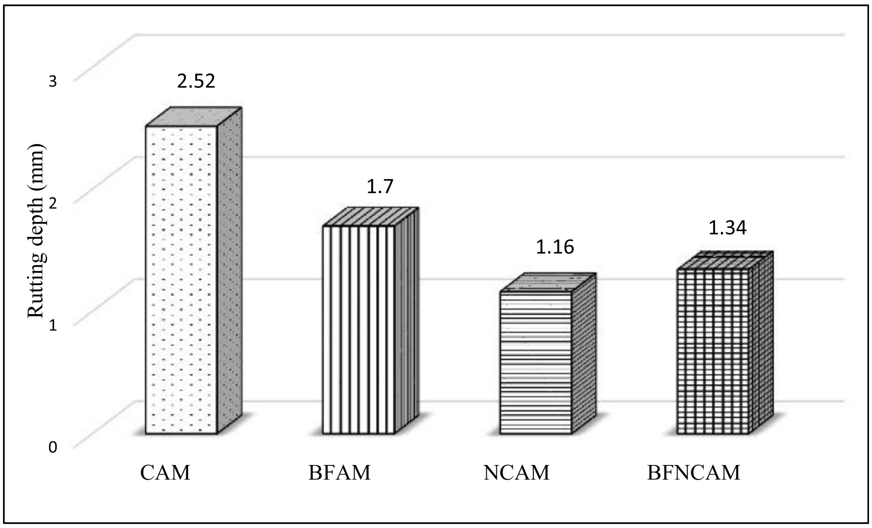

Fig. 13. Rutting depth for modified asphalt mixtures.

weight and nano-$CaCO_3$ at a rate of 8 %, the indirect tensile strength improved by 22.70 % and 7.62 %, respectively, compared to the traditional mixture as shown in Fig. 14. The indirect tensile strength is observed when both basalt fibers and nano-$CaCO_3$ are added to the asphalt mixture modified at low temperatures. Comparing the indirect tensile strength value of the modified mixture containing both nano-$CaCO_3$ and basalt fibers to that of the control mixture, it is evident that the modified mixture outperforms the control mixture by 18.94 %. This result aligns with previous studies on both nano-$CaCO_3$ and fibers. Davar et al., [7].

Basalt fibers enhance the mixture by binding the aggregate particles with the asphalt binder, thereby reducing the expected cracks up to a certain load. As a result, the failure of the specimen requires higher energy, which also aligns with Research [17]. While, nano-$CaCO_3$ has a larger surface area, which enhances its ability to absorb asphalt and contributes to its stability within voids. Consequently, this leads to increased adhesion strength between aggregate particles. Moreover, nano-$CaCO_3$ also increase the viscosity of the asphalt binder, improving the resistance to cracking and failure of the specimen [24].

The combination of basalt fibers and calcium carbonate significantly improved the indirect tensile strength compared to adding each of them separately to the mixture.

3.1.7. Immersion–compression results

The Marshall immersion test is one of the tests that assess the moisture susceptibility of the mixture by calculating RMS. Fig. 15 presents the test results, which reveal improvements in the values of RMS under both dry and wet conditions with the addition nano-$CaCO_3$ or, basalt fiber or a combination of both, the increase in RMS was observed to be 12.5 %, 6.3 %, and 10.26 % respectively.

Nano-$CaCO_3$ increases the density of the asphalt mixture, thereby reducing internal gaps and the connected pores between the aggregate and the asphalt binder. This leads to improved water stability and decreased permeability of the asphalt concrete [38].

Additionally, Fiber addition improving adhesion between the asphalt and aggregate and decreasing water erosion, which is responsible for these improvements. Furthermore, the mixture becomes stronger due to the fibrous network that forms within it.[22].

The results indicate that nano-$CaCO_3$ is the best in moisture resistance. However, when a composite of basalt fiber and nano-$CaCO_3$ is added, the basalt enhances the adhesion strength between the aggregate and the binder, but it slightly increases the voids compared to the mixture that contains only nano-$CaCO_3$. Basalt also plays a significant role in improving the asphalt mixture's resistance to low temperatures. Therefore, a mixture of nano-$CaCO_3$ and basalt fiber greatly contributes to improving the properties of the asphalt mixture.

