Research Article

Ahmed Wasfi Obaid*, Ali Al-Dahawi, Khawla K. Kawther, and Ahmed Subhi Abduljabbar

Self-sensing behavior of hot asphalt mixture with steel fiber-based additive

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Abstract: Scientists and engineers are consistently working to enhance the performance attributes of asphalt concrete mixtures. Pavement condition monitors, despite their high cost and long-term inaccuracies, are utilized for assessing pavement conditions and determining the level of deterioration. Consequently, they provide crucial data for the design, cost estimations, and development of pavement maintenance programmers. In recent times, there have been significant technological advancements and the introduction of new characteristics, such as the self-sensing feature. This study utilized this feature to build hot asphalt mixtures with several functionalities. The incorporation of conductive elements into asphalt mixtures enhances their electrical and mechanical characteristics. The objective of this study is to develop a hot asphalt mixture with electrical conductivity capable of detecting applied loads through conducting experimental tests such as the Marshall and compression tests. The asphalt grade used was between 40 and 50, and the aggregates were in proportions that met the Iraqi requirement. The asphalt mixture contained 2.5% steel fibers by volume, which were added to investigate their impact on the functional performance of the asphalt mixtures. An analysis was conducted on the samples' behavior during the tests, revealing a discernible alteration in the electrical resistance measurement. This alteration demonstrated that the asphalt mixture detected the weights exerted upon it. The findings also indicated a rise in the Marshall stability metric. The advanced asphalt mixtures and their novel features allow for the monitoring of pavement conditions. Through the resolution of monitoring device issues, they additionally offer superior performance and extended lifespan.

Keywords: steel fiber, electrical resistivity, multifunctional asphalt concrete mixtures, marshall test, hot asphalt mixture

*** Corresponding author: Ahmed Wasfi Obaid,** Department of Civil Engineering, University of Technology, Baghdad, Iraq, e-mail: bce.22.48@grad.uotechnology.edu.iq
Ali Al-Dahawi: Department of Civil Engineering, University of Technology, Baghdad, Iraq, e-mail: ali.m.aldahwi@uotechnology.edu.iq
Khawla K. Kawther: Department of Civil Engineering, University of Technology, Baghdad, Iraq, e-mail: 40232@uotechnology.edu.iq
Ahmed Subhi Abduljabbar: Department of Civil Engineering, University of Technology, Baghdad, Iraq, e-mail: 40095@uotechnology.edu.iq

