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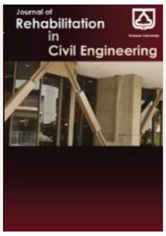

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Investigation of Rheological Characteristics of Powdered Activated Carbon Modified Bitumen for Use in Self-Healing Mechanism of Asphalt Concrete

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ABSTRACT

Asphalt pavement is used in road construction with the aim of withstanding loads and heavy traffic. Increasing axial loads and heavy vehicle traffic lead to failures, including rutting, thermal cracking, and fatigue cracking. These are the three most frequently observed distresses, especially in high-temperature regions that affect flexible pavement performance. Various studies over the years have investigated the causes of Hot mix asphalt failure and proposed a number of solutions to such failure problems. For upgrading the properties of asphalt mixtures against rutting, the asphalt bituminous exploited in the asphalt mixture was modified by employing Powdered Activated Carbon in this investigation. To apply the aging phenomenon, the specimens of control asphalt concrete and the specimens modified with Powdered Activated Carbon were held in the oven for 5 days at a temperature of 85 °C. Bending beam rheometer (BBR) and dynamic shear rheometer (DSR) tests were performed on the specimens. The results revealed that the specimens containing Powdered Activated Carbon exhibited better performance against rutting. By adding 5% Powdered Activated Carbon, the high operating temperature of pure asphalt binder in the aged state has reached from 58 °C to 82 °C.

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1. Introduction

Asphalt and flexible pavements consist of various layers, including subgrade, subbase, base, and asphalt layers. Although asphalt pavement appears to be a simple structure, however, it is indeed so complex and is probably one of the most sophisticated civil structures [1]. The rate of failures in pavements has enhanced because of environmental considerations and increasing the number of vehicles and imposed loads, as well as weather conditions [2].

Because asphalt binder constitutes the primary part of the HMA, Characteristics of asphalt mixtures and asphalt bituminous are required to be improved. Asphalt binder is a bonding agent of aggregates in asphalt concrete, which has a key role in the efficiency of the mixture. Thermal sensitivity and physical characteristics of asphalt binder influence the ultimate function of asphalt mixture [3].

Rutting failure is among the most critical and effective phenomena in the pavement's remaining service life (RSL). Rutting influences the pavement performance and flexibility and can result in the occurrence of major failures in pavement by factors such as loading and weather conditions. Besides, the hardening of asphalt binder in asphalt mixture can cause an increase in cracking problems in the pavement. Enhancement of pavement cracks can lead to other failures in pavement service time and eventually result in pavement distresses. Actually, asphalt binder is a complex chemical compound with both elastic and viscous properties, which relies on two factors of time and temperature [4]. The four main chemical components of asphalt binder are SARA (Saturates, Aromatics, Resins, Asphaltenes), reflecting the colloidal index (CI) of asphalt binder. Asphalt binder needs specific properties, including viscosity, flexibility, permanent deformation, cracking resistance, permeability, adhesion, and stability, to be used in the pavement [5]. An enhancement in the ratio of asphaltene to resin results in the formation of a grid structure with high rigidity and enhances the elasticity of asphalt binder while increasing the ratio of resin to asphaltene in asphalt binder leads to excellent temperature-time balance and asphalt binder's viscous behavior.

Asphalt binder, as a base material, contributes to the composition of asphalt pavements and their performance. The mechanical characteristics and general behavior of asphalt mixtures are influenced by the rheological and mechanical characteristics of the constituent materials. Typically, aggregates result in the strength and structural stability of asphalt mixtures, while asphalt binder operates as a cohesive material between aggregates. The bearing capacity of the pavement is dependent on the bond between the asphalt binder and the aggregates [6].

Asphalt binder, unfortunately, exhibits fluid behavior at a high temperature and brittle behavior at a low temperature, leading to the occurrence of thermal cracks at a low temperature and rutting at a high temperature, thereby declining the efficiency of asphalt binder with respect to these temperature sensitivities [7].