3.1.8. SEM and EDX results

the results of the EDX test, indicating that calcium is the main component in all asphalt mixtures due to the use of limestone in all mixtures as shown in Fig. 16. For the asphalt mixture containing basalt fibers, the second most abundant element after calcium is sulfur. Sulfur plays an important role in enhancing the performance of the mixture at high temperatures, as evidenced by the rutting test, where basalt fibers improved the mixture's resistance to rutting compared to the conventional mixture. Sulfur also contributes to moisture resistance, which is demonstrated in the Marshall immersion test.

For the mixture containing nano-$CaCO_3$, the primary components after calcium are carbon and silicon. Carbon helps improve the asphalt mixture's properties at both high and low temperatures, as demonstrated in the rutting test and the Indirect Tensile Strength test, respectively.

As for the mixture containing basalt fibers and nano-$CaCO_3$, the main component in the mixture is sulfur, followed by calcium. This indicates that this mixture performs better at both high and low temperatures, as well as in moisture resistance, as demonstrated in the previous tests.

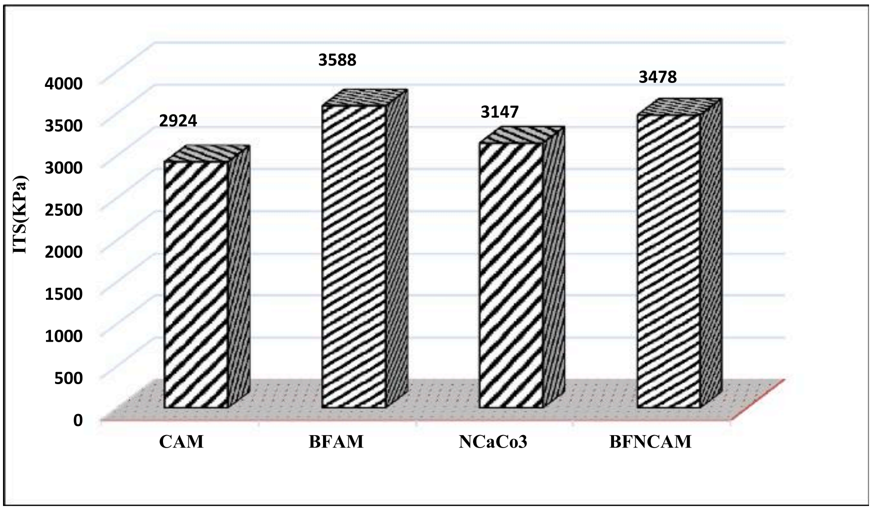

Fig. 14. Indirect tensile strength result.

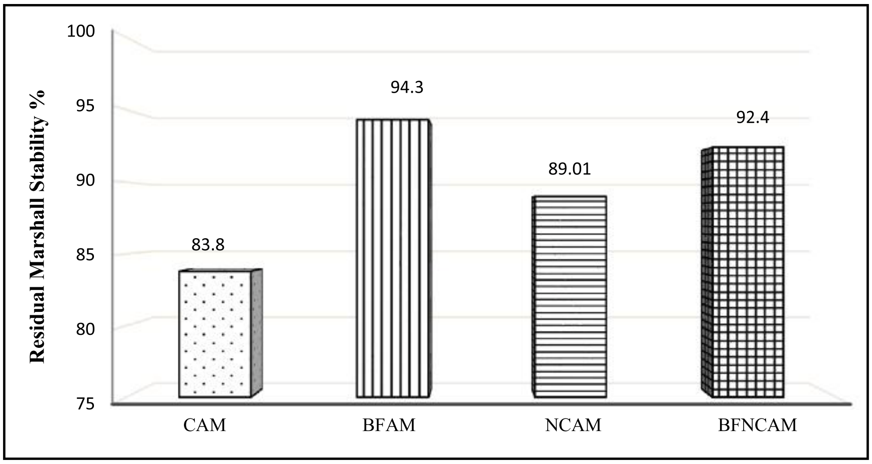

Fig. 15. The residual marshall stability.