1. Introduction

Engineered infrastructures are necessary in modern societies to support civil activities. These infrastructures, which play a significant role in our lives and include pavements for roads and airports, bridges, transit systems for the subway, dams, wastewater treatment facilities, and buildings along the coast, are always susceptible to wear and tear from environmental variables and loads. Due to the risks they pose to human activities and lives, these deteriorations necessitate systems for maintaining or replacing structures [1]. Highways are essential for connecting cities, easing transportation, and representing progress and development. Their importance to human life cannot be emphasized. The global problem of road safety requires a scientific approach to develop research procedures that produce dependable and accurate outcomes. Safe, smooth, and economical traffic movement is one of the functional goals of pavement [2–4]. The formulation of maintenance plans, controlling quality during construction, identifying deterioration early, and taking preventative action to extend the life of the pavement all depend on accurate, continuous monitoring of the tension and deformation of the pavement structure in real-time. To ensure the pavement's best performance and safety, this novel approach offers useful and important advantages [5]. The design and application of methodologies and strategies for the continuing monitoring and retention of the usefulness of a structure is known as structural health monitoring, or structure health monitor (SHM). Structures may have longer design lives, maintain public safety, and incur much lower restoration costs if SHM is used. This ground-breaking method offers continuous monitoring and early identification of possible problems, enabling fast corrective action and reducing the danger of catastrophic failure [6]. Through condition-based maintenance, implementing actual time state evaluation and SHM approaches in civil infrastructure can improve structural safety and extend maintenance intervals [1,7]. The pavements of highways in Iraq are affected by many different kinds of damage [8]. Pavement failure can occur due to congested traffic and unfavorable environmental conditions [9]. Cracking in flexible asphalt pavements is a significant cause of problems on road networks [10]. Pavement rutting is the main kind of determined deformation. The phenomenon is a result of the gradual accumulation of minor, enduring deformations in the pavement material due to repetitive driving pressures [11]. To evaluate degradation, such as that brought on by crowded cars [12,13] or fatigue from traffic, weigh-in-motion data can be used directly. Underestimating roadway use can result in overestimating service life and, as a result, unexpected structural failure [14,15]. Considering the growing traffic volumes on roadways, it is imperative to carefully analyze the reuse of components that enhance the quality of asphalt [16]. They may disrupt transportation networks, increasing expenses for motorists, traffic authorities, and the general public [17]. The capacity to identify applied stresses, monitor the progression of strain and deformation, and detect the occurrence of cracking while also providing timely notifications on the deterioration of infrastructure. The disadvantages of conventional traffic detectors are their exorbitant price, poor sensitivity, the survival rate, and poor durability. Additionally, a few of these do not work well with pavement surfaces, which reduces the lifespan of the pavement [18–23]. Asphalt is extremely temperature-sensitive, brittle at low temperatures, and fluid at relatively high temperatures. Poor characteristics are primarily to blame for the asphalt concrete's decay. From a historical standpoint, this analysis focuses on designing asphalt mixtures with many types of pavement distress, including bending, reflection cracking, fatigue cracking, and moisture damage [24]. In more recent years, many researchers have made claims about alternative prospective uses for fibers in asphalt concrete. The use of conductive fibers, such as steel, carbon, and fillers, in electro-thermal applications for asphalt concrete has been seen [25]. Initiated by Minsk in 1968, the idea of electrically conductive asphalt concrete (CAC) has seen tremendous growth in popularity over the past 10 years, leading to an increase in publications. The benefits of using the electrical characteristics of asphalt composites have served as a major driving force behind these initiatives. The application of conductive pavements to melt the purpose of melting snow and ice through electrical heating has been the subject of extensive investigation [26]. Moreover, it is anticipated that using electric heating in conductive asphalt pavements will promote self-healing by reducing the duration required for recovery. Additionally, the conductive asphalt's piezoresistivity, which describes an alteration in electrical resistance with applied mechanical pressure can be employed for the self-sensing of strain [27]. Self-sensing of damage for determining pavement distress is plausible. Furthermore, by increasing the hardness of the asphalt concrete, using fiber-type conductive additives can enhance pavement systems' potential to improve the longevity of pavement systems and promote their sustainability [28,29]. Self-monitoring refers to the inherent ability of a structural material to independently track and evaluate its own properties, such as strain and damage. Self-monitoring differs from the use of embedded or attached sensors due to their high cost, limited durability, restricted sensing capacity, and potential degradation of mechanical properties in the case of embedded sensors [30]. A different method, referred to as self-sensing, utilizes the structural material to detect its presence without the need for additional sensors. As a result, the structural material serves many functions. Self-sensing is preferable to the utilization of integrated sensors because of its cost-effectiveness, stability, extensive sensing capacity, and the absence of any negative impact on the mechanical functionality of the structure. Embedded devices generally result in a reduction in mechanical efficiency. Moreover, the repair of embedded devices involves invasive procedures [31]. Studies were conducted on the piezoresistivity mechanism of electrically CAC by examining the conductive properties and mechanisms of carbon fiber and graphite-modified asphalt concrete. In addition, a sequential model was created to explain the self-sensing ability of CAC [32]. The self-sensing behavior, mechanical properties, fatigue resistance, and morphological properties of the carbon nanotube (CNT)/epoxy resin composite were evaluated. In order to understand the fundamental conduction process related to the composite properties, different weight ratios of CNTs and the resulting evolution of conductive network systems were studied using morphological characterization [33]. The effect of steel fiber (SF) on the indirect tensile strength (ITS) of asphalt mixtures was studied. These studies have consistently demonstrated a significant enhancement in ITS when employing a composite material consisting of 11% SF as a reinforcing agent. Adding a high fiber content to the asphalt mixture reduced the thickness of the mastic film, thereby leading to a fall in the ITS. Consequently, there was a notable deficiency in the bonding strength among the constituents of the asphalt mixture [34]. Additionally, several experiments have demonstrated that various types and concentrations of conductive fibers or fillers have discernible impacts on electrical and technical properties. The selection of conductive additives is commonly impacted by the efficacy of CAC in road applications. To ensure the fulfillment of durability criteria, it must be imperative that the conductive additives do not exert any adverse impact on the engineering properties of asphalt concrete [35,36]. Monitoring pavement structural conditions, especially stress–strain parameters, etc., play a crucial role in the design, construction, servicing, costing, and maintenance of asphalt roads. In recent years, the self-sensing property has provided a new approach to technological innovation for sensing applied pressure on flexible pavements. This study aims to prepare samples of hot asphalt mixture containing an electrically conductive material and monitor the amount of change in electrical resistance when loads are applied to them, as well as compare their Marshall stability and flow values to the control sample.

