



The Effect of Adding Steel Fibers and Graphite on Mechanical and Electrical Behaviors of Asphalt Concrete

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Received 06 November 2021; Revised 13 January 2022; Accepted 21 January 2022; Published 01 February 2022

Abstract

Conductive asphalt concrete can satisfy different and multifunctional applications such as heating roads to get rid of snow and ice and assure auto-detection, auto-cure, and energy recovery. This research aims to evaluate the performance of asphalt concrete with additives like steel fibers and graphite powder. This work is based on destructive tests (direct tensile test FENIX) and non-destructive tests (electrical resistivity measures). The obtained results indicate that the tensile resistance, dissipated energy, and ductility module of asphalt concrete increased with the increasing steel fiber percentage. Direct tensile strength, cracking resistance, and dissipated energy increased as graphite percentage increased, while the ductility module decreased. Electrical resistivity decreased when it added steel fibers and graphite. Therefore, it found that tensile strength increased reversibly with electrical resistance. When adding steel fibers or graphite powder, the dissipated energy of asphalt concrete is increased while electrical resistivity is decreased. The dissipated energy of conductive asphalt concrete with steel fibers is higher than that with graphite powder. Electrical resistivity decreased significantly with increasing steel fibers, compared to electrical resistivity with graphite. The obtained results indicate that asphalt concrete cracking resistance is higher with the optimal percentage of steel fibers added at 1% and better mechanical performance.

Keywords: Asphalt Concrete; Conductor; Steel Fibers; Graphite; FENIX Test; Electrical Resistivity; Dissipated Energy; Ductility Module.

1. Introduction

Asphalt concrete is a composite material that consists essentially of asphalt as a binder along with aggregates. It is generally used as a road building material thanks to its good adhesion between the binder and aggregates [1, 2]. Due to asphalt concrete's intensive usage for non-rigid roads and rolling motion comfort, this material has become essential for research studies [3, 4]. Conducting asphalt concrete gives us a design methodology for asphalt concrete that guarantees good electrical and mechanical properties [5]. To transfer electrical conductivity in asphalt concrete, it adds different additives to asphalt or asphalt concrete [6]. Previous research studied various fibers and conducting powders such as steel fibers [6–8], carbon fibers [7, 9], steel wool [10, 11], carbon black [12] and graphite powder [7, 9, 11]. Asphalt concrete performance has been evaluated using mechanical and electrical tests such as the FENIX direct tensile test and the electrical resistivity test.

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 <http://dx.doi.org/10.28991/CEJ-2022-08-02-012>



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Adding fibers to asphalt concrete guarantees the stability of the latter's mechanical properties, reduces penetration and increases its dynamic module and behavior in fatigue and ductility. A sufficient amount of fibers changes the properties of asphalt concrete, decreasing penetration and increasing the softening point. It changes asphalt viscoelasticity as well [13-17]. Moreover, it has been noticed that fibers in asphalt concrete improve compressive strength [18-20] and moisture sensitivity [19, 20]. Fiber additives were considered as a positive reinforcement material for asphalt concrete [3]. Adding fibers improve rut resistance, activate multifunctional applications [21–26] and increase crack resistance by fatigue and crack resistance by bending [5, 27]. Many previous studies on the electrical conductivity of conducting asphalt concrete showed that conductivity is proportional to the fiber amount added [5, 28]. Graphite is one of the most common carbon additives with the most stable crystalline structure. Due to its good conduction properties and low cost, graphite is used as a popular additive to produce multifunctional composites for various engineering applications. According to the form, size, origin, and manufacturing process, there are many different types of graphite. Graphite size and form are important criteria in conductivity transfer in asphalt, but other researchers do not emphasize the asphalt type effect [6]. Previous research [29–32] found that the conductivity of asphalt is proportional to the percentage of conductive powders.

The capacity of tension auto-detection and compression constraints auto-control was higher in asphalt concrete, which contains graphite [33]. Conduction properties may be significantly improved by adding proportional carbon loads in the form of graphite powder [34]. Conductive asphalt concrete with graphite has fatigue resistance that is higher than that of ordinary asphalt concrete [35]. Graphite improves the thermal conductivity, diffusivity, and electrical conductivity of asphalt binder [36-40]. In direct tensile tests, using graphite as an electrical conducting additive in significant amounts improved rut resistance, increased dynamic module, and significantly reduced asphalt concrete cracking resistance. Huang et al. [9] studied the percolation thresholds of three additives (micro steel fiber, carbon fiber, and graphite powder) and showed that fiber additives have relatively weaker percolation thresholds than graphite powder. Much of the previous research classified fiber additives as essential conductive additives compared to powder additives because relatively smaller fiber amounts of the former are necessary to constitute conductive paths than is the case with the latter. Another potential advantage of powder additives is the gradual transition from a non-conductive phase to a conductive phase. Conductive fibers have a sudden drop in resistivity, while graphite powder allows for a relatively gradual resistivity drop [6]. Conductive asphalt concrete has a strong capacity for various multifunctional applications, such as heated roads to remove snow and ice [5, 7], auto-detection [32, 41], auto-cure (heating by induction) [42, 43], and healing recovery [44].