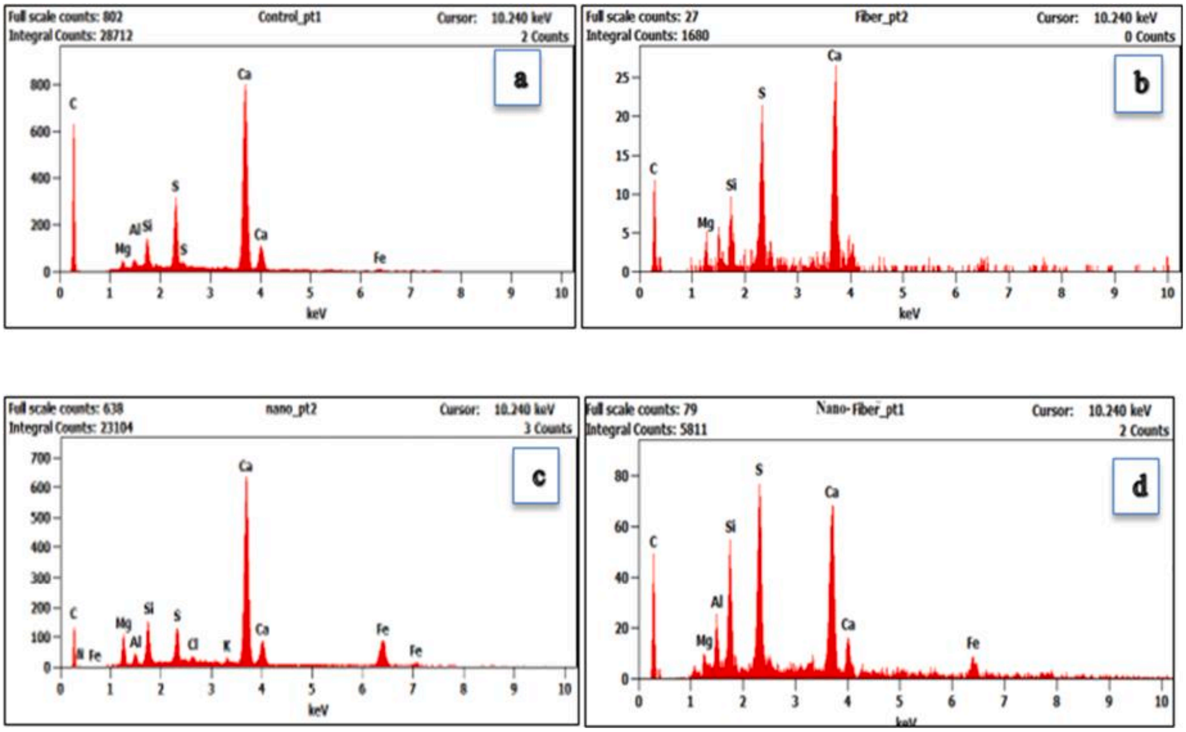

Fig. 16. EDX results for (a)CAM (b) BFAM (c)NCAM (d) BFNCAM.

As for the SEM test, Fig. 17 shows that the asphalt binder encapsulates the basalt fibers, and it also indicates a reduction in the air voids in the asphalt mixture containing nano-$CaCO_3$.

4. Conclusions and recommendations

The primary objective of this research is to determine the mechanical properties of conventional asphalt mixtures and those modified with basalt fiber and nano-$CaCO_3$. Specification number (AASHTO-T245) was used to prepare all the samples. After preparation, tests for wheel track test (WTT), indirect tensile strength test (ITS), and Marshall Immersion Test were conducted to compare the modified asphalt mixture with the conventional asphalt mixture. These tests were performed at both high and low temperatures, as well as for moisture resistance.