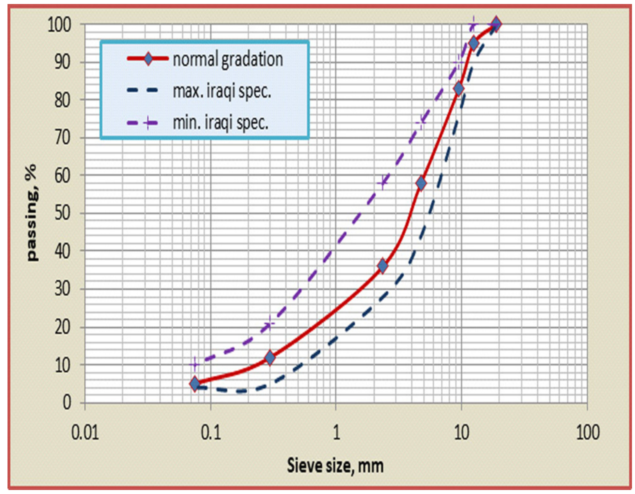

Figure 1: Selected gradations according to SCRB specifications [37].

2. Materials and experimental work

2.1 Materials

2.1.1 Asphalt

Al-Daurah Refinery produced the 40–50 penetration grade asphalt cement. The experimental work of this investigation utilized the physical properties presented in Table 1. The test results adhere to the requirements set by the State Commission on Roads and Bridges (SCRB) [37].

2.1.2 Aggregate

Al-Nibaie quarry quartz that had been crushed served as the aggregate. The coarse and fine aggregates underwent a sieving process. They were subsequently blended in the correct proportions to adhere to the specifications outlined for Type IIIA mixtures consisting of a gradation of materials used for the wearing course, as depicted in Figure 1 [37] and summarized in Table 2. Periodic assessments were conducted for evaluating the physical properties of the aggregate. The fine aggregates range from 4.75 (No. 4) to 0.075 mm (No. 200) sieve. The soil composition lacks clay, loam, other deleterious minerals, and intricate grain structures. The chemical and physical parameters of the coarse and fine aggregates are presented in Tables 3 and 4, respectively.

2.1.3 Mineral filler

The mineral filler contains Portland cement (Figure 2). It is loose and dry with accumulations of small particles. The physical and chemical properties of the mineral filler are shown in Table 5.

2.1.4 SF

SFs are 0.2 mm diameter fibers composed mostly of iron atoms. Composite materials possess several notable benefits, including exceptional stiffness, considerable tensile

Table 1: Physical properties of asphalt cement

Test	Test condition	ASTM designation	Results	Iraqi specification's standard limits (SCRB/R9, 2003)
Penetration	100 g, 25 C, 5 s, (0.1 mm)	D-5	46	40–50
Viscosity	135 C, c.p.	D-4402	612	Min. 400
	165 C, c.p.		155	—
Specific gravity	25 C	D-70	1.03	—
Flash point	—	D-92	319	Min. 232
Ductility	25 C, 5 cm/min	D-113	141	>100
Softening point	(4 + 1) C/min	D-36	52	—
After thin-film oven ASTM D1754				
Penetration of residue	—		38	55^{+}
Ductility of residue	—		109	25^{+}
Loss in weight	163 C, 50 g, 5 h		0.3	—

Table 2: Selected group of type IIIA mixes for the wearing course

Sieve	19 mm	12.5 mm	9.5 mm	No. 4	No. 8	No. 50	No. 200
%Passing	100	98.8	90.5	65.58	49.3	16.5	6.55

Table 3: Physical properties of the used aggregate

Property	Coarse aggregate	Fine aggregate	Limits SCRB/2003
Bulk specific gravity (ASTM C-127 and C128)	2.627	2.568	—
Apparent specific gravity (ASTM C-127 and C128)	2.614	2.626	—
Percent water absorption (ASTM C-127 and C128)	0.93	0.92	—
Angularity (ASTM D5821)	95%	—	Min. 90%
Toughness (Los Angeles abrasion) (ASTM C535)	20.18	—	Max. 30%
Soundness (ASTM C88)	3.9%	—	Max. 12%

strength, reduced weight, notable chemical resistance, elevated tolerance to high temperatures, and slight thermal expansion. These advantageous characteristics contribute to its widespread utilization in civil engineering (Figures 3 and 4). Table 6 highlights some of the specifications of SF material.

2.2 Mix the design with the additive

The conductive materials in the asphalt mixture could not disperse uniformly due to the mixing technique [39]. In most cases, dry conditions are used to add modifier ingredients to the mixture. To assess their impact on the distribution of components inside the asphalt materials, methods to uniformly mix additive materials have also been put forth. Three different techniques were put forth to increase the mechanical and electrical capabilities of asphalt mortars as well as the dispersion of SF-based conductive materials.