In this research, the scope is to evaluate the effects of steel fibers and graphite powder on the mechanical behavior and electrical conductivity of asphalt concrete. It also creates a correlation between mechanical and electrical properties. Conductive asphalt concrete performance is evaluated with a direct tensile test (Fénix test) and measures the electrical resistivity.

2. Experimental Work

2.1. Materials

Half-grained asphalt concrete of 0/14 class was achieved according to Marshall Design Method. Figure 1 shows the gradation curve and aggregate gradations are indicated in Table 1.

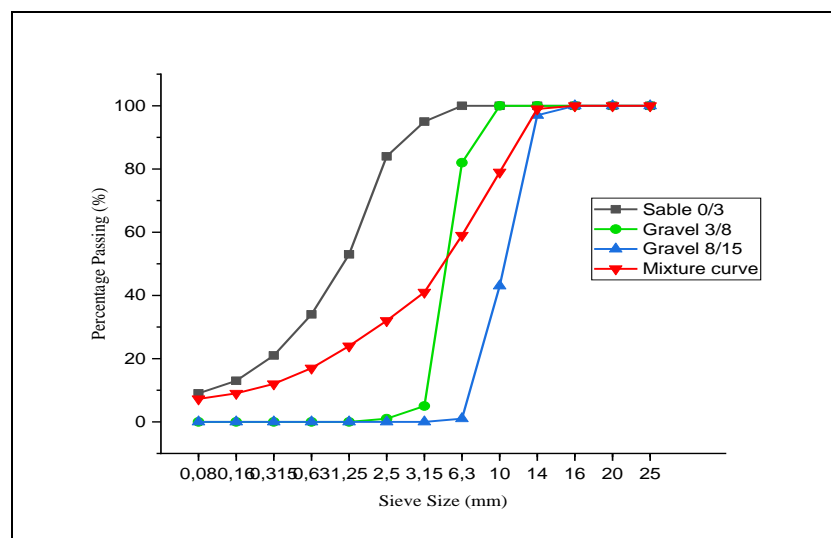


Figure 1. Gradation Curve

Table 1. Aggregate gradations

Sieve Openings (mm)	Percentage of sieve (%)		
	0/3	3/8	8/15
16			100
14			97
12.5			84
10		100	43
8		98	11
6.3		82	1
5		58	1
4	100	29	
3.15	95	5	
2.5	84	1	
1.25	53		
0.63	34		
0.315	21		
0.16	13		
0.08	9		

Concerning different aggregate grain size, it is possible to conclude percentages of the mixture which has to be inserted in reference spindle 0/14. Table 2 shows the obtained percentages.

Table 2. Mixture Percentages

Aggregate and Binder	Percentages (%)
0/3	38
3/8	21
8/15	37
Calcareous Fillers	04
Asphalt	6.22

Table 3 shows the aggregate properties and asphalt properties are:

- Ring and Ball Softening point temperature (TRB): 51 °C;
- Penetration at 25 °C (P): 43 (1/10) mm.

Table 3. Aggregate Properties

Aggregate	0/3	3/8	8/15
Density (g/cm ³)	2.71	2.71	2.71
Methylene Blue (ml/g)	0.75	-	-
Micro-Deval (%)	-	-	13.7
Los Angeles (%)	-	-	19.13
Sand Friability (%)	39.94	-	-
Sand Equivalent (%)	79.36	-	-
Electrical Resistivity (Ω .m)	> 10 ¹⁴	> 10 ¹⁴	> 10 ¹⁴

2.1.1. Steel Fibers

Steel fibers used in this study of 0.7 – 1.0 cm length and 0.10 ± 0.02 mm diameter (Figure 2), with a tensile strength that equals 502 MPa, electrical resistivity: $7 \times 10^7 \Omega \cdot \text{cm}$ and Young Module: 1345 MPa.



Figure 2. Steel Fibers

2.1.2. Graphite Powder

In this research study, it chose amorphous graphite. Graphite powder size is less or equals 80 μm manually crushed (Figure 3), electrical resistivity is 0.1 $\Omega\text{ cm}$.