According to the tests results of this study, the following can be summarized:

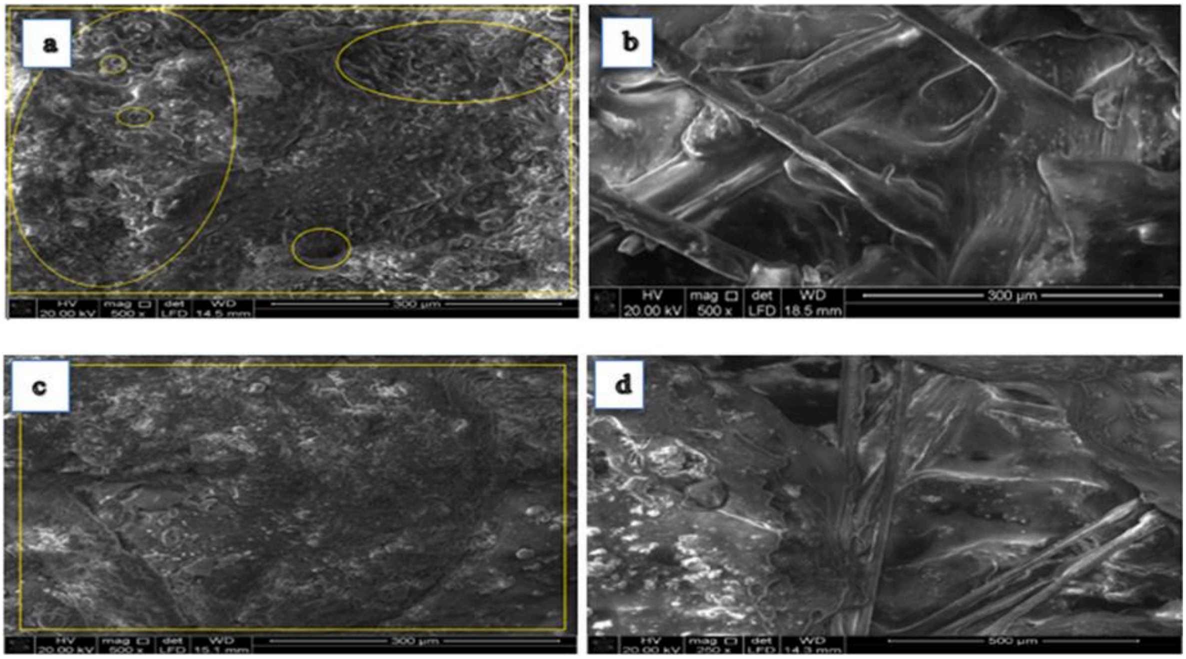

Fig. 17. The SEM for asphalt mixture; (a) CAM, (b) BFAM, (c) NCAM, (d) NCC with BA.

- The results show that the indirect tensile strength of the asphalt mixture modified with 0.5 % basalt fiber increased by 22.70 %, while the rutting resistance increased by 48.23 %, and moisture resistance improved by 6.3 %, compared to the conventional mixture. Therefore, it can be concluded that basalt fiber enhances the performance of the asphalt mixture at low temperatures according to anther additives.
- the results of the asphalt mixture modified with 8 % nano-$CaCO_3$, it is evident that the rutting resistance of the mixture increased by 53.96 %, while the indirect tensile strength increased by 7.62 %, and moisture resistance improved by 12.5 %. This indicates that the asphalt mixture modified with nano-$CaCO_3$ enhances the performance of the asphalt mix at high temperatures compared to basalt fiber.
- When both basalt fibers at a rate of 0.5 % and nano-$CaCO_3$ at a rate of 8 % are added, the rutting resistance, indirect tensile strength, and moisture resistance of the asphalt mixture increased by 20 %, 30 %, and 40 %, respectively. This clearly indicates that the asphalt mixture containing a dual addition of basalt fibers and nano-$CaCO_3$ performs better at both high and low temperatures compared to the conventional mixture, or the mixture containing only basalt fibers or only nano-$CaCO_3$. This is because each of the additives improves performance either at high temperatures or low temperatures, but not both.