To propagate the application of asphalt binder in asphalt mixtures, asphalt binder modification with additives is therefore essential. An ideal asphalt binder should be adequately soft to bear thermal stresses at a low temperature and thus solid at a high temperature to resist deformation and fatigue cracks at medium temperatures. For the choice of the best additive to upgrade the characteristics of asphalt binder against traffic loads, the pavement failures associated with asphalt binder should be detected. As asphalt pavement rehabilitation is so costly, so the prevention of such damage will be very affordable, and the modification of asphalt binders is among the approaches to prevent this deterioration. It was demonstrated in previous studies that UV absorbers (UVAs) could considerably improve resistance against aging [8]. Via absorbing the lightweight constituent of the asphalt binder, Powdered Activated Carbon (PAC) can substantially enhance the asphalt binder aging resistance. Moreover, the addition of this material as a Bio-char modifier to asphalt leads to a reduction in its temperature sensitivity and shear sensitivity [9].

Furthermore, Powdered Activated Carbon (PAC) is intended to serve as an adsorbent additive because of its pores and proper flat structure so that it can lead to reducing the emission of volatile organic compounds (VOCs) from asphalt concrete. Concerning the asphalt concrete behavior at a high temperature, the researchers concluded that adding PAC to asphalt concrete might improve its load distribution capability as well as its performance in rutting and fatigue. Of course, prior studies have shown that adding PAC to asphalt binder at a rate greater than 10% by weight might have negative impacts on the adhesion of asphalt binder and aggregates, leading to pavement durability issues [10]. Another research concluded that permeable asphalt pavement (PAP) is a viable strategy for managing pavement runoff, often referred to as source pollution. Because porous asphalt concrete is an essential component of PAP structure, The purpose of this work is to investigate the possibility of using PAC in pors asphalt mixture to improve the filtrate efficiency of pavement ranof. A series of laboratory studies were conducted to investigate the effect of PAC on the optimal asphalt content and engineering and filtration characteristics of porous asphalt mixtures. PAC increases the optimal amount of the pors mixture asphalt with respect to wear loss and binder drainage tests due to its high absorbent and surfc area. The softening effect of increasing content of asphalt and the effect of PAC hardness both have an effect on PAC strength. In addition, the PAC completely replacing the mineral filler outperforms the control sample without powdered activated carbon in filtration efficiency and moisture stability. PAC can change the absorption of the asphalt film and increase the pollutant removal rate. In addition, the residues of the acidic compound on the PAC surface penetrate into the effluent solution and slightly decrease the pH value. In addition, the effect of thickness and air void content on pollutant removal rate of PAC samples shows different trends. For permeable asphalt pavement, a PAC layer with a thickness of 6 cm and an air void content of 18% is recommended to provide optimal filtration efficiency of pavement runoff [10]. Elif Sima et al investigated the effect of PAC, derived from agricultural waste Mark and Vinas and used in bitumen modification, on the rheological properties of bitumen binder and mechanical properties of hot mix asphalt. PAC, obtained from the distillation process in the preparation of alcohol from molasses with grape marc, was used for this purpose. PAC was added to clean bitumen (PG 58-16) in 3 different proportions (5%, 10% and 15% by weight of neat glue). The following tests were used on clean and modified bitumen: DSR, BBR, classical bitumen tests. HMA samples were obtained using clean and modified binders. The following tests were used for the HMA samples: Marshall stability and flow, cyclic creep, resistance to moisture damage, indirect tensile stiffness modulus, and indirect tensile fatigue. Based on the binder test results, it was found that the use of PAC in bitumen modification increases the stiffness and high-temperature performance of bituminous binders, while it has little effect on the low-temperature performance. According to the results of the mixture tests, the use of PAC modified bitumen increased the Marshall stability, stiffness, resistance to fatigue cracking and permanent deformation of the mixtures. On the other hand, the use of PAC in bitumen modification had a negative effect on the resistance to moisture damage [11].

2. Research methodology

The main objective of study was to evaluate the addition of powdered activated carbon (PAC) to the rutting and tensile strength of asphalt mixtures. Therefore, the desired asphalt binder was modified using powdered activated carbon, and asphalt binder tests including (BBR) and (DSR) were performed on samples containing pure asphalt binder and asphalt binder modified with powdered activated carbon. Aging and aging conditions In addition, the results of (BBR) and (DSR) tests were compared in control and modified samples at different aging levels.