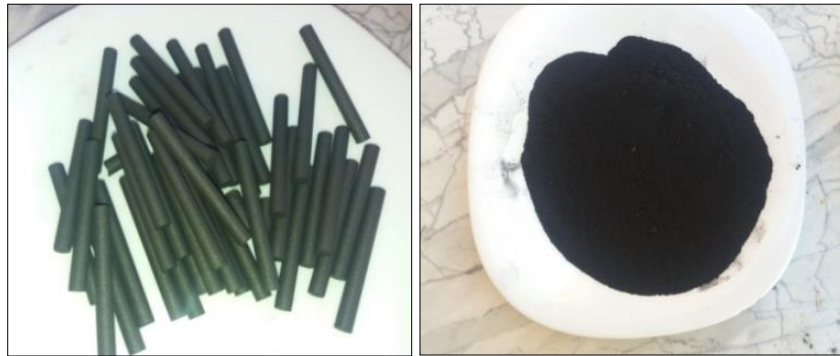


Figure 3. Graphite and Graphite Powder

2.2. Sample Preparation

Tests are carried out using cylindrical tubes of 6 cm height and 10 cm diameter (Figure 4). The binder, aggregate, steel fibers or graphite powder are heated at 150°C for two hours. They were simultaneously put in the mixer's heated container and mixed until steel fibers or graphite powder and aggregate are uniformly distributed and completely coated by the binder. The mixture was compacted in compacting molds by applying 50 strokes on each side. Specimens were taken from molds and conserved in the laboratory setting 24 hours before undertaking tests. Samples diameter and height were measured at conditioning temperature. Test tubes of Fénix direct tensile test contained 1, 3, 5, 10, 15, 20, 25 and 30% of graphite powder in asphalt volume and 0.2, 0.4, 0.6, 0.8, 1 and 1.2% of steel fiber in mixture weight. Given that Fénix test is carried out four times and electrical resistivity 3 times, 70 samples were made: 40 for asphalt concrete with steel fibers and 30 for asphalt concrete with graphite powder.



Figure 4. Asphalt concrete specimens

2.3. Methods

Figure 5 shows the Research Methodology Flowchart.

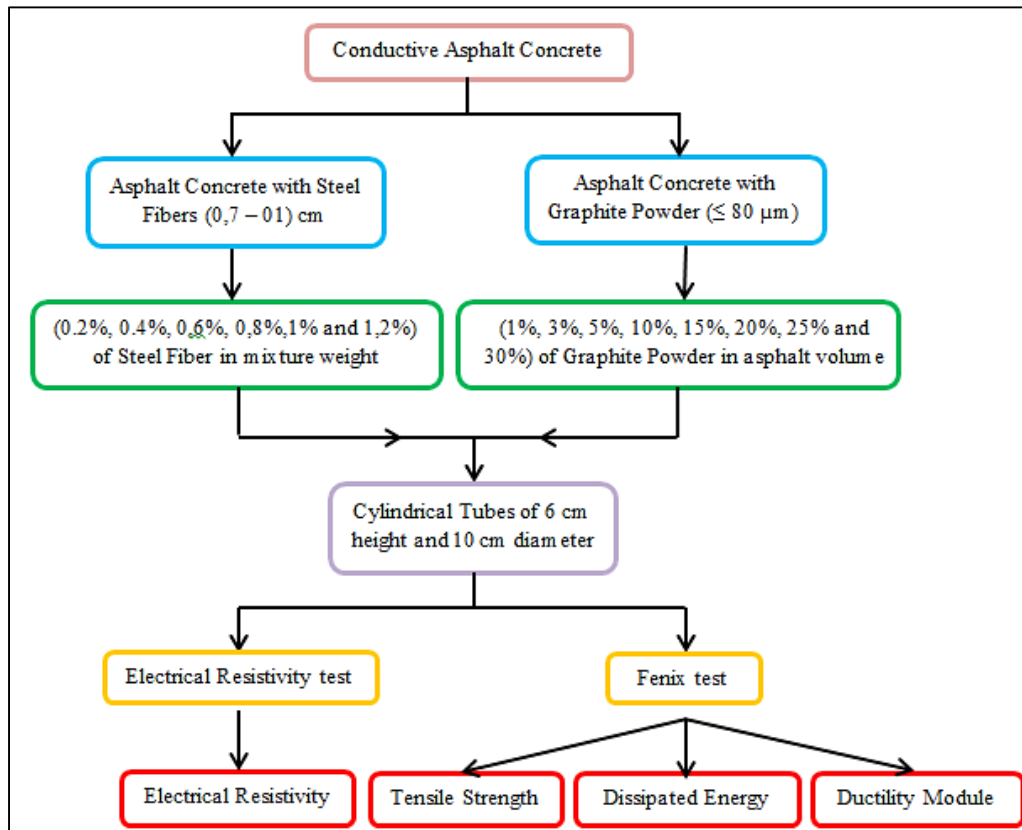
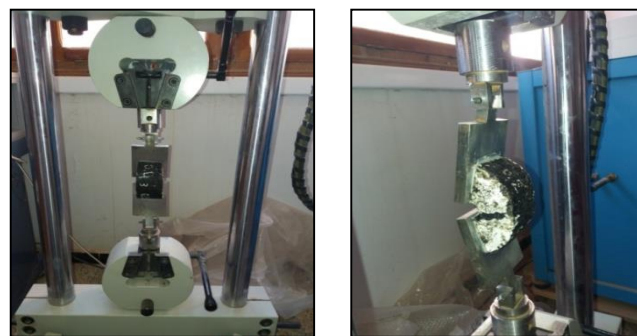


