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Presenting the Self-Healing Potential Model by Induction Heating Method in Warm Asphalt Mixtures by Artificial Neural Network

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ABSTRACT

The increasing number of vehicles in the world and the increase in the dimensions of light and heavy vehicles with different combinations, including simple and compound axles, have caused various types of damage in the asphalt, which affects the performance of the roads and requires a suitable pavement. For this reason, engineers try to improve the performance of asphalt mixture in different ways and increase their useful life. Cracking is one of the main failure modes of asphalt pavements. Fatigue cracking is the most common form of asphalt failure and is one of the important factors in reducing the life of road pavements. The purpose of this research is to investigate the index of self-healing potential (HI) of asphalt mixtures containing activated carbon and zycotherm by induction heating method and modelling by artificial neural network. First, by making warm mixture asphalt samples containing activated carbon, self-healing by induction heating method was provided in the pavement, and then the effect of traffic loading and environmental conditions simultaneously in terms of changes in loading parameters, taking into account the conditions of the service life. The results show that the use of activated carbon increases the values of shear modulus. It also improves the properties of modified bitumen at all temperatures. The resistance of the asphalt mixture against breaking and cracking, as well as the maximum force tolerance at the temperature of -16°C is higher than at the temperature of 25°C, which is one of the reasons for the reduction of flexibility of bitumen at low temperature. Also, for modelling, perceptron multi-layer neural network (MLP) with 9 input variables, three hidden layers and one output layer has been used. The results showed that the explanation coefficient of the neural network model for training, validation and evaluation data was 0.99717 for training, 0.62053 for validation and 0.9301 for testing. These values correctly show the high fitting ability of the proposed neural network model. Also, the lowest value obtained for the mean squared error is 4.9223x10^(-5) and in epoch 14.

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1. Introduction
1.1 Objective

Transportation, as one of the most important parts of human life, facilitates reaching different destinations and goals. On the roads, asphalt concrete has a high contribution to the pavement structure. The reason for that can be the use of aggregates to create resistance and bituminous adhesive to create adhesion and prevent premature failure of asphalt concrete against the incoming stresses. In the bitumen and asphalt industries, the cost of maintenance and repair of damages caused by the development of roads consumes a significant part of the country's budget every year. Any damage to the asphalt surface interferes with the performance of cars and reduces driving safety and ride comfort. While cracking is one of the most common failure modes in asphalt pavements, it may eventually cause the pavement surface to collapse. When the flexible asphalt pavement is loaded, certain tensile stresses may develop in its lower part, which causes microcracks to appear. If these cracks are not repaired, they will continue to grow under further loading and eventually become more visible. As their size increases as a result of their connection to each other, the pavement eventually collapses by Grant [1]. The self-healing ability of asphalt mixtures, which includes self-healing, restoration of mechanical properties such as lost hardness and resistance, and the return of displacement caused by the opening of cracks during the period by Qiu *et al*., [2]. The effect of temperature is one of the important factors in self-healing. The optimum temperature for softening and self-healing of bitumen during rest time was between 20 and 60 °C in studies investigating self-healing by Amani *et al*.,[3]. When bitumen is released from the solid phase at high temperatures, self-healing actually occurs, and if the resting time interval is long enough, the lost qualities may be fully recovered by Tang *et al*., [4]. The technique of increasing the temperature of the asphalt mixture with the help of heat induction from an external source is used in practical conditions where it is not possible to reduce the traffic load in order to lengthen the rest interval in order to increase self-healing. Capacity by Gallego *et al.,* [5]. The electromagnetic induction method is a well-known technique that has been proposed in most researches by among several methods for heat induction. In addition, using excessive heat increases swelling and decreases self-healing. For this purpose, it is recommended to improve the temperature sensitivity of the mixture by adding conductive particles such as fiber and conductive filler García *et al.,* [6]. On the other hand, hot asphalt pavement (HMA) consumes a lot of energy during construction in the factory and undergoes aging phenomenon and produces a lot of greenhouse gases due to its operation at high temperature. In order to preserve the environment and reduce energy consumption, the use of warm asphalt (WMA) technology has increased significantly in recent years. This asphalt mix includes the same characteristics as hot mix, with the difference that it can be spread at a lower temperature than hot asphalt. In fact, this method by adding additives reduces the viscosity and allows the production of asphalt at a lower temperature and consumes less energy during construction. The semi-hot asphalt mixing design has the potential to provide similar performance characteristics compared to standard mixes and also have better performance than hot mix asphalt. Sasobit is used as a suitable additive in the production of warm asphalt mixtures. Also, the use of zycotherm additive can lead to the improvement of bitumen performance in making asphalt mixtures. The chemical and physical properties of sasobit have caused the benefits of using it to reduce bitumen viscosity and improve its solubility in the stages of making warm asphalt mixture. In this research, activated carbon is used to the maximum and it is used for the electrical conductivity of asphalt mixture. In addition to that, Sasobit and Zycotherm are used in bitumen in order to make warm asphalt mixture and reduce bitumen hardness and its aging in the factory. Also, the induction heating method is used to raise the temperature and induce self-healing phenomenon in the asphalt mixture, and the operating conditions of the pavement and after that, the cracking of the role of self-healing in increasing the number of cycles leading to failure in the pavement is investigated.

2. Self-Healing in Asphalt Mixtures

In early 2001, for the first time, engineering materials with self-healing properties were designed by introducing a dispersed catalyst and microcapsules containing a repairing agent in a polymer matrix Huang *et al.,* [7]. The self-healing process starts in the order that the crack is starting with the breaking of the microcapsules in the structure of the self-healing polymer, which will cause the release of the repairing agent in the middle of the crack, and with the contact of the catalyst and the repairing agent, this agent starts to polymerize and as a result, this process will bring the two sides of the crack closer to each other and lead to the connection of the two sides of the crack to each other White *et al.,* [8]. Various researchers observed that the self-healing mechanism in asphalt mixtures can be divided into two categories: a) improvement of adhesion in the connection between aggregates in asphalt mixture, b) improvement of cohesion and adhesion of bituminous adhesive. Some researchers believed that when the cracks were connected to each other due to van der Waers forces, the molecules spread from one side to the other until the cracks were completely repaired and the asphalt strength returned to its original level by Shan *et al.,* [9]. Bitumen plays a key role in the asphalt self-healing process by Little *et al.,* [10]. The main problem in the self-healing process is that the self-healing of asphalt pavement is very slow at ambient temperature, so that the growth rate of cracks and damage is higher than the rate of pavement repair in a normal state, and practically asphalt cannot be repaired by itself. Also, traffic flow on the road cannot be blocked enough to improve self-healing. Self-healing is a dynamic process with high inertia that depends on the temperature and time of the healing. Also, the temperature and time of restoration depends on the type of bitumen used. The hardness and resistance of bituminous materials decreases when bituminous materials are subjected to repeated loading. The trends of microcrack initiation, propagation and macrocrack corrosion during loading cycles have been investigated by several researchers. The return of hardness of materials, increase of fatigue life and return of strength was observed for the first time in a laboratory in 1960 under a fatigue test with periods of rest by Fischer *et al.,* [11-16].