3. Materials

3.1. Asphalt binder

The behavior of the asphalt binder is among the vital components impacting the asphalt mixture function. 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, including low-temperature cracks, high-temperature rutting, fatigue crack, asphalt bleeding and aging, leading to a reduction in the pavements quality and performance [12]. In this study, PG (Performance Graded) 64-22 asphalt binder was exploited, equivalent to the properties of 60/70 penetration grade asphalt cement.

Table 1. The PG specification of asphalt binder utilized in the present study.

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

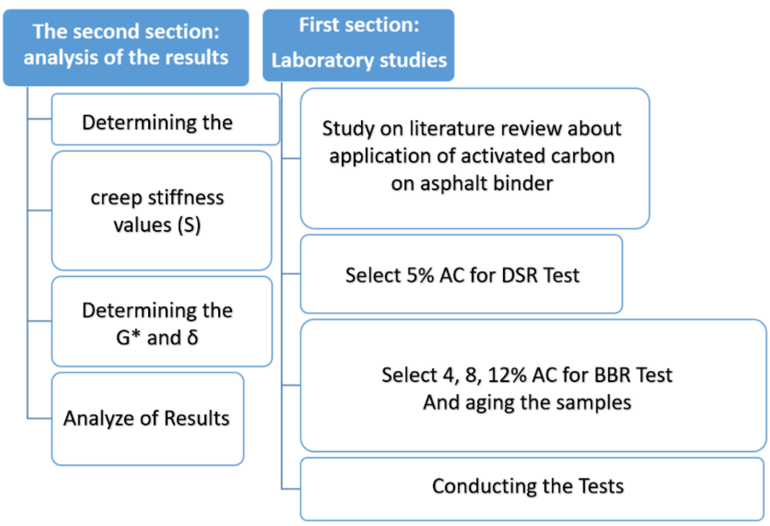

Fig. 1. flowchart of the research method.

3.2. Powdered activated carbon (PAC)

In the present research, Powdered Activated Carbon (PAC) was employed as an additive. It is one form of carbon processed to have small, compact pores, which enhance the available surface area for adsorption or chemical reactions. PAC is a highly porous carbonaceous adsorption medium with a complex structure composed mainly of carbon atoms. The pore networks in Powdered Activated Carbon are channels that form inside a rigid skeleton of irregular layers of carbon atoms, which are chemically bonded together, unevenly stacked, and have a very porous structure of corners, gaps, and gaps [13]. The physicochemical properties of Powdered Activated Carbon applied in this investigation are illustrated in Figure 2 that was prepared and purchased from Fars Avisa Industries.. With regard to previous studies, the excessive addition of PAC causes a reduction in strength. Thus, on the basis of the past studies, the optimum value of PAC in DSR test was selected to be equal to 5% by weight of asphalt binder and for BBR test was selected three percentages of 4, 8 and 12 of PAC are applied [14].

To this end, a high-shear rheometer was utilized. Powdered Activated Carbon was added to the asphalt binder heated to a temperature of 150 ° C and mixed at a shear speed of 4200 rpm for 30 min.

Table 2. Powdered 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/m³
Humidity	4% w/w≤

Fig. 2. Image of Powdered Activated Carbon.

3.3 Aging process of specimens in the laboratory

Among the initial objectives for the classification of asphalt binders is performed by Strategic Highway Research Program (SHRP) technique, in which tests should be close to field conditions. In the Hot-Mix Asphalt (HMA), as the asphalt binder is aged during the asphalt manufacturing and spreading process, an approach should be provided to model the asphalt binder aging for assessing and predicting the behavior and failure of the HMA pavement. Typically, asphalt binders lose their volatile materials in manufacturing asphalt mixture and its spreading. While the temperature increases during the process of manufacturing and spreading, volatile materials are separated from the asphalt binder leading to enhanced viscosity and aged asphalt binder. Field experiments demonstrate that asphalt binder at the site does not lose a considerable amount of its volatile material. The primary component intended in the Rolling Thin Film Oven (RTFO) Test is the drop in volatile material although numerous parameters are influential in the aging of asphalt binder [15]. The Rolling Thin Film Oven (RTFO) Test is utilized to simulate aging during the mixing and placement of asphalt mixtures; Pressure aging (PAV) testing is used to simulate aging over the life of asphalt pavements. Thus, asphalt binder tests, which are associated with mixing and spreading characteristics (such as the Dynamic Shear Rheometer (DSR) test), are performed on aged specimens obtained from the RTFO test; moreover, asphalt binder tests, which are associated with asphalt binder performance on-site (such as Bending Beam Rheometer (BBR), Dynamic Shear Rheometer (DSR), and DTT (Direct Tension Test)) is conducted on asphalt binder specimens, which were initially aged under RTFO test and then PAV test.