Figure 5. Research Methodology Flowchart

2.3.1. Fenix Test (Direct Tensile Test)

Direct tensile tests (carried out at 24° C) were executed to determine the effect of steel fibers and graphite powder volume amounts on asphalt concrete mechanical behavior. Tests were carried out with Fenix apparatus (Figure 6). Marshall test tubes were divided into two parts with a 6 mm difference and fixed on Fenix plates. It had to apply a movement with constant velocity (1 mm/min). Tensile force and vertical movement were recorded by a data acquisition system.



(a) Fenix machine

(b) Fenix test

Figure 6. (a) Fenix machine; (b) Fenix test

Once the tests are done, tensile strength is calculated by the following equation [45]:

$$R = \frac{2F}{\pi\theta h} \quad (1)$$

where R is Tensile strength (Pa), F is Total vertical load applied (N), θ is Test tube diameter (m), and h, is Test tube height (m). Loads and movement data are recorded throughout the tests to calculate parameters that are engaged in the crack process. Dissipated energy G_D is calculated by the Equations 1 and 2:

$$G_D = \frac{W_D}{h \cdot \theta} \quad (2)$$

$$W_D = \int_0^{\Delta R} F \cdot du \quad (3)$$

where; G_D is Dissipated energy during test application (J/m^2), W_D is Dissipated work during test application ($kN \cdot mm$), F is Load (kN), u is Movement (mm), and ΔR is Movement with the load F_{max} .

2.3.2. Electrical Resistivity Test

In this study, CHAUVIN ARNOUX numerical megohmmeter (Figure 7) was used to measure electrical resistance at less than $40 \times 10^6 \Omega$ and it used a multimeter to measure resistance values that are higher than the indicated value. Measures were carried out at room temperature ($20^\circ C$). It used two sensors method to measure this resistance. Two electrodes of copper plates are connected and placed at both ends to cylindrical test tubes.



Figure 7. CHAUVIN ARNOUX Meghometer

A small pressure was applied at copper electrodes to obtain good contact with the sample surface. The total contact resistance between the two electrodes was around 0.4Ω which is an insignificant value compared to higher studied resistances (higher than $100 k\Omega$ in the samples). Once the resistance was measured, electrical resistivity was obtained by the second Ohm law by Rew et al. (2017) [6]:

$$\rho = \frac{RS}{h} \quad (4)$$

where ρ is Electrical resistance ($\Omega \cdot m$), h is Test tube height (m), S is Electrode conduction surface (m^2), and R is Measured resistance (Ω). The electrical field is supposed constant and the final effects are negligible.

3. Results and Discussion

3.1. Direct Tensile Strength

Direct tensile strength is a parameter that indicates binder gluing force with aggregates and may be used as an indicator for mixture homogeneity [46]. Cracking resistance indicates that the crack localized spread begins at the peak point of the resistance/movement curve [21]. Direct tensile strength, dissipated energy and ductility module are obtained from Fénix tensile test at the temperature of $24^\circ C$.

3.1.1. Direct Tensile Strength of Asphalt Concrete with Steel Fibers

The generated interconnection between granulated masses and fibers enables the material to sustain supplementary deformation energy before that cracks occur. This fact is of great importance to have long-lasting and safe roads. Figures 8 to 10 compare results of asphalt concrete direct tensile strength, dissipated energy and ductility module having different percentages of steel fibers with their respective witness.

