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Short communication

Investigating the healing capability of asphalt modified with nano-zycotherm and Forta fibers

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ABSTRACT

Self-healing, is related to the repair of cracks caused by loading. It can be considered a reversible fatigue phenomenon. This phenomenon depends on various factors, such as temperature, rest time, crack width and the features of bitumen and asphalt, and is activated by rising temperatures. Self-healing is investigated in two areas of rejuvenators and accelerated heating. Temperature effects on self-healing is seeking the best and most economical means of creating heat in asphalt. Such methods involve heating through electromagnetic waves and microwaves. Microwave waves increase the internal temperature of the asphalt in a short time that help self-healing process. There are various methods to assess the quality and quantity of self-healing, such as fatigue-based tests, rupture tests, and non-destructive tests. In this research, the healing ability of asphalt modified with Forta fibers and Nano-zycotherm, and non-additive asphalt is investigated through rupture-based experiments, three-point bending tests. The samples were repaired by heating with microwave radiation for 24-hour period, then determined the degree of healing. According to the experiment results, the asphalt comprising zycotherm and Forta fibers additives exhibited the highest initial resistance compared.

1. Introduction

The maintenance and repair of existing roads is very expensive and difficult. An economic and environmental conservation strategy lies in the design, construction, and maintenance of such strategy. This sort of strategy is aimed at identifying new ways to improve asphalt performance, maintain resources using recovery techniques, increase energy efficiency and protect the environment by reducing the release of harmful substances.

Among the most deliberated topics since the 1960s related to asphalt road maintenance is self-healing. The self-healing or refining capability of bitumen materials has been the focus of laboratory and field research, with various studies carried out on bitumen, mastics, asphalt mixes and dense asphaltic concrete [1].

Fatigue damage consists of two forms: reversible and irreversible. Irreversible damage entails the accumulation of failure over time and reversible damage is related to two factors, namely thixotropy and self-healing. Thixotropy is linked to the non-Newtonian behavior of fluid and when the damage-causing agent (e.g. loading) is removed, the object tends to return to its original state. In other words, thixotropy is the intrinsic ability of materials to retrieve their microstructural properties before cracking and acts at loading times. Self-healing only occurs after cracking has taken place and it facilitates the

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recovery of some lost cracked asphalt properties like resistance. It is important to note that thixotropy can occur in many materials, such as metals, ceramics, wood and bitumen, but only a few materials including bitumen have the healing capability as an intrinsic property [2,3].

With this knowledge, maintenance costs and preventing damage to the environment due to the production of asphalt can be reduced. To identify self-healing behavior and interpret the performance, researchers have suggested several models. Certain models based on the theory of energy describe the failure level in the self-healing equation of asphaltic concrete as a relation between the amount of repair and fracture surface energy [4].

Self-healing is investigated in two areas of rejuvenators and accelerated heating. In temperature effects on self-healing researchers are seeking the best and most economical means of creating heat in asphalt. Various researchers have described the mechanism of polymer healing and published models based on which polymer healing is divided into two sections: crack surface wetting and actual healing. Other researchers have found that the surface cracking wetting step is short, while the real repair stage is long and can be explained by the molecular diffusion mechanism. Garcia and colleagues proposed a capillary current model based on the theory of capillaries. The model was applied in temperature conditions suitable for capillary flow in small cracks, which resulted in cracking, while the resistance between contact surfaces was gradually restored due to molecular diffusion. They described the two-stage repair process using the capillary and diffusion theories. Accordingly, if a material is heated to a transition temperature it becomes a Newtonian fluid, which penetrates existing cracks aided by capillary force. The fluid moisturizes the inner surfaces after filling the cracks with the help of the gradient, pressure and concentration (diffusion theory), thus increasing the stiffness and strength of the two pieces and ultimately restoring the cracks [3].

Self-healing speed, quantity, quality and other properties or phenomena are influenced by a number of factors. Researchers have investigated some of the most important factors, including temperature, bitumen characteristics, asphalt mix, rest periods, crack width, additive modification, humidity, and loading conditions. Obviously, these factors sometimes interact with one another and their effects may differ [1].

The self-healing capability of bitumen, mastic and asphalt has also been evaluated in the laboratory and more recently in the field. For this purpose, a range of methods of examining bitumen and asphalt self-healing molds have been described experimentally. There are generally three types of fatigue-based tests, including rupture-based and non-destructive tests. In fatigue-based tests, samples are placed for a given period of time under abrupt and repetitive loading conditions (e.g. in a normal fatigue test). Loading is carried out through a two-point bending test, a four-point bending test (4PB), or sometimes an inertial tensile test to evaluate the repair ability of asphalt mixtures [1].