Asphalt binder aging is among the main causes of asphalt binder failure in the pavement that has occurred during mixing, construction and during the remaining life of road pavement. What causes asphalt binder to age is the release of oxygen and ultraviolet (UV) rays, which has a clear effect on the aging of the upper pavement layers [16].

Aging techniques in the laboratory are primarily established on the basis of increasing the oxidation rate and accelerating the evaporation of asphalt binder petroleum oils. To speed up the deterioration phenomenon, the following methods are exploited: A) increasing the temperature, b) reducing the tested asphalt binder thickness, c) increasing the asphalt binder surface exposed to oxygen, d) increasing the airflow (blowing oxygen or air on the asphalt binder specimen), and e) increasing the pressure.

Asphalt binders before DSR test are aged with pave method to determine the fatigue property and aged with RTFO method to determine the G* and rutting resistance.

4. Tests

4.1. Rolling thin film oven test (RTFOT)

This test simulates the short-term aging conditions of the asphalt binder. The way of conducting the RTFO test in AASHTO T240 and AASHTO D2872 standard has been expressed.

4.2. Bending beam rheometer (BBR) test

A test employed to evaluate the performance of the asphalt binder at a low temperature is the bending beam rheometer test. This test was applied to specify the creep value of an asphalt binder at a constant temperature and load. To assess the impact of Powdered Activated Carbon (PAC) on thermal crack resistance, a flexural beam rheometer was carried out at three temperatures of -12, -18 and -24 ° C on pure and modified asphalt binders. The results are shown in Fig. 3 and 4 shows the m value for aged asphalt binders tested under pressure aging tank (PAV).

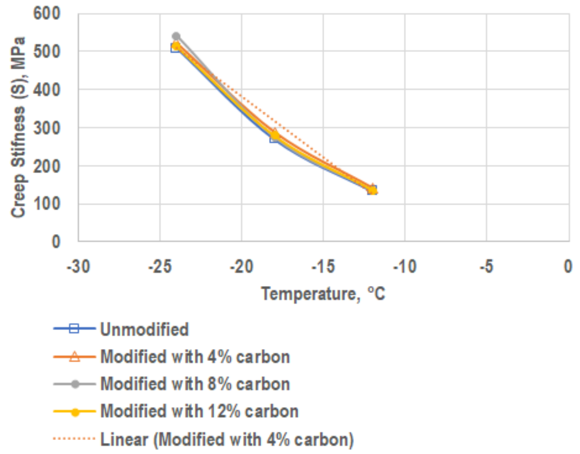

Fig. 3. Results of creep stiffness values (S) in terms of temperature.

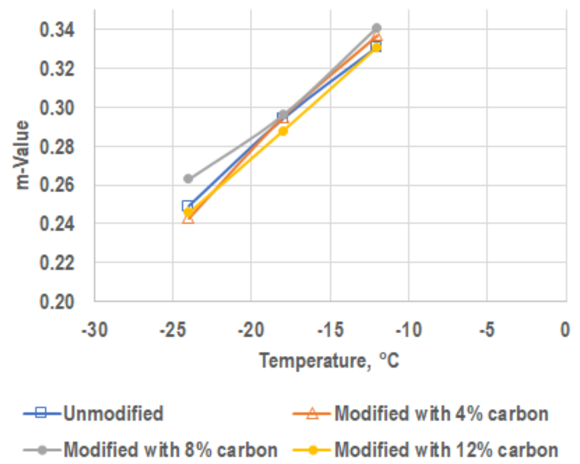

Fig. 4. Results of the m-values in terms of temperature.