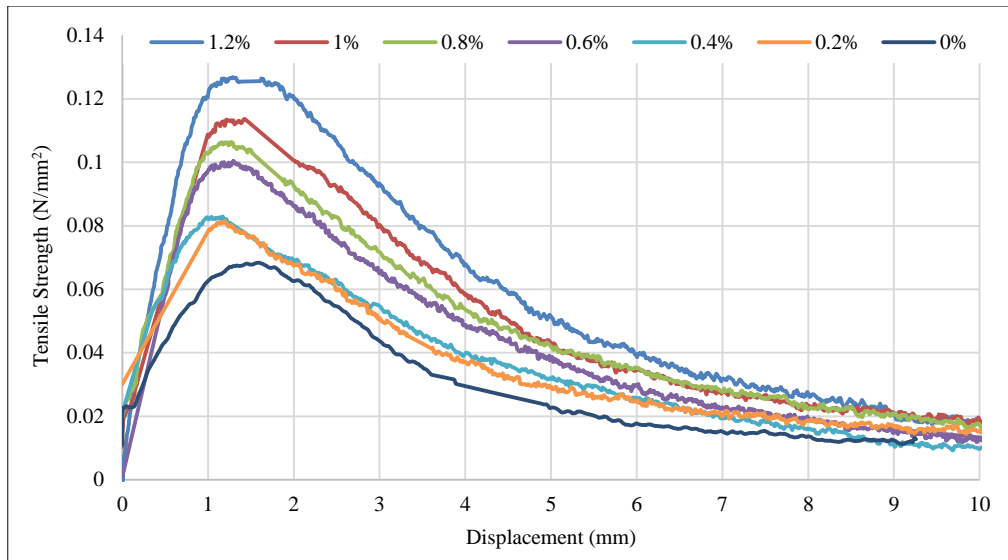


Figure 5. Asphalt concrete tensile strength in terms of the displacement of different percentages of steel fibers

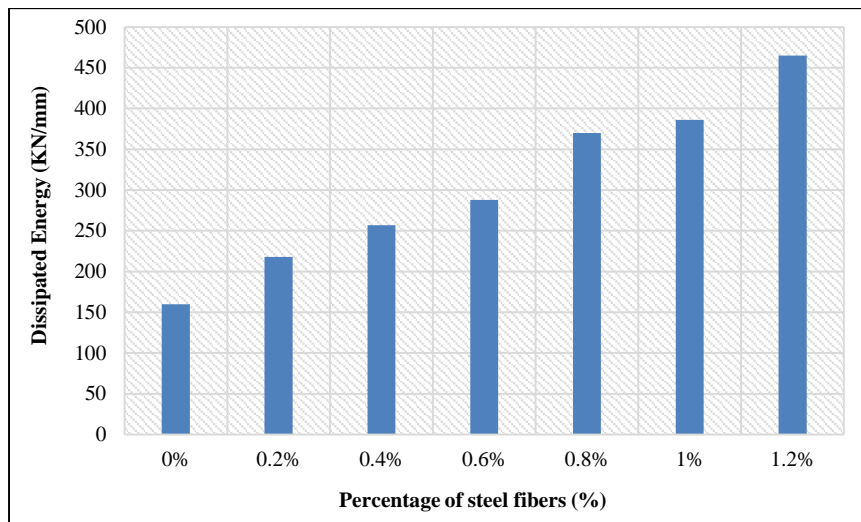


Figure 6. Dissipated energy in terms of different percentages of steel fibers

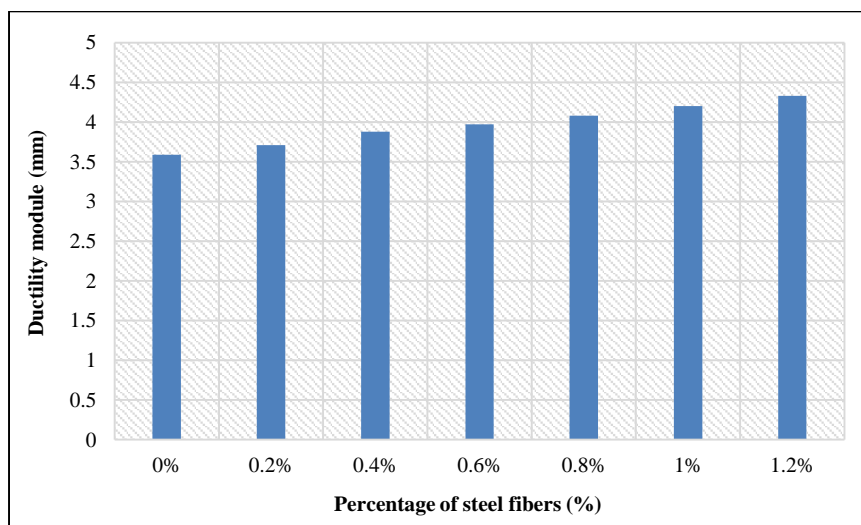


Figure 7. Ductility module in terms of different percentages of steel fibers

These results indicate that asphalt concrete's direct tensile force, dissipated energy, and ductility module are increased with the increase of steel fiber percentages because the fiber tensile stress itself is higher. Steel fibers