According to Bazin and colleagues' laboratory research on the fatigue of asphalt mixtures, resting periods had a beneficial effect on bitumen, which was fatigued and even ruptured. Moreover, the tested specimens exhibited superior healing capability, especially at relatively high temperatures. The researchers pointed out that several other parameters may nonetheless affect this phenomenon [5].

Temperature is deemed the most significant external factor affecting repair ability. A suitable temperature to trigger the restoration process depends on the bitumen number from 30 to 70 °C. In this temperature range, bitumen acts as a Newtonian fluid, thus facilitating the recovery process. The chemical properties of bitumen also significantly influence healing capability. Besides, various molecules in bitumen, including asphaltenes, resins, aromatics and saturated colorless fluids that are found in chains, rings and other forms, vary with each type of bitumen, giving bitumen diverse properties [6].

Quan Lv (2016) carried out BBS and CT-Scan experiments to investigate the factors affecting bitumen repair ability. They found that with increasing temperature the bitumen healing capability increased, while temperature was much more effective than restoration time [7].

The properties of bitumen are highly effective on the repair ability of asphalt mixtures, which is why many researchers have investigated the asphalt healing capability of bitumen. Bitumen is a viscoelastic material, whereby at high temperatures it acts as a Newtonian fluid and penetrates cracks through its fluidity (including capillary and flow properties), resulting in asphalt restoration [8].

Fiber asphalt has also been studied by many researchers investigating the effect of fiber on repair ability, heat absorption, energy, and other factors associated with healing. Some researchers added wool fiber to asphalt mixtures and examined their impact on the mechanical and physical properties of asphalt mixtures. For this purpose, several different types of asphalt with certain percentages of metallic fiber were tested. It was found that adding metal fibers facilitated and accelerated the temperature increase in asphalt specimens, especially with the microwave heating method. On the other hand, asphalt modified with metal fibers exhibited an increase in the percentage of free space, reduced density and increased asphalt resistance against wear and impact (less drop) [8].

In order to create, develop and accelerate self-healing, it is necessary to increase the asphalt temperature. Accordingly, researchers are attempting to devise methods that are environmentally friendly as well as the most advantageous in terms of energy consumed, increasing heat rates, facilities, equipment, heat generation costs and operationally for field pavement. Some means of generating heat are induction heating, microwave heating and solar-powered heating (with infrared waves) [8]. Microwave waves increase the internal temperature of the asphalt in a short time that help self-healing process.

One way to expand and accelerate heat is to use microwaves, which has been studied at the laboratory level and is now in the initial stages of laboratory research. The wavelength of visible light is between $4 * 10^{-7}$ (purple) and $7 * 10^{-7}$ (red) meters, while microwaves are electromagnetic waves with wavelengths between 3 mm and 3 m and accordingly, frequencies between 100 MHz and 100 GHz. Microwave heating can be generated using a 700 W device with a frequency of 2.45 GHz that emits 120 mm wavelengths [8].

Rupture-based restoration tests are performed to evaluate the healing results of two broken bitumen object surfaces. Previously, a number of researchers have made concrete asphalt beams by testing a three-point bending beam under repetitive and rotating rupture-restoration conditions. They determined the degree of restoration in each cycle based on the resistance after splitting restoration compared to the initial resistance. Other researchers cut Marshall specimens into two semi-cylindrical specimens using a three-point bending test [8].

Crack width is one of the factors affecting self-healing. A group of researchers carried out microscopic and macroscopic observations and investigated the repair of bitumen cracked to different extents. In this regard, they compared the density of bitumen in cracked regions with intact bitumen as the basis for calculating healing. The researchers found that at smaller widths repair was superior and healing recovery was faster [9].

Non-destructive tests employed in some studies are divided into wave-based techniques. Sun and colleagues examined tensile testing using fluorescence microscopy and image processing of the restoration process of bituminous samples. They also determined the two main steps of wetting and molecular diffusion [11]. Shihui Shen (2016) examined the evolution of bitumen repair using FESEM imaging. According to a direct analysis of the photographs, Shen concluded that the extent of bitumen repair varies over time with nonlinear changes. The researcher also found that the temperature and aging of bitumen have an important effect on bitumen restoration. Moreover, Shen determined that restoration is caused by the mechanism for emitting bituminous molecules using the MD simulation method. Meanwhile, the most important finding was that the crack width is effective on bitumen healing, whereby bitumen with smaller crack widths can be restored more quickly [9]. Fig. 1 shows this situation.