Also, the IR[1] parameter was used to evaluate the SHRP researchers, employing the time-temperature rule in cohesive materials, argue that the equivalent creep stiffness can be considered through an increase in the test

[1] Improvement Ratio

temperature at a rate of 10 ° C and using a load for 60 seconds, which results in specifying the test result in a shorter time. According to the requirements of the Superpave mix design method, the creep stiffness should not exceed 300 MPa in 60 seconds.

4.3. Dynamic shear rheometer (DSR) test

This test measures the viscosity and elasticity of asphalt binders. It determines the δ and the G* at moderate to high temperatures (5 to 80 °C), which can be used for asphalt binders with dynamic shear modulus from 100 Pa to 10 MPa. All DSR tests are performed using the SHRP method with a frequency of 10 radians per second is to 1.59 Hz (cycles per second). G * represents the overall resistance of an asphalt binder to deformation under sinusoidal shear stress. Complex shear modulus consists of two components: viscous (irreversible) and elastic (permanent). The phase angle also indicates the relative amount of permanent and irreversible deformations. The amount of phase angle and complex shear modulus for asphalt binders mainly depends on the temperature and loading frequency. The rutting is controlled by limiting the value of G*/Sinδ to a value higher than 1 kPa for pure asphalt binder and 2.2 kPa for asphalt binder due to the aging process of the rolled thin film furnace test. In addition, fatigue cracking is controlled by PAV by limiting the value of G* × Sinδ for the aged asphalt binder to less than 5000 kPa at the test temperature.

A dynamic shear rheometer (DSR) test was performed at a constant frequency of 10 radians per second under controlled strain. The applied strain was small enough so that all tests be performed in the Linear Viscoelastic Region (LVER). The overall shear stress modulus and phase angle at different temperatures were achieved to be between 52 and 64 ° C during the tests. Figures 5 and 6 represent the tests' results for pure and modified asphalt binders.

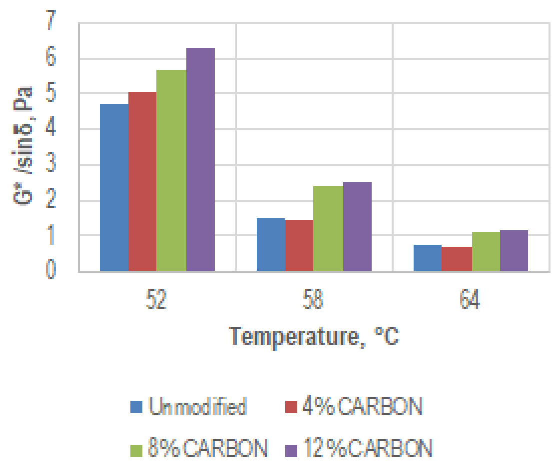

Fig. 5. The ratio of G*/Sinδ against temperature for pure and modified asphalt binders.

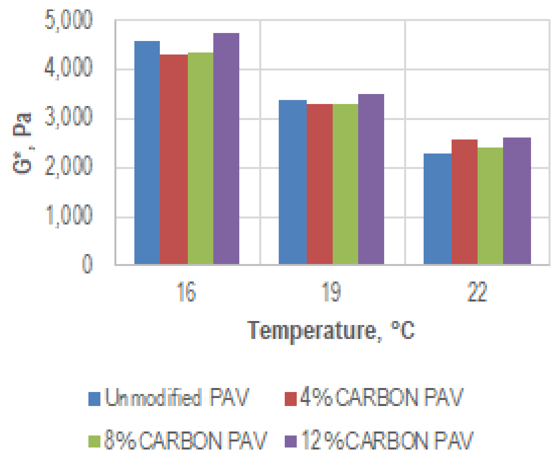

Fig. 6. Total shear modulus stress against temperature for pure and modified asphalt binders.

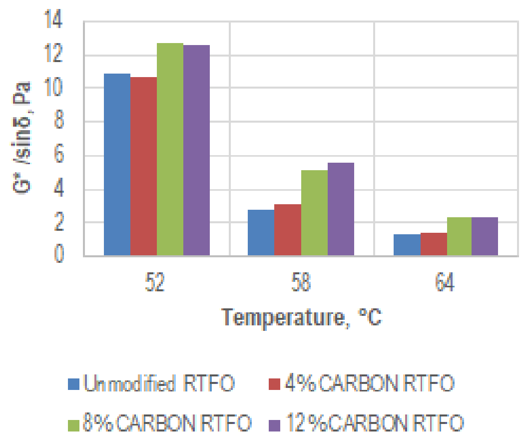

Fig. 7. The ratio of G*/Sinδ against temperature for pure and modified aged asphalt binders.