significantly improve asphalt concrete cracking resistance; the higher percentage of 1.2% steel fibers gives the best performance. Also, 1% steel fibers make for good asphalt concrete. Hence, when steel fibers are well distributed in asphalt concrete, they constitute a three-dimensional lattice structure. Structure mesh has a reinforcement effect in the mixture, something that contributes to the increased tensile strength of asphalt concrete.

Dissipated energy results during cracks reveal that the mixture had the highest dissipated energy value with better cracking behavior. The mixture of steel fibers and bitumen creates resistance to microcracks, which plays a more important role in increasing the tensile strength value of asphalt concrete [15]. The discovered results are consistent with previous research. The research of Lau et al. (2020) found that when the steel fibers increase, the fatigue resistance and dissipated energy increase [15]. Paluri et al. (2020) found that steel fibers could enhance the flexural and split tensile strength [16]. Xiong et al. (2015) and Acevedo et al. (2019) found that adding fibers to asphalt concrete guarantees the stability of the latter's mechanical properties [13, 14].

3.1.2. Direct Tensile Strength of Asphalt Concrete with Graphite Powder

Figures 11 to 13 compare the results of asphalt concrete direct tensile strength, dissipated energy, and ductility modules having different percentages of graphite powder with their respective witnesses.

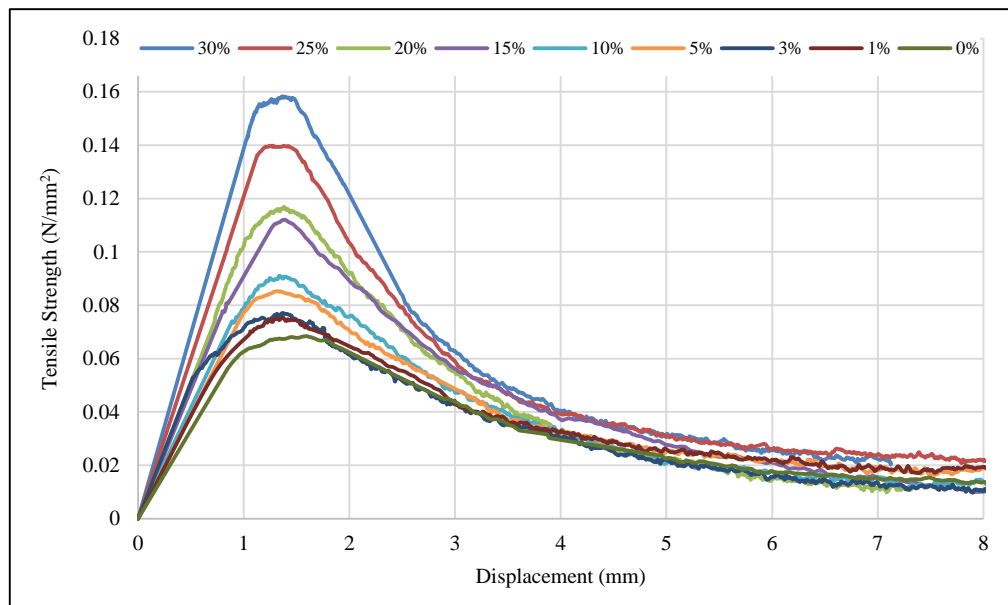


Figure 8. Asphalt concrete tensile strength in terms of the displacement of different percentages of graphite powder