2.1 Strategies to Improve the Phenomenon of Self-Healing

The results of investigating the effects of modifiers (additives) on the self-healing ability of asphalt materials have been reported in scattered form. Lee et al compared the repair of asphalt mixtures with different modifiers such as (SBR), (SBS) and (GIL). They concluded that asphalt mixtures with SBS modifier show the best performance in terms of fatigue, rutting and repair. Kim's evaluation of the effect of SBS modifier on repair and cracking properties showed that SBS modifier has a relatively small effect on the repair rate of asphalt mixtures. In addition, Little concluded that the addition of SBS and low-density polyethylene (LDPE) acted as a filler system, to the extent that it inhibited the repair ability of pure bitumen. The interpretation of the negative effect of polymer additive on repair may be based on the effect of polymer on bitumen composition. The polymer networks in bitumen are made bulky by bitumen, and the cause of this swelling is the absorption of components more compatible with bitumen by bitumen, so what remains is bitumen with higher asphaltene components. Bitumen with asphaltene with a higher concentration has a lower probability for fluidity and repair. Little also described the possible effect of hydrated lime (HL) on bitumen repairability. Addition of hydrated lime to high aromatic bitumen with very low asphaltene content (AAM) showed a decrease in repair capacity. Although the addition of hydrated lime to AAD bitumen, a very dependent bitumen and one with high asphaltene breakdown, increased the repair capacity. This can be due to the surface adsorption of hydrated lime or internal interactions with a part of the more polar asphaltene fraction in AAD bitumen, which may increase the psychological and repair properties. Bahia tested two unmodified bitumen, two plastomer-modified adhesives and two oxygen-modified (oxidized) adhesives. He concluded that the modified adhesive showed better HPI than the original bitumen. The results showed that modification technology can change the repair performance by Menozzi *et al.,* [17-22].

2.2 Measuring Self-Healing Potential

After introducing the nature of self-healing in asphalt and bituminous mixtures, the important discussion is to present a suitable method to measure this potential and determine the amount of this effect, so that the effect of self-healing can be included in fatigue life calculations and pavement designs. Also, another issue that exists is determining the effective parameters in the self-healing process and determining the contribution of each of these parameters and their importance. In the field of measuring this potential, there have been many studies, most of which are applied to the samples to investigate the fatigue and self-healing behavior, alternating loading with/without a rest period and in one of the two states of constant stress or constant strain. In order to apply intermittent load and simulate fatigue behavior, different tests have been proposed, for example, uniaxial test, 3-point and 4-point bending test, indirect tension test with superior pavement standard, and beam test with elastic base; that the 3-point bending test and beam with elastic base will be better than other cases due to the absence of permanent deformations in the sample during the fatigue process [15].

3. A Review of Related Studies on Warm Asphalt Mixtures

Hot asphalt pavement produces a lot of greenhouse gases due to its operation at high temperature. In order to preserve the environment and reduce energy consumption, the use of warm asphalt technology has increased significantly in recent years. There are different technologies for making WMA asphalt. In 2021, researchers investigated the induced repair behaviors of Aspha-Min-made warm mix asphalt (WMA) reinforced with steel fibers and hot mix asphalt (HMA) reinforced with steel fibers through degradation-repair-degradation test. They compared the results of the tests showed that the WMA mixture made with Aspha-Min has a slightly lower self-healing ratio than the HMA mixture, and also the induction heat can greatly increase the self-healing ability of WMA [23]. In 2013, XIN LU investigated the effect of two additives Sasobit and Evotherm on the fracture repair characteristics of WMA and observed that these two additives do not significantly change the fracture repair characteristics of the asphalt binder layer except Sasobit increases the initial dynamic shear modulus and prolongs the fatigue life [24]. In 2012, Munir Nazzal et al. evaluated the repair characteristics of WMA including Sasobit and Advera and found that both additives had an adverse effect on the repair behavior despite improving adhesive intrinsic healing. Cohesive intrinsic healing is added to the asphalt mixture, and Sasobit reduced the rate of cracking by Munir *et al.,* [25]. In 2013, Aboelkasim Diab et al. evaluated half-heated asphalt mixture (WMA) including nano-hydrated lime (NHL) and normal hydrated lime (RHL) and showed that to reduce rutting instead of using normal hydrated lime (RHL) with a dose of 20% By weight of binder, nano hydrated lime (NHL) can be used with a dose of 5% by weight of binder [26]. In 2014, Aboelkasim Diab et al compared half-heated asphalt mixture (WMA) containing nano-hydrated lime (NHL) and normal hydrated lime (RHL) and concluded that nano-hydrated lime (NHL) compared to normal hydrated lime (RHL) It is a more effective method in reducing wrinkles. The reaserchers investigated the effect of hydrated lime particles on the moisture sensitivity of warm asphalt mixture (WMA). The results showed that the mixture containing sub-nano hydrated lime (SNHL) increases the indirect tensile strength (ITS) by 8% and the tensile strength ratio (TSR) by 10% compared to the mixture containing regular hydrated lime (RHL). They evaluated water-containing additives in warm asphalt mixture (WMA) such as Aspha-Min and Advera and found that these two additives weaken the resistance of WMA mixture to moisture deterioration. Also they evaluating two types of warm asphalt mixture (WMA), one of which was made in a conventional way (using Sasobit) and the other containing Zycosoil nanomaterial, they concluded that the role of nanomaterial in comparison With other parameters, it has a greater effect on increasing the moisture resistance of the WMA mixture. they investigated the effect of different levels of nanosilica in improving the physical, rheological and mechanical characteristics of half-heated asphalt mixture (WMA) containing 2% sasobit. The results of the tests showed that increasing the percentage of nanosilica improves the performance of the WMA mixture, which includes a slight increase in the Resilient modulus of the mixture, improving the response of the pavement to traffic load at 25 oC, reducing the crack depth in loading cycles, reducing the hardness of the modified sample compared to the control sample., increasing the fatigue life of asphalt concrete and reducing the depth of rutting. they found out that the WMA mixture containing FORTA fibers has better crack growth resistance than the WMA mixture containing fiber by [27-34].