Zigeng Wang employed elastic support to model elastic pavement. To guide the failure and cracking in the middle of the sample (bending failure), they placed a small groove below the sample and transversely in the middle (Fig. 2) [10].

In this research, it is investigated that the effect of using nano-zycotherm and Forta fibers on asphalt self-healing capability. Accordingly, asphalt healing is expected to be better with these additions. Four kinds of asphalt were made, namely additive-free, and modified with nano-zycotherm, Forta fibers and both nano-zycotherm and Forta fibers together.

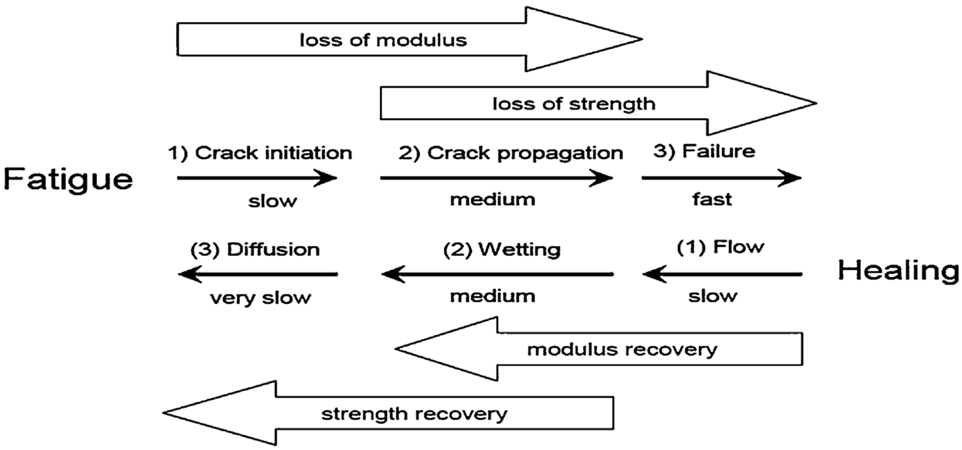

Fig. 1. Fatigue relationship with self-defense [4].

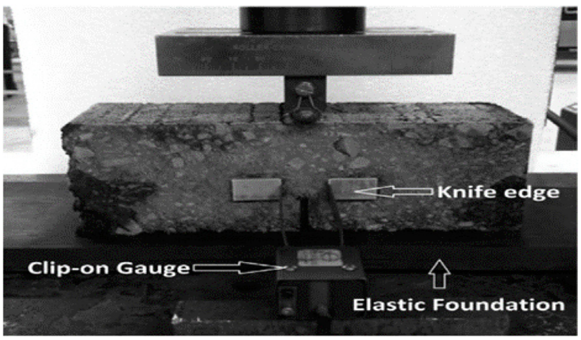

Fig. 2. Three-point bending test on elastic support [10].

The samples were loaded until failure in a three-point bending test, then heated by microwaves, allowed to restore for a 24-hour rest period, and then again placed in a three-point flexural strength test device.

2. Materials and methods

The materials employed in this research include aggregate, bitumen, nano-zycotherm and Forta fibers. These were first evaluated and specimens were made using an asphalt with bitumen mixing method and the Marshall method. Subsequently, the combinations of the aforementioned materials based on the mixing plans of 4 types of asphalt (i.e. asphalt with no additive, asphalt with nano-zycotherm, asphalt with Forta fibers, and asphalt with both nano-zycotherm and Forta fibers) were tested.

2.1. Aggregate and bitumen

The aggregates selected for producing asphalt binders were prepared according to the mix percentages in Table 1 and the specimens were made according to the diagram in Fig. 3. In Fig. 3 the middle curve, refer to existing aggregate and other curves refer to the border of acceptable range of aggregates. The bitumen used in this study is PG 64-22 Fig. 4 shows the forta fiber properties.

2.2. Nano-zycotherm

Zycotherm is an omega-oxygen additive from the Si—OH group to bitumen, which is improved with the help of nanotechnology. This material was introduced and produced by ZYDEX Company.

Zycotherm is a nano-organic additive from the silanol group (Si-oH) to bitumen. Table 2 shows the characteristics of the zycotherm:

In order to produce asphalt, the zycotherm should be added to the bitumen before mixing it with aggregate, and its consumption depends on the type of bitumen, which varies from 0.05 to 0.2 percent. The asphalt produced for this study is prepared according to the manufacturer's proposal of 0.1, 0.15 and 0.2% bitumen. Adding zycotherm to asphalt helps the asphaltic treatment to be resistant to the following injuries:

Stripping: This occurs due to the strong chemical bond between bitumen and rocky materials, because zycotherm modifies the aggregate material surface in nanometer dimensions and converts it from a hydrophilic to a rough surface. The permanent chemical bond created between bitumen and aggregates leads to excellent asphalt performance against the

Table 1
Mixing ratios of asphalt mixes.