2.2.1 The first method

All raw, dry components were combined for 10 min in a mortar mixer. The raw materials collected all the SFs for 10 s.

Figure 2: Portland cement (filler).

Table 4: Chemical composition of the used aggregate

Chemical composition	% Content
Silica, SiO_2	82.6
Lime, Cao	5.38
Magnesia, MgO	0.77
Sulfuric anhydride, SO_3	2.71
Alumina, Al_2O_3	0.47
Ferric oxide, Fe_2O_3	0.68
Loss on lenition	6.65
Total	99.26
Mineral composition	
Quartz	80.35
Calcite	10.78

Table 5: Physical and chemical properties of the mineral filler

Chemical composition	% Content
Silica, SiO_2	21.52
Lime, Cao	62.51
Magnesia, MgO	1.6
Sulfuric anhydride, SO_3	5.62
Alumina, Al_2O_3	3.76
Ferric oxide, Fe_2O_3	3.36
Loss on lenition	1.35
Total	99.72
Physical properties	
%Passing sieve No. 200 (0.075 mm)	97.8
Apparent specific gravity	3.101
Specific surface area (m^2/kg)	357

Figure 3: SFs.

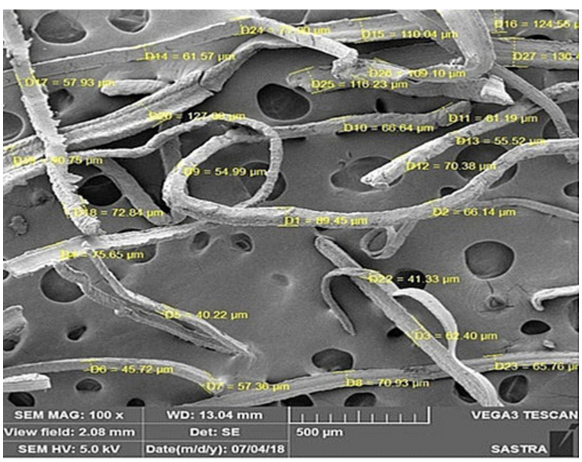

Figure 4: SEM image of SF [38].

2.2.2 The second method

In this method, raw materials are mixed with dry state for 5 min, mixed with asphalt and heated to 150°C. The additive was gradually added during mixing and the mixing process continued for 15 min.

2.2.3 The third method

The third method involved mixing of the raw materials in a dry state with SF for 10 min after physically separating the fibers. Next, the asphalt was added, and the mixture was heated to 150°C and mixed for at least 15 min. The principle of temperature distribution is considered a factor affecting the mechanical properties of hot-mix asphalt [40].

Table 6: Specifications of SF material

Property	Unit	Value
Length	mm	10
Diameter	mm	0.2
Unit weigh	g/cm^3	7.8
Tensile strength	MPa	2,600
Tensile modulus	GPa	200

2.2.4 Method used

After experimenting with the above three methods, it was found that the best way to mix fractions and disperse the SFs homogeneously is by performing the procedures used in the third method, as shown in Figure 5. The detailed structure of the modified asphalt mixture by SF is shown in Figure 6.

The microstructure and dispersion quality of the additive in the modified asphalt mixture were examined using a scanning electron microscope (SEM). Figure 7 displays the SEM images of the asphalt mixture enhanced with SF. The figure shows the uniform dispersion of SF inside the asphalt mixture, which ensures excellent bonding between all the components of the modified asphalt mixture and accurate electrical resistance measurements.

2.3 Mechanical tests of the mixtures

2.3.1 Marshall test

The optimum asphalt content (OAC) for conventional and modified asphalt mixes with five main asphalt concentrations between 4 and 6.5% (by total weight of the mixture) with an increase of 0.5% was calculated by examining a series of Marshall tests (stability, density, and air voids), according to ASTM D2726-08. Three samples with aggregate 12.5 mm (nominal maximum size gradation) in each mixture were created and tested. The OAC for the wearing course layer was accepted using the average value (max stability, max bulk density, and 4% air voids). Marshall samples, created in a Marshall hammer with 75 blows on each side, measuring 2.5 in. in height and 4 in. in diameter, were used in the Marshall test to determine the Marshall parameters. The optimum asphalt, mass, and temperature ratios were among these variables. Among these factors the most suitable proportions were of asphalt, bulk specific gravity, air void volume, aggregate mineral voids, Marshall stability, and flow value. At a loading rate of 50.8 mm/min,

Figure 5: Stages of the method used to mix SF with hot-mix asphalt (HMA).

this test was carried out in a water bath for 60 min at 60°C. The steps for the Marshall test are shown in Figure 8.