3.1 Scope and Innovation

The final goal of this research is to provide a behavioral model of the self-healing potential by the induction heating method in warm mixtures asphalt (WMA) in terms of changes in different levels of pavement life and environmental conditions by Artificial neural network, so that a suitable model can be used to determine the effect of different parameters on the self-healing potential of the warm mixtures asphalt. In this research, in order to achieve the desired goals, the variables considered to investigate the self-healing potential of asphalt mixtures include different levels of applied stress, different traffic during the pavement operation period, different environmental and temperature conditions, different loading cycles and time and different types of pavement life. Warm mixture asphalt (WMA) includes bitumen modified with sasobit and also zycotherm in order to reduce bitumen viscosity during construction and stone materials containing activated carbon in order to thermally induce electrical conductivity in the repair stages. In recent years, the use of self-healing technology in the construction of asphalt concrete has received attention, which can be one of the options for pavement maintenance during its lifetime, in addition to increasing the life of flexible pavement. Influential parameters such as the life of asphalt pavement, bitumen aging during the production of asphalt mixture in the factory, and the frequency of pavement loading during the operation period and different environmental conditions have a significant impact on the self-healing of asphalt pavement, which is less than a number of these parameters presented in the research were used previously and few researches have been done in relation to the effect of these parameters on warm asphalt mixtures, as well as providing a behavioral model to predict the self-healing potential of warm asphalt mixtures (WMA) by simultaneously considering the effect of changes in parameters Pavement life, aging and different environmental conditions are other innovations of this research.

4. Research Methods

The main factors affecting the self-healing potential of asphalt mixtures include environmental conditions, pavement life, and loading conditions, which are unavoidable during the pavement design period. In this research, all the above three factors are the variables discussed in this research. The research method is as follows: in the first stage, bitumen is mixed with sasobit and in the second stage with zycotherm, and it is used in the production of warm asphalt mixture, and then activated carbon and iron powder is used in the production of asphalt samples as filler , and by the production of asphalt samples containing different percentages of bitumen and conducting Marshall test, Marshall resistance and optimal bitumen percentage are selected and then it is used to make asphalt samples. In the next step, all the samples are subjected to the semicircular bending (SCB) test to determine the self-healing potential. At this stage, the semi-circular bending test (SCB) is performed to determine the self-healing potential in three stages of repetition, considering two loading frequency levels and at two different temperatures, according to the Table 1. Marshall's test was performed for asphalt samples containing 0.1% sasobit and 2% zycotherm in different percentages of bitumen, and the optimal amount of bitumen for both modified bitumen models is shown in Table 1. For each experiment, 3 repetitions have been done in order to reduce the amount of human error in the laboratory and unrelated data were removed from the analysis to have a better correlation between the data.

Table 1
Influential parameters in the three-point bending test in asphalt mixtures containing activated carbon

Additives	Amount	Temperature (°C)	Pulse (KHZ)	crack depth (mm)	Time of Healing (s)	Bitumen Percentage
Zycotherm	0.1	-16	88	10	60	5.8
Sasobit	2	25	89	20	90, 120	5.5

The purpose of this research is to investigate the self-healing properties of warm asphalt mixtures and to make warm asphalt mixtures from bitumen modified with sasobit and also zycotherm in order to reduce the viscosity of bitumen during construction and stone materials containing activated carbon in order to thermally induce electrical conductivity in repair steps are used. The purpose of using additives is not to investigate the rheological properties of bitumen and there is no need to test in different percentages of additives. Therefore, according to previous researches, 2% of sasobit by weight of bitumen, 0.1% of zycotherm by weight of bitumen and 5% of activated carbon by weight of bitumen and 7 gram of iron powder as filler have been used, which have the greatest effect on the performance characteristics of bitumen and asphalt mixtures.

Also, the aim of this study is to investigate the effect of pavement fatigue parameter and increase in crack depth and environmental conditions on the self-healing potential of warmed mixture asphalt. The work process at this stage is as follows: first, the half-heated asphalt mixture cracks under different sizes, and then it is subjected to self-healing phenomenon with the induction heating method, and after applying the rest period, it is subjected to loading again. And the same process is repeated in order to evaluate the impact of loading frequency and different temperature conditions on the repaired samples at different levels and the required breaking force for the samples before self-healing and after the repair operation will be obtained. Finally, the behavioral model of self-healing potential by induction heating method in warmed asphalt mixtures (WMA) will be obtained in terms of changes in different levels of pavement life and environmental conditions for the tested asphalt samples, which can be calibrated with laboratory results and finally The criteria for decision-making and determining the time of self-healing operations during the pavement design period will be determined, which will lead to the reduction of maintenance costs during the pavement design period. The research flow chart is presented in Figure 1.