The percentage of mixing of aggregates	Specifications of aggregates(mm)
–	Coarse Gravel (25-19)
13%	Medium Gravel (19-12.5)
35%	Fine Gravel (12-6.5)
47%	Sand(0-6)
5%	Filler

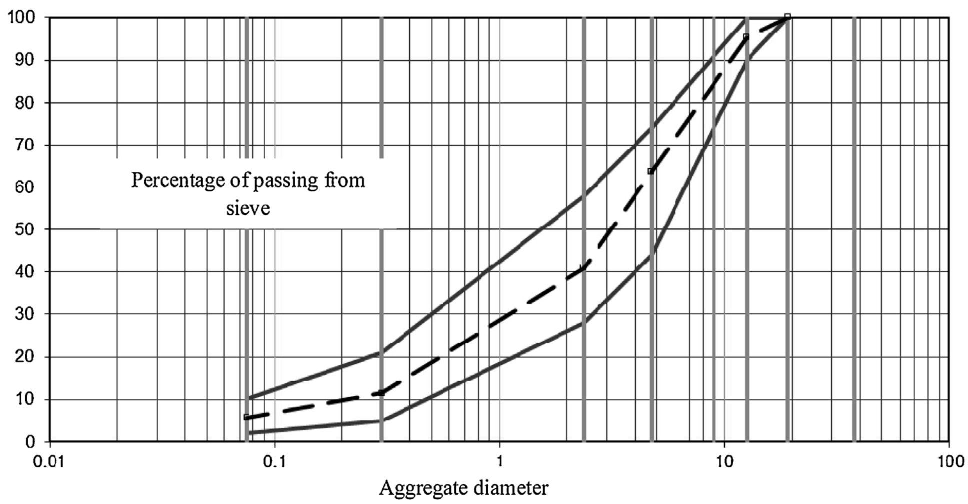

Fig. 3. Grading aggregate charts.

Fig. 4. Forta fiber properties.

Table 2
Zycotherm specifics.

Colour	Light yellow
Shape	Liquid
Freeze point	5-7 °C
Flash point	>80 °C
Density	1.01gr/cm^3

nibbling phenomenon. On the other hand, this material prevents the separation of bitumen from rock materials and asphalt grains [12].

Oxidation or aging: Owing to the complete bitumen coating of aggregate materials, it is possible to coat rock materials 100% with 30–40% less mixing time. Hence, this facilitates energy saving as well as full coverage of fillers and fine grains [13].

Fatigue: Superior performance and consistent and coherent density at lower temperatures increase the asphalt's resistance to fatigue [13].

In addition, zycotherm is environmentally friendly and allows the production of asphalt at lower temperatures (10–15 °C) and asphalt densities at lower temperatures (30–40 °C). In order to produce asphalt, zycotherm should be added to bitumen before mixing with aggregate in varying proportions between 0.05% and 0.15% depending on bitumen content [13].

In this research, the amount of zycotherm used in asphalt production was equal to 0.15% bitumen, and an electric mixer was used to add the bitumen.

2.3. Forta fibers

The Forta fibers used in this study are HMA Blend type with hot asphalt added. This type of fiber is a mixture of synthetic fibers consisting of poly-aramid and polyolefin fibers and other materials. Forta fibers are known for their high durability and good adhesion properties. They are a mixture of woven netting and single-stranded fibers. The fiber length is 19 mm on average and in this study, 0.5% fiber was considered in the asphalt weight [13]. In appearance, these fibers are a mixture of woven netting and single-stranded fibers that measure 19 mm in length.

Marshall method has been used for asphalt mix design. The optimum percentage of bitumen is 4.8%. Four types of asphalt mixes were prepared containing 4.8% pure bitumen with and without additives, with 75 impacts applied to each side of the sample and the Marshall method. For each aforementioned asphalt mix, 10 specimens and a total of 40 Marshall samples were made. In the next step, the specimens were cut through the middle of the cylinder head and divided into two half cylinders. To control the cracks caused by a three-point bending test, it was necessary to have a gap of 4 mm and a depth of 4–6 mm in the samples. Fig. 1 shows the flexural cracking. Fig. 6 shows the three point bending test that used for this study (Figs. 5 and 6).