2.3.2 Compression test

According to ASTM D695, a compression test is shown in Figure 9. A compression test involves subjecting a material to compression, resulting in its deformation, such as squashing, crushing, or flattening. The test sample is typically positioned between two plates that evenly distribute the applied force over two of the test sample's opposing faces. The sample then flattens as a result of a universal test device pushing the plates together. A compressed sample generally experiences contraction along the direction of the applied forces and expansion in the direction perpendicular to those forces. The compression test is the antithesis of the tension test, a more commonly employed method. The following equation can be used to calculate the amount of stress:

$$q = F/A, \tag{1}$$

where q is the stress, F is the load applied (kN), and A is the area (m^2).

2.4 Techniques for measuring electrical resistivity in composites asphalt

According to previous research, electrical resistance in asphalt compounds is often evaluated by passing a known current between two electrodes inserted or attached to the

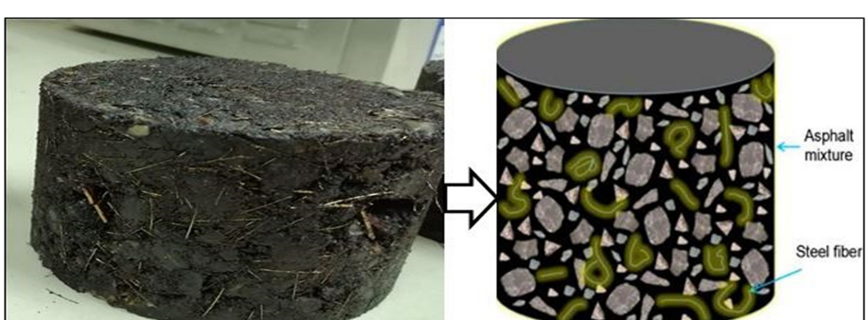

Figure 6: Detailed structure of HMA modified by SF.

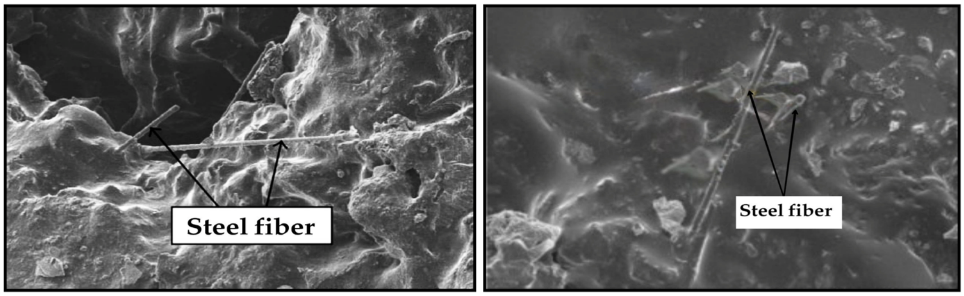

Figure 7: SEM images of the asphalt mixture enhanced with SF.

Figure 8: Marshall test stages.

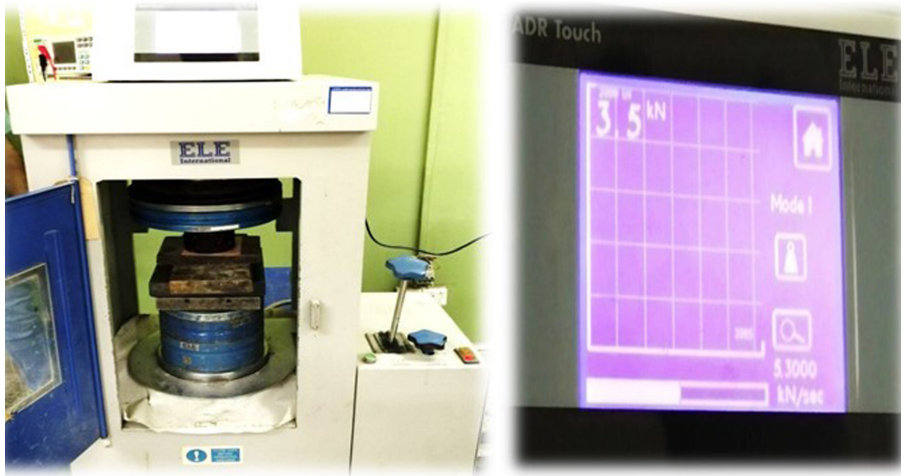

Figure 9: Compression testing.