Rutting is considered the natural effect of cyclic loading under constant stress. A certain part of the work is performed to deform the pavement during the cyclic loading of passing traffic. Part of the work performed is damped by the elastic and reciprocating motion of the pavement surface, whereas the rest is done., which is denoted by Wc, leading to deformation and heat on the pavement surface. In order to decline the rutting, the Wc value, noted in the following equations, should be therefore reduced.

$$Wc = \pi\partial \in \sin\partial \tag{1}$$

With regard to the constant value of stress and the correlation between ε, σ, and G*, in Equations 2 and 3 is gained:

$$\partial = \partial \frac{\in}{G*} \tag{2}$$

$$W = \pi \frac{\partial^2}{\frac{G*}{\sin\theta}} \tag{3}$$

Concerning Equation 3, one can infer that any rise in G* or drop in sinδ results in a reduction in Wc. This association reveals that the asphalt binder will be rigid as the G * is higher, and the resistance against the pavement surface deformation will be greater. Besides, as the sinδ value is lower, the asphalt binder elasticity is higher, and the damping section of the work performed on the pavement surface increases. Hence, the asphalt binder resistance to rutting will be greater as the G*/Sinδ value is higher. The majority of studies have demonstrated that the energy dissipation under repeated loads will be faster as the G*×Sinδ value is more, and the resistance to fatigue damage of asphalt binder and asphalt mixtures will be less. Hence, G* × Sinδ is named the fatigue factor. Moreover, G∗/sinδ indicates the rutting factor. Thus, dynamic tests have more visual and realistic benefits to assess the functioning of asphaltic binders compared to static tests (e.g., penetration and softening point). As previously noted, two specimens were prepared using the results of the DSR test to compare modified and pure asphalt binders. The first specimen was prepared from the pure asphalt binder and the second specimen from the modified asphalt binder. In accordance with what is represented in the figure, the modified asphalt binder chart is placed at the top of the pure asphalt binder chart. This means that the G*/Sinδ value for modified asphalt binder is greater than that in pure asphalt binder at any constant temperature. Therefore, one can realize that the rutting resistance in the modified asphalt binder is much higher compared to the non-modified asphalt binder. As seen in figures 5 to 7 the G*/Sinδ index has been intended as a criterion to investigate the resistance of asphalt binder to rutting in the technical specifications of the Superpave mix design method. The more the value of the G*/Sinδ index, the asphalt binder resistance to permanent deformation will be higher. Compliance with the SHRP standard, the G*/Sinδ value is suggested at least 1 kPa for the unaged asphalt binders and 2.2 kPa for the aged asphalt binders after the RTFO test to prevent the occurrence of the rutting phenomenon. The high operating temperature of pure asphalt binder has increased in both the unaged and aged scenarios. Another important thing is the impact of Powdered Activated Carbon on the rutting parameter. As can be observed, Powdered Activated Carbon causes an enhancement in the G*/Sinδ value, thereby improving the performance of the asphalt binder at a high temperature. The addition of Powdered Activated Carbon to asphalt binder results in a network skeleton formation in asphalt binder molecules, leading to increasing the complex shear modulus G* and reducing the value of the phase angle δ. Hence, the asphalt binder resistance to rutting is enhanced by increasing the elastic deformation rate. The results illustrate that the rutting index of asphalt binder samples is increased with the addition of Powdered Activated Carbon. Utilizing the Powdered Activated Carbon causes an increase in the friction between the Powdered Activated Carbon and the asphalt binder chains and amongst the asphalt binder chains together. It appears that these engagements will lead to an enhancement in the resistance of asphalt binder chains to external forces and resistance to deformation and failure.