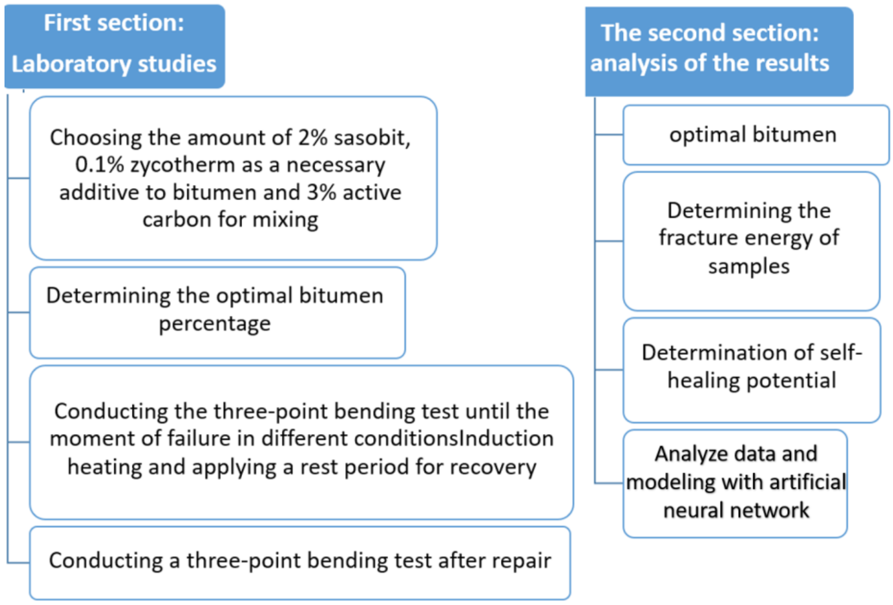


Fig. 1. Image of research flow chart

5. Materials

5.1 Asphalt Binder

The behavior of the asphalt binder is one of the key elements affecting the performance of the asphalt mixture. Failure of pavements could be decreased via the appropriate selection of the type of asphalt binder, which is desirable for weather and traffic conditions in terms of behavior such that increasing traffic factors including heavy loads, high volume of traffic, pressure caused by the wheels, as well as environmental and weather conditions, have resulted in the occurrence of failures such as high-temperature rutting, low-temperature cracks, medium-temperature fatigue, abrasion, asphalt bleeding, and aging, leading to a reduction in the pavements quality and performance [35].In this study, PG (Performance Graded) 64-22 binder are used. This asphalt binder is equivalent to the property's of 60/70 penetration grade asphalt binder that the physical properties of the bitumen used in this study id presented in Table 2.

Table2
The physical properties of the bitumen used in this study

Property	Test method	Quantity	Specification limit
Penetration at 25 °C, 100g, 5 s (deci-mm)	ASTM D-5	61	60-70
Softening Point, ring and ball (°C)	ASTM D36	51	49-56
Flash Point, Cleveland open cup (°C)	ASTM D-92	262	Min 232
Rotational Viscosity at 135 °C (Pa.S)	ASTM D-4402	2.42	Max 3
Ductility at 25 °C at 5 cm/min (cm)	ASTM D-113	110.5	Min 100
Solubility in trichloroethylene, (%)	ASTM D2042-76	99.5	Min 99
Loss on heating, (%)	ASTM D-6	0.06	Max 0.8

5.2 Activated Carbon (AC)

In this study, activated carbon (AC) was employed as an additive. Activated carbon is a form of carbon processed to have small, low-volume pores that increase the surface area available for adsorption or chemical reactions. Activated carbon is a carbonaceous, highly porous adsorptive medium that has a complex structure composed primarily of carbon atoms. The networks of pores in activated carbons are channels created within a rigid skeleton of disordered layers of carbon atoms, linked together by chemical bonds, stacked unevenly, creating a highly porous structure of nooks, crannies, cracks, and crevices between the carbon layers [36].

The physicochemical properties of activated carbon applied in this investigation are illustrated in Figure 2 and Table 3. With regard to previous studies, the excessive addition of AC causes a reduction in strength. Thus, on the basis of the past studies, the optimum value of AC was selected to be equal to 5% by weight of asphalt binder [37]. To this end, a high-shear rheometer mixer was used. According to previous studies to achieve the Homogenous mixing of bitumen and nano additives, the best speed of mixer is 4200 rpm at a mixing temperature of about 135 ˚C for 30 minutes when the bitumen is in a fluid state by Manider *et al*,.[38]

Table 3
Activated carbon properties

Name	PAC-AC80-100
Size	<0/074 mm <0/3 mm
Ashes left over from burning	8%≤
PH	6 w/w≥
Stiffness	> 50
Density	230-300 kg/m^3
Humidity	4% w/w≤

Fig. 2. Image of activated carbon

5.3 Sasobit

Sasobit (Figure 3) is an aliphatic hydrocarbon obtained from coal. This material is a homogeneous solution containing bitumen and melts between 70 and 110 ^{o}C. Sasobit is used as a suitable additive in the production of warm asphalt mixtures. Sasobit increases the behavior of the asphalt mixture under loads and prevents bitumen hardening by reducing the mixing and compaction temperature. This reduces air pollution and energy consumption. The physical characteristics of sasobit is shown in Table 4.

Fig. 3. A picture of the Sasobit

Table 4
Physical characteristics of sasobit

Viscosity	Density (kg/m^3)	Flash point	Penetration at 25 ˚C (in tenths of millimeters)	Melting point
10-14	622	290	13	75 ^{o}C

The chemical and physical properties of sasobit have caused the benefits of using it to reduce bitumen viscosity and improve its solubility in the stages of making warm asphalt mixture. Therefore, Sasobit chosen as one of the basic materials for mixing with bitumen in the production of hot asphalt mixture, which is added to bitumen at about 2% by weight (according to previous researches).

5.4 Zycotherm

The characteristics of the zycotherm used in this research are presented in the Table 5.

Table 5
Characteristics of Zycotherm

Viscosity	PH	Freezing point	Density (g/mlit)	Flash point	Color	State of
100-500	Slightly acidic	5	1.01	80	Light yellow	Liquid

5.5 The Method of Preparing and Making Samples

In this research, in order to prepare modified bitumen, more mixing method will be used. At first, heat the bitumen until it reaches a temperature of 135 ^{o}C so that it becomes molten and fluid. Then it is placed under the high shear mixer (homogenizer) at a speed of 4200 rpm. Gradually, the amount of 2% sasobit is added to the bitumen, and in the other case, the amount of 0.1% zycotherm [39] and after 15 minutes of mixing by the homogenizer and cooling the sample, the modified bitumen required for asphalt samples will be prepared. After preparing the bitumen and mixing stone materials with metal wool, Marshall's mixing design method is used to determine the optimal bitumen of asphalt mixtures. For this purpose, the asphalt mixture will be made according to the following steps: first, the bitumen and aggregate mixture is placed at a temperature of 110 ^{o}C for 2 hours, and then it is stirred, and in the last 15 seconds of the mixing process and before the compaction stage, the temperature of the asphalt mixture is almost at the compaction temperature. Asphalt is approaching. Also, for semi-circular bending (SCB) test, Marshall specimens are made with a height of 70 mm and then divided into 4 parts and semi-circular specimens with a diameter of 10 mm and an approximate thickness of 30 mm are prepared as shown in Figure 4. In addition, to create a uniform crack in the direction of the load axis of the sample during the 3-point bending test, a crack depth of 10 mm and one with a length of 20 mm is created in the center of the sample and in the direction of the load axis of the sample.