In summary, one can have said that the double-adding technology into asphalt mixtures demonstrated a greater ability to improve the all over performance and lifespan of the road pavement in comparison with single additives.

Finally, the authors recommend conducting additional tests, including creep and three-point bending tests, to evaluate the cracking behavior when using these additives at different temperatures. Also, explore how these modified asphalt mixtures can be incorporated into recycling processes. It is also recommended to explore the impact of these additives on the sustainability and recyclability of asphalt mixtures. Additionally, a theoretical analysis should be performed using a finite element program (Abaqus) to understand the material behavior and its performance under various loading and environmental conditions.

CRediT authorship contribution statement

Ahmed Gamal: Writing – review & editing. **Moustafa Abdelsalam:** Writing – review & editing. **Ahmed Hassan:** Writing – review & editing. **Mohamed Samir Eisa:** Writing – review & editing.

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.

Data availability

Data will be made available on request.

References

1 (AASHTO), Standard method of test for hamburg wheel-track testing of compacted hot mix asphalt (HMA), Am. Assoc. State Highw. Transp. Off. T 324 (11) (2013) 1–10 (withdrawn).
2 AASHTO, AASHTO t 283 standard method of test for resistance of compacted asphalt mixtures to Moisture-Induced damage, 2021, in: American Association of State Highway and Transportation Officials, 14, 2021.
3 Talaat Abdel-Wahed, Ashraf Abdel-Raheem, Ghada S. Moussa, Performance evaluation of porous asphalt mixtures modified with basalt fiber, Rev. De. La Construccion 21 (1) (2022) 93–104, https://doi.org/10.7764/RDLC.21.1.93.
4 Amjad H. Albayati, Aliaa F. Al-Ani, Juliana Byzyka, Mazen Al-Kheetan, Mujib Rahman, Enhancing asphalt performance and its long-term sustainability with nano calcium carbonate and nano hydrated lime, Sustainability 16 (4) (2024), https://doi.org/10.3390/su16041507.
5 ASTM D1075, Standard test method for effect of water on compressive strength of compacted bituminous mixtures, Am. Soc. Test. Mater. (2007) 1074–1075.
6 Pengjian Cheng, Junyan Yi, Shaohua Guo, Zhongshi Pei, Decheng Feng, Influence of fiber dispersion and distribution on flexural tensile properties of asphalt mixture based on finite element simulation, Constr. Build. Mater. 352 (April) (2022) 128939, https://doi.org/10.1016/j.conbuildmat.2022.128939.
7 Arash Davar, Javad Tanzadeh, Omid Fadaee, Experimental evaluation of the basalt fibers and diatomite powder compound on enhanced fatigue life and tensile strength of hot mix asphalt at low temperatures, Constr. Build. Mater. 153 (2017) 238–246, https://doi.org/10.1016/j.conbuildmat.2017.06.175.
8 Arash Davar, Javad Tanzadeh, Omid Fadaee, Experimental evaluation of the basalt fibers and diatomite powder compound on enhanced fatigue life and tensile strength of hot mix asphalt at low temperatures, Constr. Build. Mater. 153 (2017) 238–246, https://doi.org/10.1016/j.conbuildmat.2017.06.175.
9 V. Fiore, T. Scalici, G. Di Bella, A. Valenza, A review on basalt fibre and its composites, Composites Part B Eng. 74 (2015) 74–94, https://doi.org/10.1016/j.compositesb.2014.12.034.