5. Statistical studies

In order to get the effect of all three variables by considering the conditions that existed for each variable, we used an objective function. The objective function is the sum of the differences of each variable from its minimum value. The third variable is considered with a negative sign because it must be far from the maximum value. To achieve the best result according to the existing conditions, the objective function must have its maximum value. For the three available temperatures denoted by t1, t2 and t3. The value of this function was calculated in percentages of 0, 4, 8 and 12 percent. The optimal percentage is the percentage in which the value of the objective function is maximized. At temperature t1, this maximum value occurred at 0%, but at temperatures t2 and t3, this maximum value occurred at 4%. It may be concluded that by increasing the percentage, the value of the function always decreases and the maximum value always occurs between 0 and 4%.

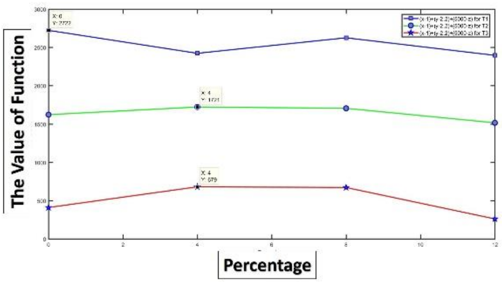

Fig. 9. Results of the electrical resistance of mixtures.

6. Electrical resistance of bitumen test

To study the activated carbon impact on the electrical conductivity of asphalt mixtures, asphalt samples containing 4, 8, and 12 percent of activated carbon were subjected to electrical resistance tests. To evaluate the electrical resistance of the asphalt sample, a precise digital nano Siemens multimeter connected to two aluminum electrodes with dimensions of 110 x 110 mm was used. Fig. 10 depicts the electrical resistance results of each of the mixtures. According to the results, the electrical resistance of the asphalt mixtures decreases with the increase in the percentage of active carbon in the asphalt mixtures.

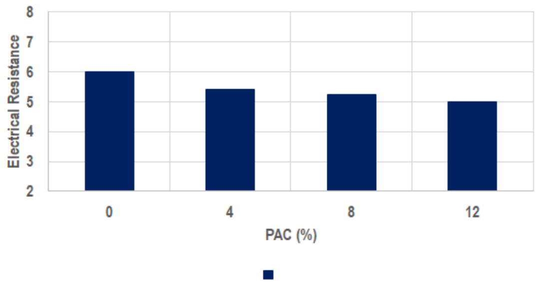

Fig. 10. Results of the electrical resistance of mixtures.

7. Conclusion

The main aim of this paper is to identify some of the mechanical and rheological characteristics of asphalt binders modified with Powdered Activated Carbon (PAC) and examine the application of PAC to improve the rutting resistance of asphalt mixtures aimed at the self-healing phenomenon of asphalt mixtures. Adding modification factors to pure asphalt binder, which is associated with some bugs, upgrades its viscoelastic behavior and varies its rheological characteristics. The following results and conclusions were achieved on the basis of laboratory tests performed on asphalt binder with various percentages of additive and analyzing the performed and compared data:

The study outcomes reveal that employing Powdered Activated Carbon enhances the shear modulus values. Moreover, Powdered Activated Carbon improves the modified asphalt binder properties at all temperatures.

Adding PAC to asphalt binder results in the formation of a network skeleton in asphalt binder molecules, leading to increasing the complex shear modulus G* and reducing the value of the phase angle δ. Hence, the asphalt binder resistance to rutting is enhanced by increasing the elastic deformation rate. The results illustrate that the rutting index of asphalt binder samples rises with the addition of Powdered Activated Carbon. Utilizing the PAC causes an increase in the friction between the Powdered Activated Carbon and the asphalt binder chains and among the asphalt binder chains together. It appears that these engagements will lead to an enhancement in the resistance of asphalt binder chains to external forces and resistance to deformation and failure. Considering the reasonable price of Powdered Activated Carbon and considering the use of a low percentage in producing bitumen and asphalt mixtures, along with considering that the use of Powdered Activated Carbon leads to the creation of a magnetic field to healing the asphalt mixture to self-healing, it can be stated that the use of Powdered Activated Carbon has properties that the polymer does not have and are not comparable, and we will pursue more goals from using Powdered Activated Carbon in addition to improvement of the mechanical characteristics of bitumen.

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