2.4. Three-point bending test

The specimens prepared in the previous stage were subjected to a three-point bending test SH-300 device. The device was applied to the specimens at a speed of 1 mm/min and load was applied until the samples cracked. Once a crack was established, the load was automatically stopped. This load speed used for debarment from specimens' separation and there is no standard about that Fig. 7 shows the flowchart of this research.

2.5. Preparing of samples

The Marshall method was used to prepare the asphalt mixtures. Optimum bitumen and selected aggregate were used to apply 75 strokes to each side of the specimen, and the following four types of asphalt were used:

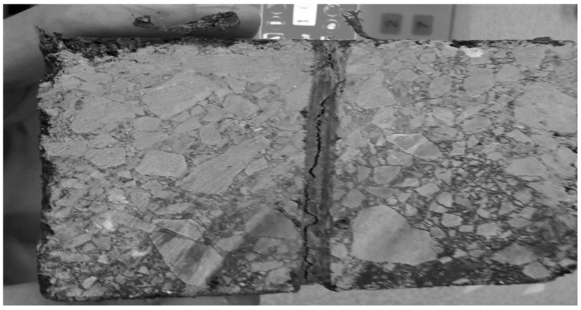

Fig. 5. Flexural cracking occurred in the place of the semi-cylindrical sample groove after the flexural failure in the three-point bending test.

Fig. 6. Three-point bending test on a semi-cylindrical sample.

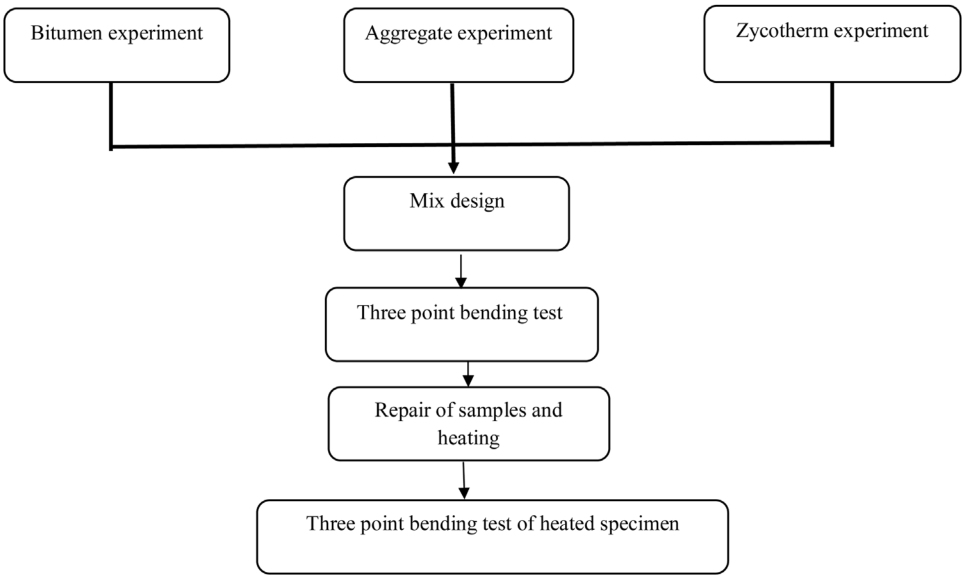

Fig. 7. Experimental flowchart.

- Asphalt without additives
- Asphalt with Nano zycotherm
- Asphalt with Forta fibers
- Asphalt with Forta fibers and Nano zycotherm

10 samples and a total of 40 Marshall Samples were prepared for each of the asphaltic compounds. The prepared specimens were cut in the middle of the cylinder head and divided into two half cylinders.

2.6. Repair of samples broken by microwaves

The samples were placed in a microwave oven and heated for different time periods. The microwave has 700 w power and 2.45 GHz frequency. The radiation times selected were 40, 60, 80, 100 and 120 s. The samples were then placed in the microwave at 20 °C for 24 h, and the bending test was performed again.

3. Results

The average initial flexural strengths of all four asphalt types used in this study were calculated, and the following results were obtained:

Average initial flexural strength of asphalt without additive F_{ave} = 1100 N

Average initial flexural strength of asphalt with nano-zycotherm F_{aven} = 1140 N

Average initial flexural strength of asphalt with Forta fibers F_{avef} = 1430 N

Average initial flexural strength of asphalt with Forta fibers and nano-zycotherm F_{avenf} = 2010 N

The results indicate an increase in the initial resistance with additives. Hence, the asphalt modified with both nano-zycotherm and Forta fibers concurrently exhibited the highest initial resistance, while ordinary asphalt without additives had the least resistance. This can be explained in two ways:

1 As noted in the introduction, nano-zycotherm reduces the viscosity of bitumen, thereby facilitating condensation (even at a lower temperature). It is possible, it can changes the bonds between aggregate and bitumen from strong chemical bonds to weak physical bonds, which can increase the initial flexural strength. This criteria can discovered by more tests.
2 According to the data provided on the Forta website and as mentioned in the introduction, these fibers have very high tensile strength. Therefore, as flexural cracks form below the sample and in the tensile region, these fibers act somewhat similar to weak reinforcements that increase the flexural strength of the asphalt.