10 Fucheng, G. (2020) 'Evaluation of the Effect of Fiber Type, Length, and'.
11 Alvaro González, José Norambuena-Contreras, Lily Poulikakos, María José Varela, Jonathan Valderrama, Alexander Flisch, Martín Arraigada, Evaluation of asphalt mixtures containing metallic fibers from recycled tires to promote crack-healing, Materials 13 (24) (2020) 1–17, https://doi.org/10.3390/ma13245731.
12 Qianli Gu, Aihong Kang, Bo Li, Peng Xiao, Hao Ding, Effect of fiber characteristic parameters on the high and low temperature rheological properties of basalt fiber modified asphalt mortar, Case Stud. Constr. Mater. 17 (June) (2022), https://doi.org/10.1016/j.cscm.2022.e01247.
13 Qinglin Guo, Lili Li, Yongchun Cheng, Yubo Jiao, Chun Xu, Laboratory evaluation on performance of diatomite and glass fiber compound modified asphalt mixture, Mater. Des. 66 (PA) (2015) 51–59, https://doi.org/10.1016/j.matdes.2014.10.033.
14 Gholam Hossein Hamedi, Fereidoon Moghadas Nejad, Khosro Oveisi, Investigating the effects of using nanomaterials on moisture damage of HMA, Road. Mater. Pavement Des. 16 (3) (2015) 536–552, https://doi.org/10.1080/14680629.2015.1020850.
15 Yingxin Hui, Guangyu Men, Peng Xiao, Qin Tang, Fangyuan Han, Aihong Kang, Zhengguang Wu, Recent advances in basalt fiber reinforced asphalt mixture for pavement applications, Materials 15 (19) (2022).
16 Saeed Ghaffarpour Jahromi, Ali Khodaii, Effects of nanoclay on rheological properties of bitumen binder, Constr. Build. Mater. 23 (8) (2009) 2894–2904, https://doi.org/10.1016/j.conbuildmat.2009.02.027.
17 Jeffrey J.Stempihar, PE; Mena I. Souliman. 2011. "Fiber_Reinforced_Asphalt_Concrete_as_Sus.Pdf."
18 H. Jia, et al., Effect of synthetic fibers on the mechanical performance of asphalt mixture: a review, J. Traffic Transp. Eng. (Engl. Ed.) 10 (3) (2023) 331–348, https://doi.org/10.1016/j.jtte.2023.02.002.
19 Ahmed Khater, Dong Luo, Moustafa Abdelsalam, Yanchao Yue, Yueqin Hou, Mohamed Ghazy, Laboratory evaluation of asphalt mixture performance using composite admixtures of lignin and glass fibers, Appl. Sci. 11 (1) (2021) 364, https://doi.org/10.3390/app11010364.
20 Mohammad Jamal Khattak, Ahmed Khattab, Hashim R. Rizvi, Pengfei Zhang, The impact of carbon nano-fiber modification on asphalt binder rheology, Constr. Build. Mater. 30 (2012) 257–264, https://doi.org/10.1016/j.conbuildmat.2011.12.022.
21 Kateryna Krayushkina, Olegas Prentkovskis, Andrii Bieliatynskyi, Johny Gigineishvili, Aleksandra Skrypchenko, Alfredas Laurinavičius, Kasthurirangan Gopalakrishnan, Jurijus Tretjakovas, Basaltfiibri kiudude kasutusperspektiivid maanteede ja lennuradade katete ehitamisel ja remondil, Balt. J. Road. Bridge Eng. 11 (1) (2016) 77–83, https://doi.org/10.3846/bjrbe.2016.09.
22 Zhenxia Li, Tengteng Guo, Yuanzhao Chen, Menghan Zhang, Qingyu Xu, Jing Wang, Lihui Jin, Study on properties of drainage SBS modified asphalt mixture with fiber, Adv. Civ. Eng. 2021 (2021), https://doi.org/10.1155/2021/7846499.
23 Rongwei Liang, Wei Yu, Zengjie Luo, Laboratory investigation on pavement performance of basalt fiber-reinforced asphalt mixture under the coupling effect of freeze-thaw cycles and aging, Front. Mater. 9 (July) (2022) 1–16, https://doi.org/10.3389/fmats.2022.930056.