Figure 10: Stages of sample preparation and electrodes embedment.

examined sample. After measuring the voltages generated by the electrical current flowing through the electrodes, Ohm's law is used to calculate the resistance across the electrodes. The electrode resistance and the measured resistance accounts for the contact resistance between the electrodes and the asphalt-based substance, resulting in an overestimation of the actual electrical resistance, which is often lower. The electrodes used must be made of materials with high electrical conductivity, such as copper, to reduce the effects of contact resistance. Figure 10 shows the steps for preparing the samples with electrically conductive materials and the mechanism of implanting the electrodes. The voltage (mV) and current (A) per second can be measured with a DC source meter to obtain the electrical resistance (ER) values needed for self-sensing. As previously stated using Ohm's law, electrical impedance is calculated in Ohms by dividing the measured voltage by the applied current. Using geometric factors and Eq. (2), impedance values have been converted into resistance values:

$$\rho = RA/L, \tag{2}$$

where ρ, R, A, and L stand for resistivity (Ωm), measured resistance (Ω), the cross-sectional area of the contact area between electrodes and asphalt concrete (m^2), and distance (m) between the internal electrodes, respectively.

Figure 11: Stages of electrical resistivity measurement under Marshall test.

2.4.1 Electrical resistivity measurement under Marshall test

Marshall samples were prepared to contain SF where the copper electrodes were implanted to be well conductive and then placed in the stability and flow measuring device, the wires are connected to the electrodes and then shed load and monitor scale stability, flow, and resistance measuring device using a video camera to study the behavior of the asphalt sample during a certain time and the extent of the change of electrical resistance readings and recording the results for study and analysis. Figure 11 shows the inspection mechanism of the test.

2.4.2 Electrical resistivity measurement under compression test

The same samples used in the Marshall test mentioned above are prepared in terms of containing the SF material, but differ in terms of the way and form of placing the electrodes inside the sample and then putting two pieces of cardboard above and below the sample and then connect the wires of the resistance measuring device. The specimen is placed inside the compression machine, where the load is gradually shed on the model and monitored the load and the amount of change in the measurements of the electrical impedance at the same time using a video recording camera to record the data for studying and analyzing the results. Figure 12 shows the inspection mechanism of the test.

3. Results and discussion

3.1 Marshall test

A set of samples from the Marshall tests (stability, density, and air voids) were investigated to determine the optimal amount of asphalt (OAC) for asphalt concrete mixtures (40–50), with five different asphalt contents for each mixture ranging from 4 to 6% (depending on the weight of the total mixture) with an increment of 0.5%. A maximum size gradation of 19 mm was used in the preparation of three samples for each mixture. In both the traditional and modified mixtures, the OAC percentage was 5%. According to

Figure 12: Stages of electrical resistivity measurement under compression test.

Table 7: Marshall test results for conventional and modified mixtures

Asphalt mixtures	SFs in asphalt mixtures				
	0%	1%	2%	2.5%	3%
Marshall stability (kN)	10	13.1	16	17.3	18
Flow (mm)	3.1	3.301	3.65	3.9	4.2
Bulk density (g/cm^3)	2.34	2.32	2.301	2.276	2.262

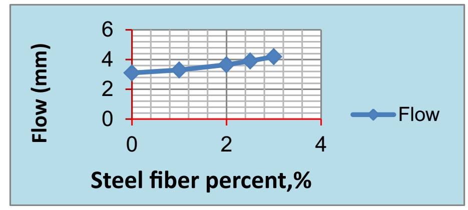

Figure 14: Marshall flow with SF.

SCRB's 2003 study [30], the OAC's Marshall characteristics have been put to the test, and it was determined to be as per Iraq's requirements. The results in Table 7 and Figures 13–15 for Marshall stability and flow tests showed an increase in the stability value from 10 to 18 compared to traditional mixtures by adding 15, 12, and 13% to SFs, respectively, as a percentage of the mixture weight for modified mixtures. The observed phenomenon can be attributed to the evenly distributed SFs within the bituminous matrix. These fibers effectively resist shear displacement and prevent any movement of aggregate particles. This increase in the Marshall stability value results in high performance of the asphalt mixture. To measure the required ER for self-sensing, voltage (mV) and current (A) per second are measured using a DC source meter. The results also showed that the flow value increased from 3.1 to 4.2 when adding the same percentages of SFs mentioned above. This rise was caused by the mixture's fibers clustering, which prevented the aggregate particles from interlocking completely and perhaps losing touch. A decrease in bulk density was also observed. The optimum for SFs for a mixture to meet the standards (SCRB, 2003) for stability and flow was determined to be 2.5%.