Fig. 4. Image of SCB samples test

It is note that warm mixtures asphalt (WMA) is a new technology that has been used in the asphalt industry in order to concerns about global warming and energy consumption. The production of WMA allows the mixing and compaction temperature to be reduced by 10 to 38 oC compared to the common hot asphalt mixtures (HMA). Sasobit is used as a suitable additive in the production of warm asphalt mixtures. Sasobit increases the behavior of the asphalt mixture under loads and prevents bitumen hardening by reducing the mixing and compaction temperature. This reduces air pollution and energy consumption. Reducing the production temperature reduces the required fuel, which naturally reduces the energy cost required for asphalt production. So, the temperature of mixing is 110 ^{o}C and compaction is 90 ^{o}C.

6. Experiments

6.1 Semicircular Bending Test (SCB)

The semicircle bending test has been evaluated in previous studies to evaluate the tensile strength and fracture toughness of asphalt concrete. The findings of this study show that the semi-circular bending specimens perform better than other proposed tests due to their simplicity, ease of preparation, significant reduction of undesirable deformation under the loading blade, and little effect of geometrical characteristics (thickness and diameter) on the results. The figure of three point bending test (SCB) is shown in Figure 5.

Fig. 5. Three point bending test (SCB)

Cylindrical samples obtained by preparing asphalt mixture and compacting it are cut by the machine until its height reaches 25 mm and then it is cut into two half circles. To load the semicircle, the asphalt concrete sample is placed on two roller supports at a distance of 2s=1.6r. The diameter of the roller supports is 6.25 mm and the diameter of the loading cylinder is 9.4 mm.

6.2 Evaluating the Fracture Toughness of Samples in The Semi-Circular Bending Test Before Applying Self-Healing Based on Temperature

In Figure 6 and at medium temperature (meaning 25 ^{o}C), the stiffness of the mixture of the samples modified with zycotherm has led to an increase in the critical load of failure, and therefore their fracture toughness has increased compared to the samples modified with Sasobit.

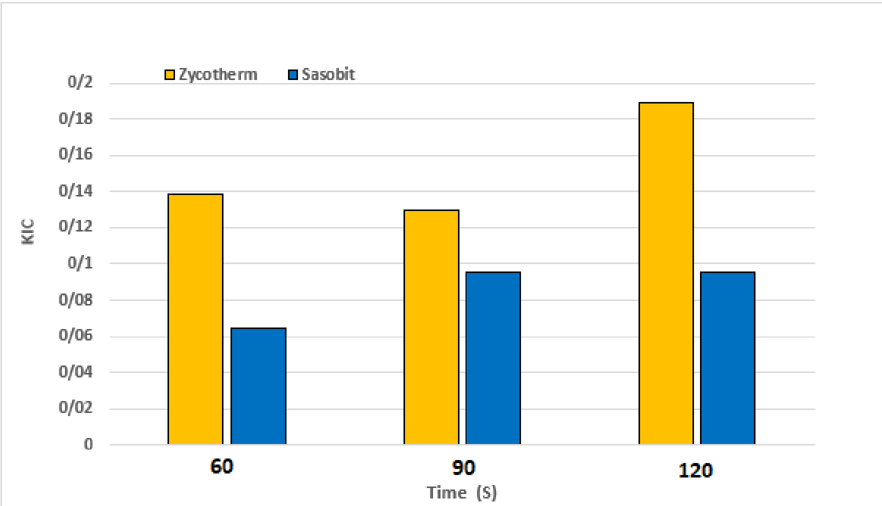
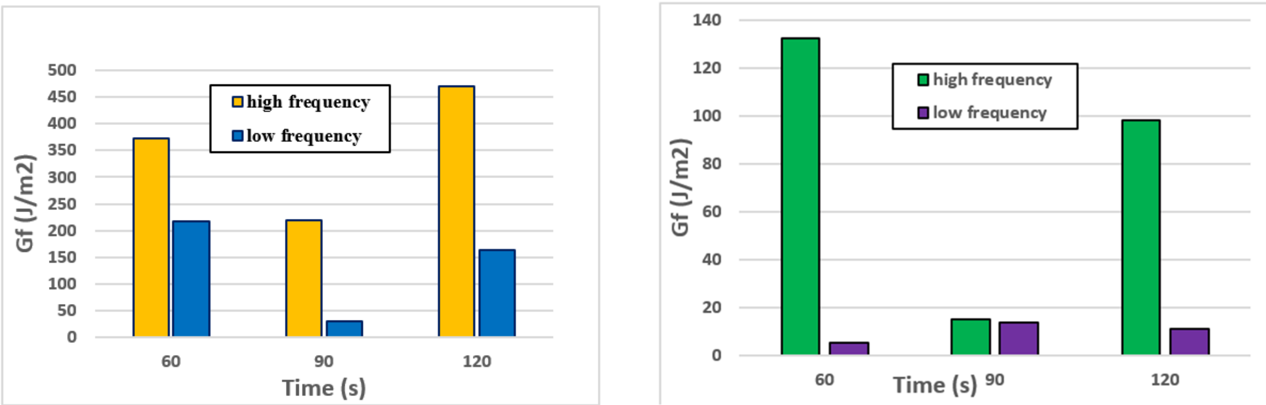


Fig. 6. The graph of the fracture toughness of the samples at 25 ^{o}C before healing

The results show that the modification of bitumen with activated carbon has increased the self-healing index, which may have happened because the high reactivity of activated carbon led to the reaction between bitumen, activated carbon and aggregates, and through this the mastic phase is improved and the result will be improved performance of the asphalt mixture against crack growth. According to previous studies, in order to evaluate the resistance of asphalt mixture against crack growth at low temperature, a combination of load and deformation should be considered for a better evaluation. For this reason, the test standard suggests calculating the area under the force-displacement diagram to evaluate the resistance of the asphalt mixture to thermal cracking. However, only calculating the area under the diagram is not enough, and considering that accurate and similar cutting of asphalt mixture samples is considered a difficult task, therefore, the area under the diagram should be calculated on the surface of the interface, which is the result of multiplying the thickness of the sample in the distance from the edge of the crack to the top of the sample split because the crack will grow from this level. The obtained parameter is called the fracture energy.