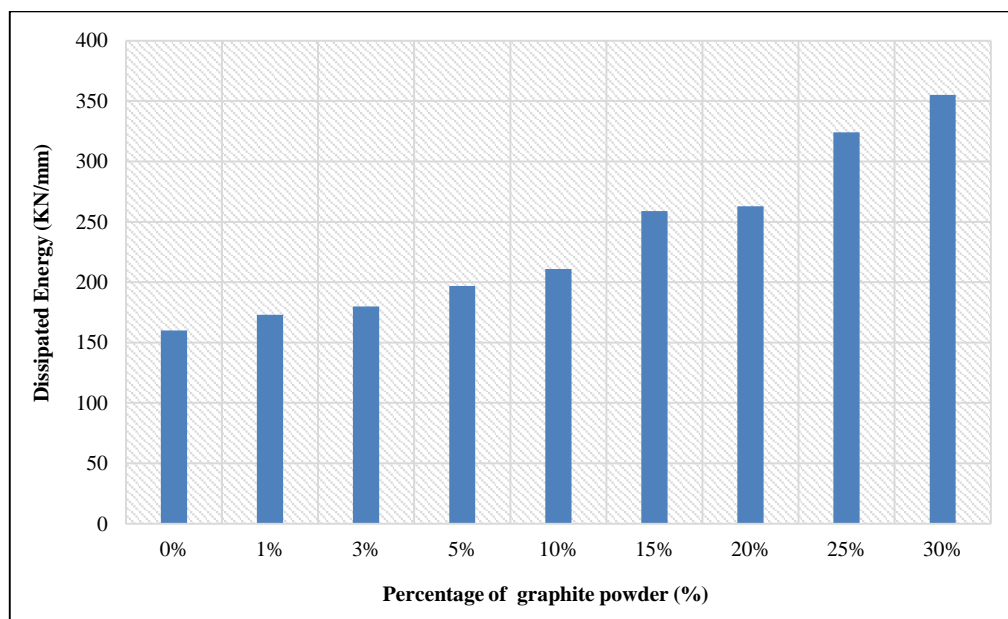


Figure 9. Dissipated energy in terms of different percentages of graphite powder

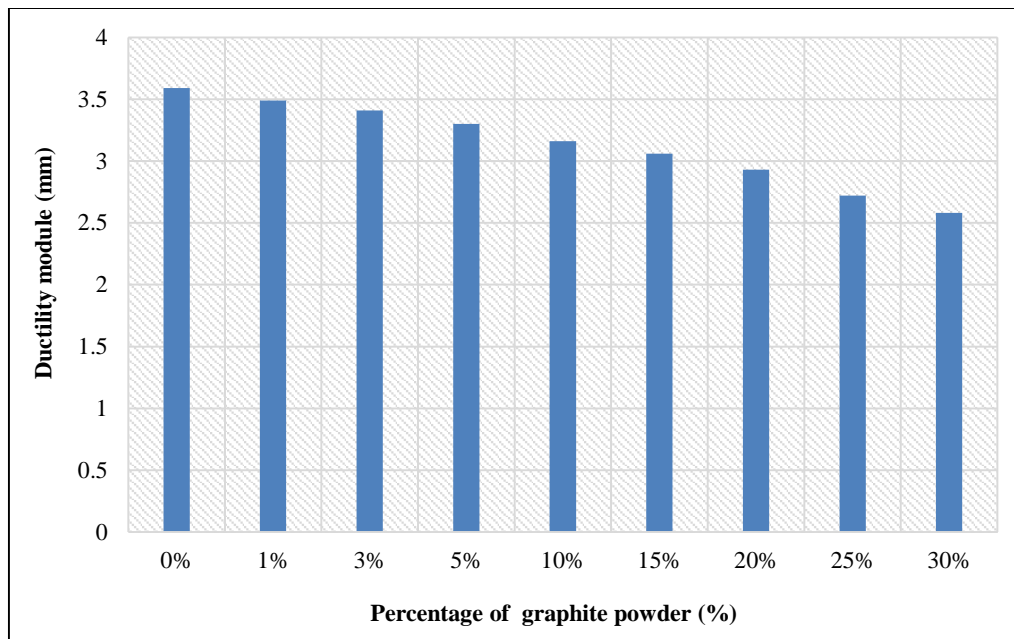


Figure 10. Ductility module in terms of different percentages of graphite powder

It remarks that when graphite powder percentage increases, direct tensile strength increases. Due to the special layered structure of graphite powder, there are molecular interactions between layered structures inside graphite. Therefore, (asphalt concrete containing graphite in the mixture tends to produce an insert slide when asphalt concrete samples are under tensile force) [5]. Graphite has a lubricating effect to diminish adhesion force between asphalt binder and aggregates. The percentage 30% of graphite powder gives high values of tensile strength and dissipated energy, but it is not good in front of ductility. Another, the graphite powder improves the bond between the bitumen and the aggregates. It can fill the initiates with microcracks and slow the propagation of cracking [47]. The fond results are in accord with previous research. The study by Eisa et al. (2021) found that the results showed that the mechanical properties of asphalt concrete increased with the contents of graphite powder [47].