The average recovery percentages calculated for the four samples subjected to fixed-time microwave heating are tabulated in Table 3. The recovery percentage is secondary strength per primary strength. Based on the Table3 and Fig. 8 indicates the recovery percentage versus heating time. Similarly, Table 4 and Fig. 9 demonstrate secondary resistance versus heating time.

According to Table 3 and Fig. 8, the highest repair percentage of 64% was for asphalt without additives, followed by asphalt containing nano-zycotherm and asphalt containing both nano-zycotherm and Forta fibers (57% repair or resistance return).

Table 3
Asphalt samples repair percentage.

Asphalt with Nano Zycotherm and Forta additive (%)	Asphalt with Forta Additive (%)	Asphalt with Nano Zycotherm additive (%)	Asphalt without additives (%)	Heating time (s)
34	28	47	57	40
37	34	55	60	60
57	34	57	64	80
44	53	55	56	100
37	53	53	53	120

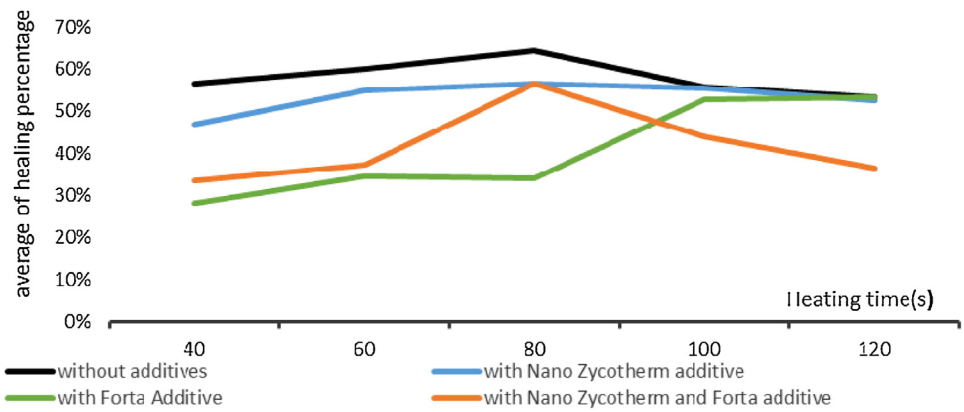

Fig. 8. Graph of healing percentage - Heating time.

Table 4
Secondary strength of asphalt samples.

Asphalt with Nano Zycotherm and Forta additive (%)	Asphalt with Forta Additive (%)	Asphalt with Nano Zycotherm additive (%)	Asphalt without additives (%)	Heating time (s)
34	28	47	57	40
37	34	55	60	60
57	34	57	64	80
44	53	55	56	100
37	53	53	53	120

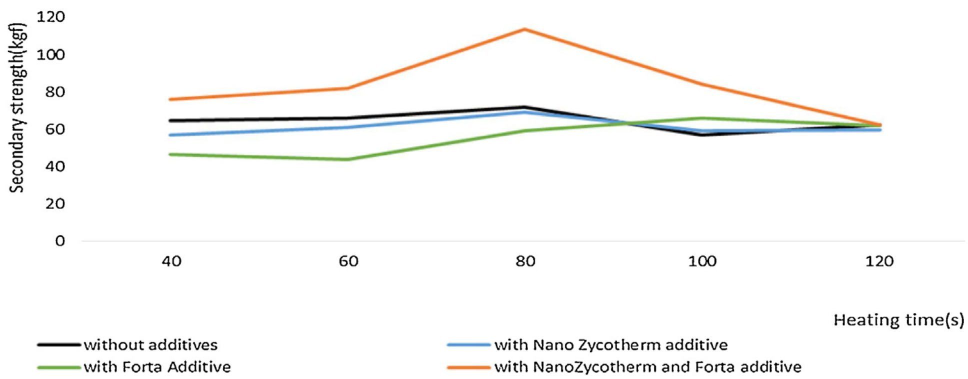

Fig. 9. Secondary resistance diagram - Heating time.