Another fundamental failure that occurs in asphalt pavements, especially in cold regions, is thermal cracks. These failures occur perpendicular to the direction of traffic and at similar intervals in the pavement. Failure to repair this damage can cause other damages such as potholes in the flexible pavement due to water intrusion and melting and ice events in cold regions. Considering the ability of the induction self-healing method to improve and repair the cracking damage, it is necessary to evaluate the inductive self-healing ability of the asphalt mixtures proposed in this project in repairing the cracking damage at a lower temperature.

According to the diagram in Figure 7, at a temperature of 25 ºC, the samples modified with zycotherm before applying self-healing have the highest amount of fracture energy, which indicates the better endurance of the tested samples due to the effective presence of bitumen, while maintaining the adhesive properties and high viscosity compared to other samples.

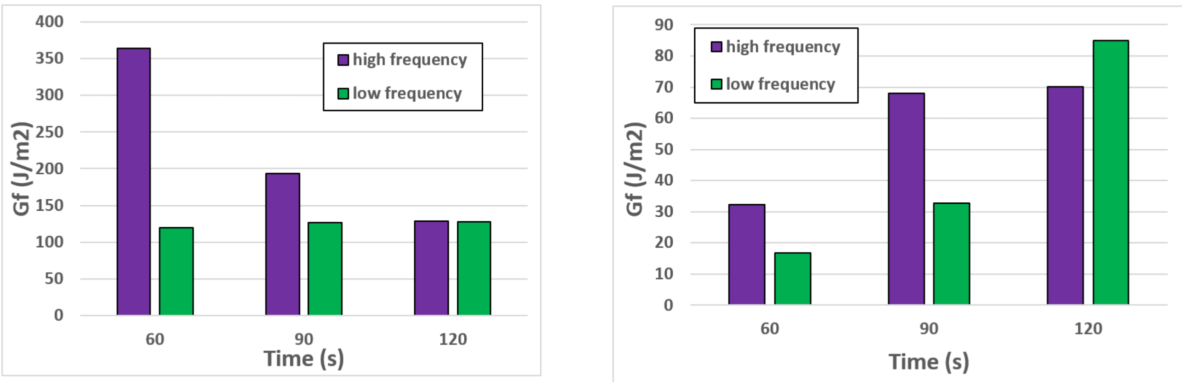


(a) Before healing (b) After healing

Fig. 7. Fracture energy in asphalt mixtures containing zycotherm, crack depth 10mm/temperature 25

6.3 Results of Fracture Energy Before and After Repair In Asphalt Mixtures Containing Sasobit

Based on the Figure 8, at 25°C and with a crack depth of 10 mm, samples containing *Sasobit* have experienced the highest fracture energy. Also, by increase of loading frequency, the amount of failure energy has increased. Nano zycotherm lowers the viscosity of bitumen and thus facilitates compaction and restoration, and on the other hand, it changes the bond between aggregate and bitumen from a weak physical bond to a strong chemical bond, so it alone can increase the initial flexural strength to some extent



(a) Before healing (b) After healing

Fig. 8. Additive fracture energy of crack depth10/temperature 25

6.4 The Effect of Frequency on Self-Healing with Sasobit Additive in Warm Asphalt Mixture

In this research, using the semi-circle bending test, the process (failure-repair-failure) was used to determine the self-healing rate of semi-hot asphalt mixtures. The temperature of 25 ^oC was used as the temperature of samples repair. Figure 9 show the results of the self-healing index of warm asphalt mixture with a crack depth of 10 and 20 mm and a temperature of 25 ^oC.

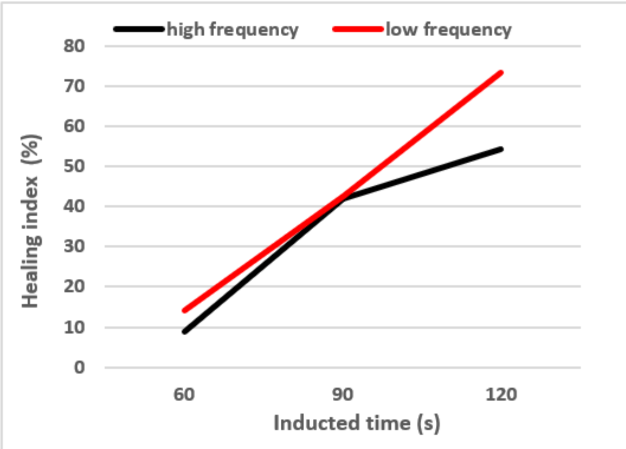


Fig. 9. Self-healing index in terms of fracture energy of warm mixture asphalt with a crack depth of 10 (mm) and a temperature of 25 (°C)

It can be seen in the figure that with the increase of the induction time, the amount of self-healing index has increased. The reason is that with the increase of the induction time, the temperature of the asphalt sample increases and the bitumen viscosity decreases and it reaches the softening point of the samples faster. As a result, it shows more self-healing ability considering the fact that power has an inverse relationship with frequency, it can be seen that the restoration index increases with reduce in frequency. In the induction time of 60 seconds, the self-healing in both frequencies is lower than in the other two times, which means that self-healing does not take place enough in this time.

6.5 The Effect of Crack Depth on Self-Healing with Sasobit Additive in Warm Mixture Asphalt

Figure 10 show the results of the self-healing index of warmed mixture asphalt with a frequency of 88 kHz and a temperature of 25 ^oC. With the increase of the induction time, the self-healing is also increased. By changing the depth of the crack from 10 to 20 mm, the healing index has increased. This is due to the fact that with the increase in the depth of the crack, the area of the ligament has decreased and less cracking has occurred.

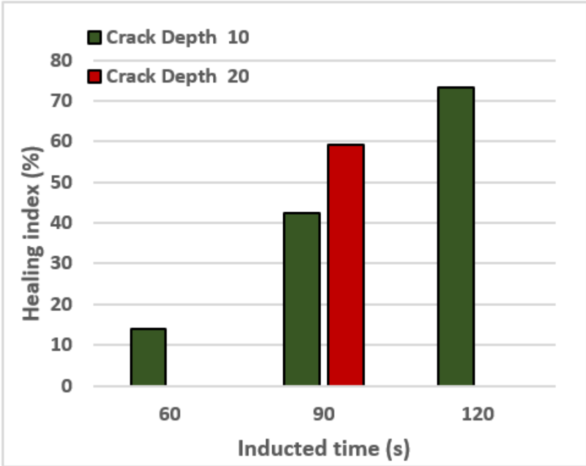


Fig. 10. The results of the repair index self-healing index in terms of fracture energy of warm asphalt mixture with a frequency of 88 kHz and a temperature of 25 ˚C

In the Figure 11 and 12, the results of self-healing index of warm mixture asphalt with frequency of 88 kHz and temperature of 25 and -16 ^{o}C are shown. With the increase of the induction time, the self-healing is also increased. In the figures, by changing the depth of the crack from 10 to 20 mm, the healing index has increased. But the healing index is reduced for the crack depth of 20 mm with the frequency of 88 kHz.