3.2 Results behavior of the asphalt mixture of electrical resistivity by Marshall test

Three asphalt samples with electrical conductivity were employed in the Marshall test, along with the previously stated sample preparation process. These samples were equipped with copper electrodes that were implanted within them to establish a connection with an electrical resistance measurement apparatus. As the load gradually started to control the model through the loop, the test started with the device turned on. A measuring equipment was used to track the electrical resistance at the same time, and the findings were recorded. In Figure 16, the electrical resistance test results are displayed. It was discovered that there was no change in the value of the electrical resistance after completing the Marshall stability test for model No. 1 with the electrical conductivity and analyzing the results. The sample electrodes that were connected to the ohmmeter were horizontal or parallel to the instrument's base, as should be noted. The electrical resistance value increased from 44.5 to 103.9 Ωm when sample No. 1 and sample No. 2, which were tested using the same test procedure, were held vertically. This was determined by the Marshall stability device. Afterward, the Ωm value dropped from 103.9 to 0.426. The Marshall stability test was performed once again on sample No. 3 in the vertical direction, the same way as the electrodes used in sample No. 2. According to the data, the electrical resistance rose from 58.4 to 83.2 Ω, then fell from (83.2 Ω). The Marshall stability test was performed once more on sample No. 3 in the vertical direction, the same way as the electrodes used in sample No. 2. According to the measurements, the electrical resistance rose from 58.4 to 83.2 Ω, then fell to 83.20 Ω (0.42 Ω). Applying Marshall test loads to the asphalt mixture sample treated with SFs resulted in a decrease in electrical resistance and an increase in electrical conductivity. This is a result of the proximity of the particles in the asphalt mixture. It indicates the existence of an inverse relationship between electrical

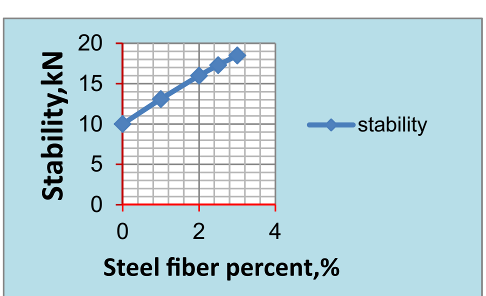

Figure 13: Marshall stability with SF.

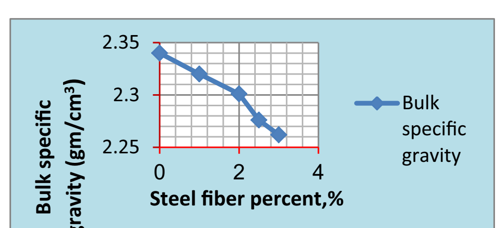

Figure 15: Bulk specific gravity with SF effects.

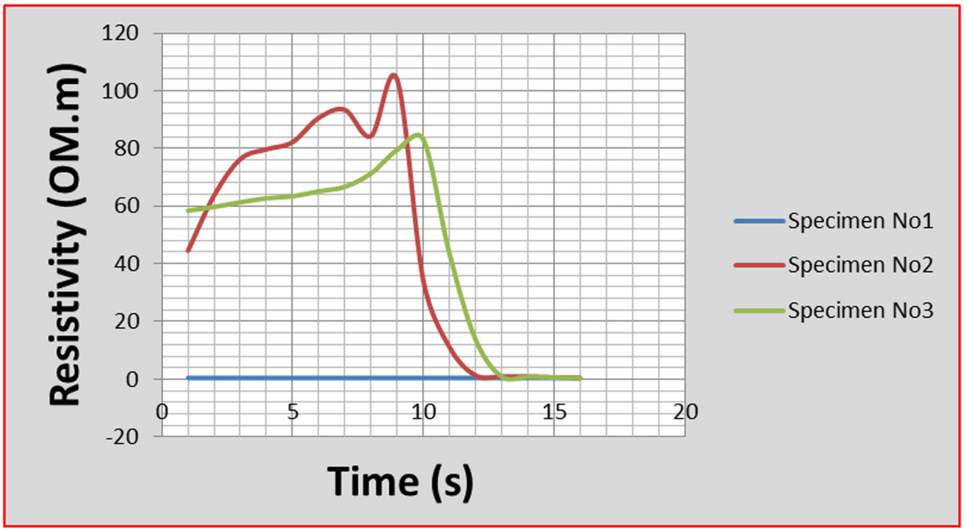

Figure 16: Results of electrical resistivity by Marshall test for specimen Nos. 1, 2, and 3.

conductivity and electrical resistance, and this behavior indicates the ability of the modified asphalt mixture to sense the loads applied to it. This method of operation allows us to monitor and evaluate the condition of the pavement throughout its life.