In all three types of asphalt mentioned above, the maximum flexural strength occurred from heating for 80 s, but the asphalt made with Forta fibers exhibited a maximum secondary resistance of 53% from heating for 100 s. Hence, the asphalt with no additive seemed to have greater healing capability. However, according to Table 4 and Fig. 9 for the second bending resistance, the asphalt made with two additives (Forta fibers and nano-zycotherm) presented the highest secondary resistance of 114 kg. Another significant point is that even with the average flexural strength of asphalt without additives, this asphalt seems to be more suitable than others due to the high initial flexural strength as well as the highest secondary flexural strength. In fact Self- healing needs two parameter: rejuvenator, and internal heating. Zychoterm works as a rejuvenator, and forta Fiber as a healing conductor. Therefore healing capacity has been better when these materials has been added to asphalt mixture.

The average temperature generated by each of the steady-state microwave radiation patterns was calculated and presented along with the recovery percentages in Table 5. According to this table, Fig. 10 is plotted. Similarly, the average temperatures obtained and the secondary resistance results are given in Table 6, based on which a graph is plotted in Fig. 11.

According to the diagrams above, the following results can be extracted: for three types of asphalt, i.e. without additive, with nano-zycotherm and with both nano-zycotherm and Forta fibers, the maximum secondary resistance recovery rate was obtained at an internal temperature of about 70 °C. For asphalt with Forta fibers, the maximum secondary resistance recovery rate was attained at an internal temperature of about 80 °C.

Thus, it can be concluded that asphalt made with Forta fibers and nano-zycotherm presents the most uniform internal temperature and satisfies the highest initial resistance and secondary resistance criteria. Moreover, at a higher temperature (70 °C), asphalt with these additives exhibits the most self-healing.

Table 5
Average temperature and healing percentage.

Asphalt with NanoZycotherm and Forta additive		Asphalt with Forta Additive		Asphalt with Nano Zycotherm additive		Asphalt without additives	
Resistance (%)	Temperature (c)	Resistance (%)	Temperature (c)	Resistance (%)	Temperature (c)	Resistance (%)	Temperature (c)
34	44	28	55	47	53	57	57
37	57	34	72	55	65	60	71
57	71	34	88	57	77	64	85
44	78	53	101	55	95	56	100
37	96	53	108	53	109	53	114

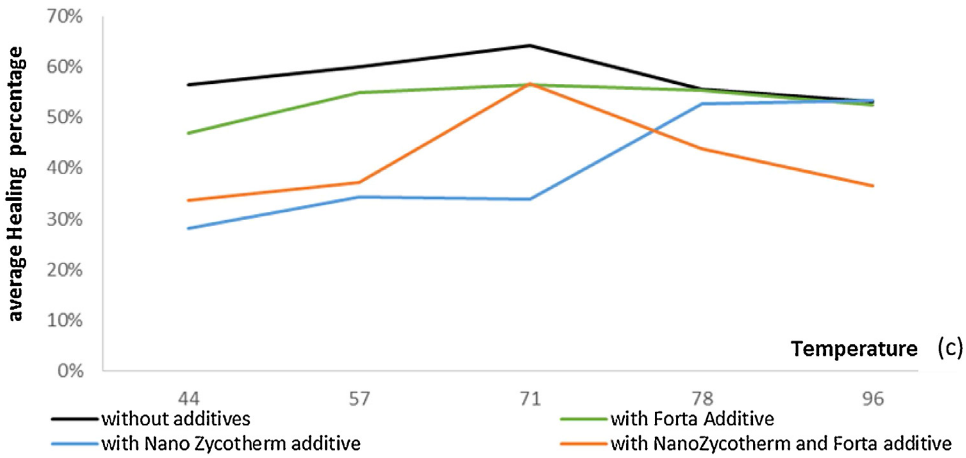

Fig. 10. Healing percentage – temperature.

Table 6
Average temperature and secondary resistance.