Effect of temperature on self-healing with sasobit additive in warm mixture asphalt. In Figure 10 and 11, the results of self-healing index of warm asphalt mixture with crack depth of 10 mm and frequency of 88 kHz are shown. By increasing the induction time, the self-healing index has increased. By changing the temperature from 25 to -16 ^{o}C, the healing index has increased. This is because it takes more time for the sample to reach the softening point at lower temperatures, but it reaches the softening temperature faster at medium temperatures.

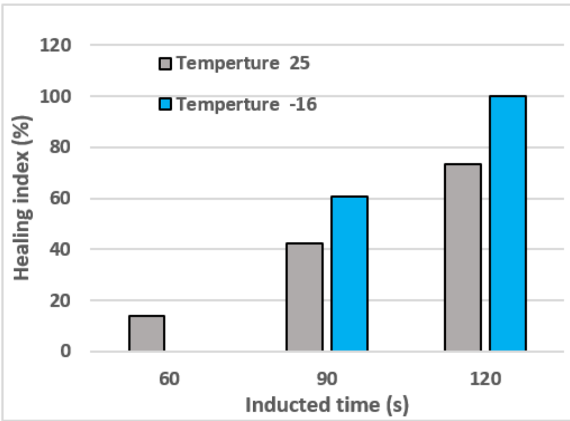


Fig. 11. Self-healing index in terms of fracture energy of warm mixture asphalt with a crack depth of 10 mm and a frequency of 88 kHz

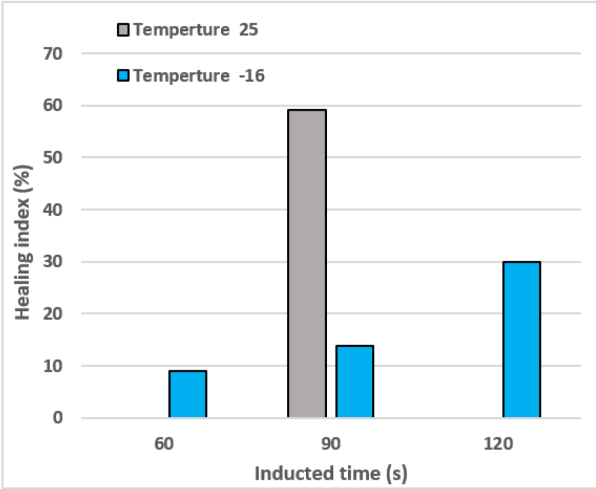


Fig. 12. Self-healing index in terms of fracture energy of warm mixture asphalt with a crack depth of 20 mm and a frequency of 88 kH

7. Artificial Neural Network Model

MLP Perceptron multilayer neural network with 9 input variables, three hidden layers and one output layer has been used for modeling. The weight of each variable was defined in such a way as to establish a meaningful relationship between the input data vector and the output data vector. In this way, small weights were given to each of the variables and then, using the algorithm, the feedback of the errors was adjusted. The first step in following the neural network is to determine the data of the input space and the target, in which the parameters of induction time, test temperature, fracture toughness, frequency, notch length and area are investigated as network inputs and the self-healing index measured as the target. The network was considered. The main problem in designing these networks is to determine the appropriate number of hidden layers and the number of hidden neurons in the middle layers. An artificial neural network can have two or three hidden layers. In general, the higher the number of layers, the more complex the system is able to understand, although on the other hand, the higher number of layers reduces the prediction accuracy and may prevent the convergence of the network. Multilayer networks are very powerful, for example, a two-layer network with the first sigmoid layer and the second linear layer can estimate any arbitrary function with a limited number of discontinuity points. Figure 13 shows the perceptron neural network model with 9 inputs, 3 hidden layers.

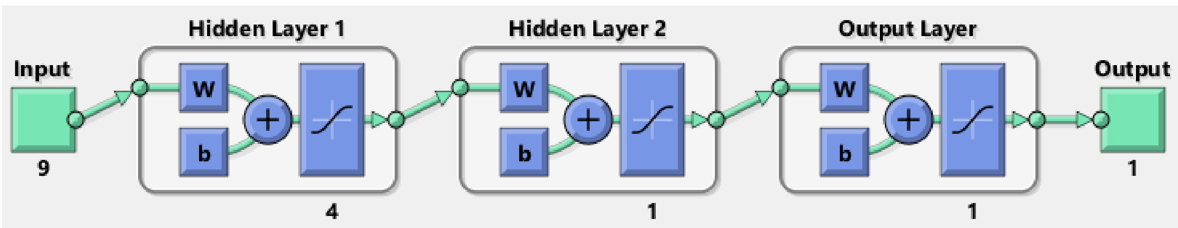


Fig. 13. Perceptron neural network model with 9 inputs, 3 hidden layers

In a multilayer neural network, each layer has a weight matrix, bias vectors and specific outputs. and the output of each middle layer is used as the input of the next layer. For this reason, in solving such problems, neural networks are used, which consist of several neurons or several layers and work together in parallel. Therefore, in the present study, a three-layer neural network was considered due to its great ability to model complex and nonlinear systems with two hidden layers with a sigmoid function and a linear transfer function for the output neuron. The optimal neural network is selected from among 100 trained neural networks with the least error.

Figure 14 show the regression diagram shows the outputs of the neural network according to the objectives of training, validation and test sets. For a perfect fit, since most of the data is located along a 45 degree line, then there is a perfect fit between the datasets for learning the network. Also, this graph shows that the coefficient of explanation of the neural network model for training, validation and evaluation data is 0.99717 for training, 0.62053 for validation and 0.9301 for testing. These values show the high fitting ability of the proposed neural network model correctly.