3.3 Results of electrical resistivity by compression test

The design of asphalt mixtures has to take into consideration the direct stress on the asphalt. To link the copper electrodes inside the specimens to electrical resistance measuring equipment, samples of the asphalt mixtures that conduct electricity were made. The load was gradually applied to the specimen while being tracked and recorded. The electrical resistance is measured while applying the load at every second of time. Figure 17 shows the results for electrical resistance and load. By studying the results of the compression test for the electrical conductivity of asphalt, model No. 1, it was found that the load increased over time from 1.0 to 6.4 kN, but the electrical resistance decreased from 11.873 to 0.35 Ω. The same test method was used to compare sample Nos. 1, 2, and 3 with sample No. 1.

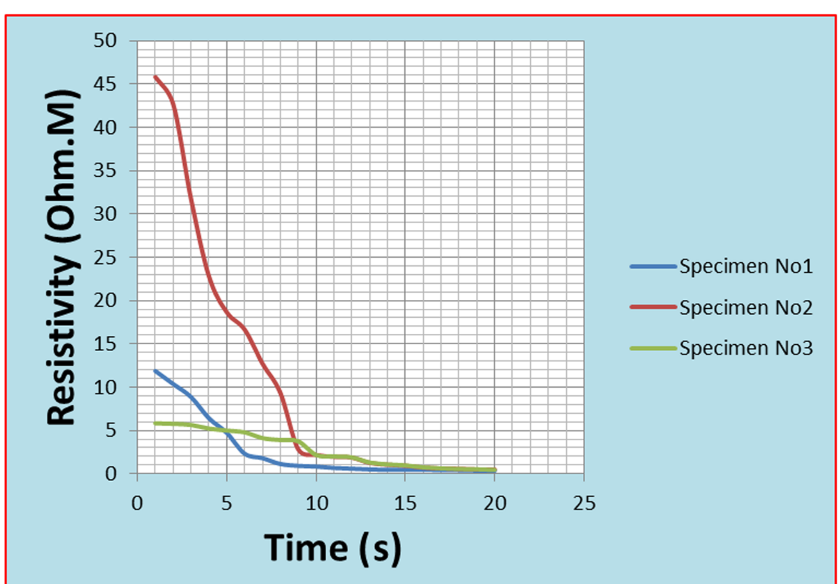

Figure 17: Results of electrical resistivity compression test for specimen Nos. 1, 2, and 3.

When the electrical resistance drops from 5.825 to 0.442 Ω and the load rises from 1.0 to 11.5 kN, sample test results are displayed. Three samples' colors can be attributed to the fact that, as the load grows over time, electrical resistance lowers as a result of the proximity of the conductive material-containing components in the samples. Electrical resistance therefore lowers as electrical conductivity rises. The Marshall verification procedure proved to have been a good example of this idea.

4. Conclusions

Based on the results of the laboratory investigation, the following conclusion may be drawn:

- The results show that the increase in SFs results in an increase in the value of Marshall stability.
- As the added SF ratio (SF%) rises, it was found that the Marshall flow value also increases.
- 2.5% is adopted as a volumetric ratio of SF additive to the asphalt mixture to meet the requirements of SCRB 2003.
- The optimum bitumen content of 5.0% was used to prepare the specimens. The rate maximum value of Marshall stability for three samples was 17.3 kN when the SF was added 2.5%.
- The electrical resistivity value of the samples under influence of the loads of Marshall stability and compression test devices began to decrease due to the convergence of the components of the samples from each other which led to increased electrical conductivity.
- The asphalt mixture before adding the SF is not electrically conductive; however, after adding the SF to the mixture it becomes a good electrical conductor considering the increased value of stability.
- The results of the behavior of the samples (three samples were used) show that the change of the values of electrical resistance gives a good impression of the achievement of the objectives of this study, which is self-sensing of the asphalt mixture.
- This study presents a method for detecting traffic volumes on asphalt without the need for any additional devices or components. The technology described in this study can be applied to both current and newly constructed pavements. It is connected with cost-effectiveness, excellent quality of life, a significant sensing ability, and the maintenance of mechanical properties.

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Conflict of interest: The authors state no conflict of interest.

Data availability statement: Most datasets generated and analyzed in this study are comprised in this submitted manuscript. The other datasets are available on reasonable request from the corresponding author with the attached information.

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