Asphalt with NanoZycotherm and Forta additive		Asphalt with Forta Additive		Asphalt with Nano Zycotherm additive		Asphalt without additives	
Healing (%)	Temperature (c)	Healing (%)	Temperature (c)	Healing (%)	Temperature (c)	Healing (%)	Temperature (c)
75.75	44	46.25	55	56.75	53	64.50	57
81.75	57	43.75	72	61	65	65.75	71
113.75	71	59	88	69.25	77	71.75	85
84.25	78	66	101	59.25	95	57.00	100
62.25	96	62	108	59.5	109	62.50	114

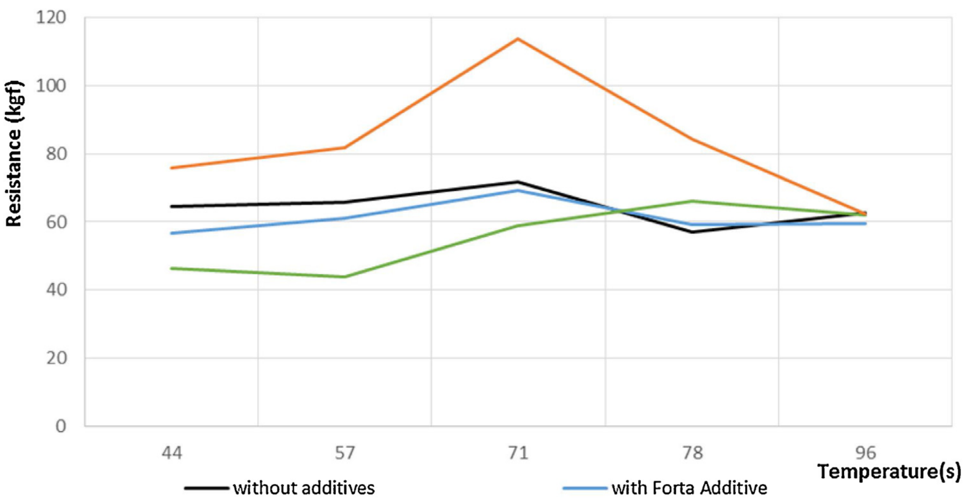

Fig. 11. Diagram of secondary resistance vs temperature.

4. Discussion and conclusions

Self-healing is defined as a behavior that is the opposite of fatigue failure. Fatigue failure is caused by the formation of small cracks and their enlargement, whereas self-healing entails the active closure of cracks and the gradual recovery of resistance. There is a difference between self-healing and thixotropy, in that residual thixotropy occurs when the causative agent such as loading is removed. Thixotropy also only takes place before cracks start. However, self-healing after cracking causes resistor recovery and superior properties.

Temperature is the most important phenomenon affecting healing capability. According to previous research, the best temperature to initiate healing is between 30 and 70 °C. Another factor affecting self-healing is the rest period, which includes the time needed to complete propagation. Additionally, crack restoration capability is influenced and enhanced by cracks with smaller widths.

Different methods are used to measure healing capability, most notably fatigue-based tests (four-point bending), rupture-based tests (three-point bending) and non-destructive tests. Among rupture-based experiments is the three-point bending test, according to which an asphaltic mold of a semicircular Marshall beam or semicircular sample is cracked by a three-point bending machine; after repair, the test is repeated to determine the degree of initial resistance recovery.

In this study, four different kinds of asphalt were produced, including asphalt without additives, asphalt with nano-zycotherm added, asphalt with Forta fibers added and asphalt with both nano- zycotherm and Forta fibers added. Before making Marshall semi-cylindrical samples for testing in three-point bending, the bitumen without additive and bitumen containing nano-zycotherm underwent four tests to determine the degree of penetration, softness point, degree of ignition and viscosity. Subsequently, bitumen without additive was used to prepare the Marshall specimens of four asphalt types based on the aggregate and bitumen contents specified in the mixing plan.

After the Marshall samples were prepared, they were cut into two semi-cylindrical samples and a rope was created in the middle of the sample base. Then a three-point bending test was performed on the samples, which were exposed to hot microwaves for a rest period of 24 h followed by a three-point bending test again. The secondary resistance was calculated. According to the experiments carried out, the following general results were found:

1 The initial resistance of the asphalt made with nano-zycotherm and Forta fiber additives was much higher than that of other asphalts. The reason is that the presence of nano-zycotherm increased the density and the presence of Forta fibers increased the tensile strength of the asphalt. In fact these materials affected the compaction in asphalt specimens. Therefore a higher resistance was made. As a result, the combination of the two substances increased the initial flexural strength.
2 The return strength, or non-additive asphalt restoration percentage was higher than that of other asphalts. Nonetheless, this does not mean this asphalt was better. The asphalt made with nano-zycotherm and Forta fiber additives had the highest secondary resistance (approximately equal to the resistance of the primary asphalt without additives).
3 Adding Forta fibers or Nano-zycotherm separately did not have a significant effect on self-healing capability. But the simultaneous use of these two substances has a great impact on increasing the initial resistance and the ability to self-healing. This can be due to interactions between two additive substances. More studies are needed to find out this phenomena.

Conflict of interest

There are no conflict of Interest in this paper.

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