24 Alexandre Luiz Manfro, João Victor Staub de Melo, Joe Arnaldo Villena Del Carpio, Wellington Borba Broering, Permanent deformation performance under moisture effect of an asphalt mixture modified by calcium carbonate nanoparticles, Constr. Build. Mater. 342 (March) (2022), https://doi.org/10.1016/j.conbuildmat.2022.128087.
25 Mithil Mazumder, Raju Ahmed Ahmed Wajahat Ali, Soon Jae Lee, SEM and ESEM techniques used for analysis of asphalt binder and mixture: a state of the art review, Constr. Build. Mater. 186 (2018) 313–329, https://doi.org/10.1016/j.conbuildmat.2018.07.126.
26 Ahmed M. Mohammed[1], and Alaa Abed[1]. 2023. "Nano 25pdf."
27 Nihat Morova, Investigation of usability of basalt fibers in hot mix asphalt concrete, Constr. Build. Mater. 47 (2013) 175–180, https://doi.org/10.1016/j.conbuildmat.2013.04.048.
28 S. Pirmohammad, Y. Majd Shokorlou, B. Amani, Laboratory investigations on fracture toughness of asphalt concretes reinforced with carbon and kenaf fibers, Eng. Fract. Mech. 226 (ember 2019) (2020) 106875, https://doi.org/10.1016/j.engfracmech.2020.106875.
29 Mostafa Sadeghnejad, Gholamali Shafabakhsh, Use of nano SiO2 and nano TiO2 to improve the mechanical behaviour of stone mastic asphalt mixtures, Constr. Build. Mater. 157 (2017) 965–974, https://doi.org/10.1016/j.conbuildmat.2017.09.163.
30 Chenchen Shen, Rui Li, Jianzhong Pei, Jun Cai, Tao Liu, Yang Li, Preparation and the effect of surface-functionalized calcium carbonate nanoparticles on asphalt binder, Appl. Sci. 10 (1) (2020), https://doi.org/10.3390/app10010091.
31 Carlos J. Slebi-Acevedo, Pedro Lastra-González, Pablo Pascual-Muñoz, Daniel Castro-Fresno, Mechanical performance of fibers in hot mix asphalt: a review, Constr. Build. Mater. 200 (2019) 756–769, https://doi.org/10.1016/j.conbuildmat.2018.12.171.
32 Wynand JvdM. Steyn, Applications of nanotechnology in road pavement engineering, Nanotechnol. Civ. Infrastruct. (2011) 49–83, https://doi.org/10.1007/978-3-642-16657-0_2.
33 Bangwei Wu, Zhaohui Pei, Chufan Luo, Ji Xia, Chuangchuang Chen, Aihong Kang, Effect of different basalt fibers on the rheological behavior of asphalt mastic, Constr. Build. Mater. 318 (ember 2021) (2022) 125718, https://doi.org/10.1016/j.conbuildmat.2021.125718.
34 Shaopeng Wu, Qunshan Ye, Ning Li, Investigation of rheological and fatigue properties of asphalt mixtures containing polyester fibers, Constr. Build. Mater. 22 (10) (2008) 2111–2115, https://doi.org/10.1016/J.CONBUILDMAT.2007.07.018.
35 Yanchao Yue, Moustafa Abdelsalam, M. S. Eisa, Aggregate gradation variation on the properties of asphalt mixtures, Coatings 12 (11) (2022) 1–13, https://doi.org/10.3390/coatings12111608.

36 Yanchao Yue, Moustafa Abdelsalam, Dong Luo, Ahmed Khater, Josephine Musanyufu, Tangbing Chen, Evaluation of the properties of asphalt mixes modified with diatomite and lignin fiber: a review, Materials 12 (3) (2019), https://doi.org/10.3390/ma12030400.
37 Awais Zahid, Sarfraz Ahmed, Muhammad Irfan. 2022. "Experimental Investigation of Nano Materials Applicability in Hot Mix Asphalt (HMA)."
38 Wenhui Zhao, Xiangbing Xie, Guanghui Li, Jiuguang Geng, Meng Bao, Mingwei Wang, Research on the influence of nanocarbon/copolymer SBS/rubber powder composite modification on the properties of asphalt and mixtures, Adv. Mater. Sci. Eng. 2020 (2020), https://doi.org/10.1155/2020/8820202.