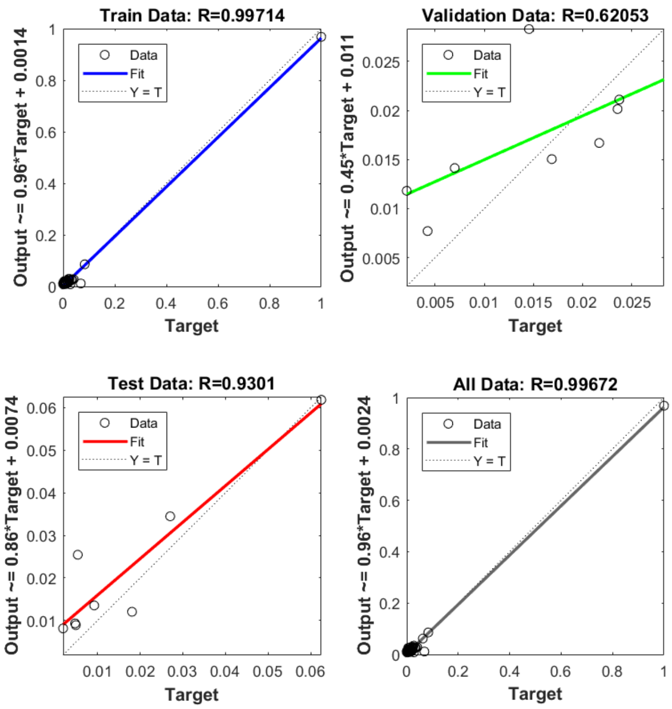


Fig. 14. Linear regression results between experimental values and artificial neural network model

As can be seen in the Figure 14 and 15 the mean square error of the grid starts from a large value and gradually decreases. This means that the learning process of the network has progress. The above diagram has three lines, where the input and target vectors are randomly divided into three training sets. The validation set is used in order to maintain the generality of the network. The training procedure continues until the network error shows a decrease in the case of the evaluation network. In this way, overfitting of the network on the training set is prevented. Also, this diagram shows the MSE error values obtained by the model, as it can be seen from the data validation process in this Figure 15, the lowest value obtained for the mean squared error is 4.9223x10^(-5) and in epoch 14 Is.

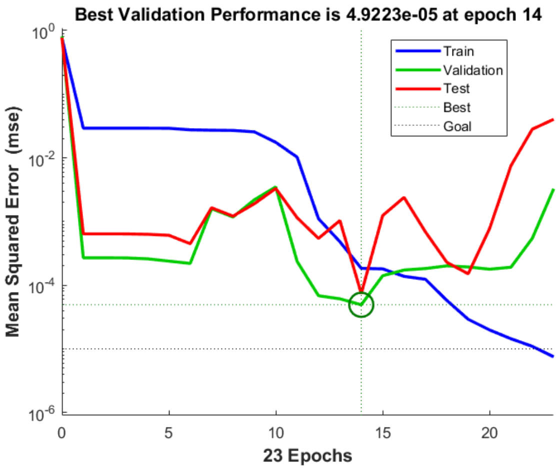


Fig. 15. Optimal learning model of MLP neural network

The results obtained in this experimental study are analyzed comparing with data from other studies. In the research done by researchers they prove that Electrical conductivity and induction heating rate of asphalt concrete increase significantly by adding conductive materials and in this study, we prove that By increasing the presence and size of conductive additive (iron powder) in the asphalt mixture, the ability to create and maintain a magnetic field in induction heating increases. This issue will increase the temperature of the sample and optimal repair of the samples.

In another study by researchers the prove that Non-uniform distribution of additives leads to non-uniform temperature distribution in asphalt mixtures, which causes overheating and aging phenomenon in bitumen due to the proximity of inductive additives. And we prove with the increase in the presence of iron powder, the induction power and time equal to the temperature of the sample increased, and also with the increase in the size of the iron powder in the asphalt mixture due to the tendency to create a larger and larger magnetic field, the maximum temperature of the mixture is higher than the iron powder with a smaller size. As a result, if the size of iron powder increases in the asphalt mixture, the temperature of the sample increases to some extent, but the spread and spread of temperature is less due to the decrease in the amount of iron powder in the same weight on the surface of the sample. In another study done by researchers their result showed that Bitumen, as the main binder of asphalt particles and mixture, is very effective in the development and improvement of asphalt self-healing. The self-healing ability increases continuously with increasing temperature. Repair temperature is more important than repair time and we prove that in self-healing by induction heating method, due to the creation of magnetic field in asphalt samples, temperature and duration are equally important.

8. Conclusion

One of the goals of this research is to determine some of the mechanical and rheological properties of bitumen's modified with activated carbon and to investigate the use of activated carbon in improving the rutting resistance of asphalt mixtures with the aim of self-healing asphalt mixtures. Adding modifiers to pure bitumen, which has some weaknesses, improves the viscoelastic behavior of bitumen and changes its rheological properties. Based on the laboratory tests performed on bitumen with different additive percentages, as well as the analysis of the performed and compared data, the following results and summaries have been obtained: The results show that the use of activated carbon increases the values of shear modulus (G*). It also improves the properties of modified bitumen at all temperatures. Adding activated carbon to bitumen leads to the formation of a network structure in bitumen molecules, which increases the composite modulus G*.

i. The presence of active carbon as a part of the asphalt mixture filler maintains and increases the resistance, as well as improves the tendency to absorb electromagnetic currents to apply the repair in the form of induction heating.
ii. The resistance of the asphalt mixture against breaking and cracking, as well as the maximum force tolerance at the temperature of -16°C is higher than at the temperature of 25°C, which is one of the reasons for the reduction of flexibility of bitumen at low temperature.
iii. Induction heating is a desirable method with economic and environmental benefits, taking into account the positive effect on the repair of asphalt mixture, and it brings the temperature of the asphalt mixture to the desired and desired level in a short period of time and by spending less energy than other methods.

For modelling, perceptron multi-layer neural network (MLP) with 9 input variables, three hidden layers and one output layer has been used. The results showed that the explanation coefficient of the neural network model for training, validation and evaluation data was 0.99717 for training, 0.62053 for validation and 0.9301 for testing. These values correctly show the high fitting ability of the proposed neural network model. Also, the lowest value obtained for the mean squared error is 4.9223x10^(-5) and in epoch 14.

9. Recommendations

Among the suggestions to continue the process of this research in order to achieve other results is to examine the semicircular bending test process at a temperature lower than -16 ^{0}C.

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