3.2. Asphalt Concrete Electrical Resistivity

Electrical resistivity of the mixture with different percentages of steel fibers and graphite is illustrated in Figure 14.

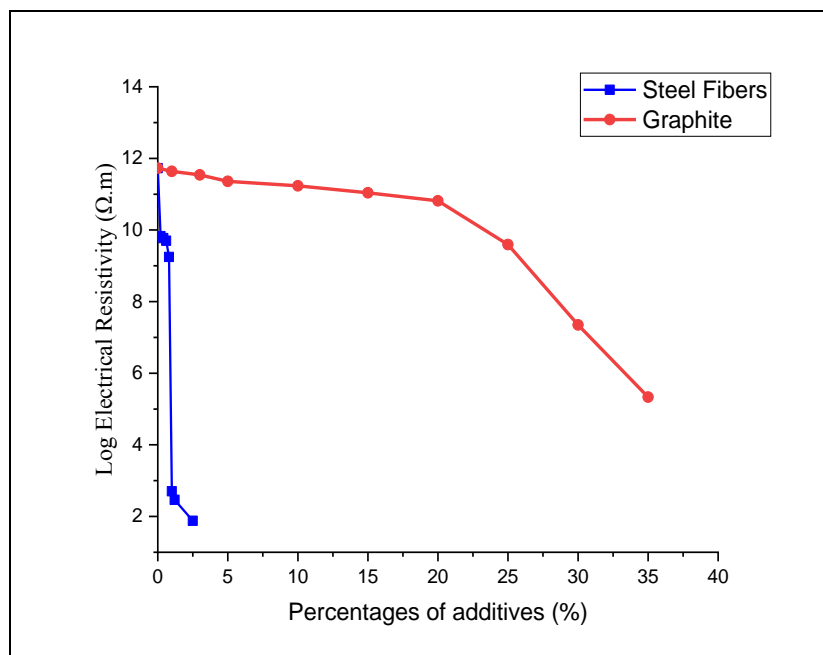


Figure 11. Asphalt Concrete Electrical Resistivity in terms of Steel Fibers and Graphite Different Percentages

3.2.1. Steel Fibers Effect

The effect of steel fibers amounts on bituminous concrete is illustrated in Figure 14. Samples resistivity showed three stages: Higher resistivity stage with fiber amounts less than 0.8%; Transition stage with fiber amounts at 0.8% to 1%; Third stage: Weak resistivity with fiber percentages higher than 1%. Samples with less than 1% fibers showed an insulation behavior with strengths higher than $10^9 \Omega \cdot m$. During the transition stage (fibers between 0.8% and 1%), sample electrical resistivity noticed a sharp drop from $1.77 \times 10^9 \Omega \cdot m$ to $5.06 \times 10^2 \Omega \cdot m$. According to percolation theory [5], fibers distribution in asphalt concrete samples is as follows: When 5% of steel fibers are added to the mixture, they are uniformly distributed and cannot have contact with each other as there is a little resistivity decrease compared to the witness sample. When more steel fibers are added to the mixture, they start to be in contact with each other, something that provokes a progressive resistivity decrease. If fiber content reaches more than 0.8% (percolation threshold), first conduction paths are formed in the sample. This corresponds to a resistivity fold. Beyond the percolation threshold, the conduction network develops and spreads progressively in three dimensions with an increase of steel fiber amounts. When fibers amounts are higher than 1%, steel fibers are in contact with each other in all directions and in many networks and constitute conduction paths that correspond to very inferior values of resistivity to which more steel fibers do not give a further reduction in sample resistivity.

If it imagines conduction fibers like little roads for electrons. In the beginning, when a few fibers are added to the mixture, if they are well distributed, they will remain isolated from each other. If sample electrical resistivity is measured, it remarks that this latter is slightly inferior to that of asphalt concrete only. It can consider that because electrons reach higher electrical strengths through asphalt, they reach electrically conducting fiber which eases their way. If more fibers are added, electrons will have more conducting paths and resistivity will continue its decrease [11].

Finally, there will be enough fibers that they will be connected to the sample two ends, and electrons will not need to go very far in the asphalt. This first conduction path will be very curvy. A small volume of other fibers increases along this conduction path by straightening it and increasing conductivity. This process is logical because once the conduction path reached its shortest length; active fibers will not reduce mixture resistivity [11]. According to these ideas, it is logical that fibers could be more efficient than during composite resistivity reduction: they constitute long conduction paths, while the same load volume quantity will be scattered around the mixture. Asphalt concrete cracking resistance is higher with the optimal percentage of added steel fibers 1% and better mechanical performances. The found results are in accord with previous research. The research of González et al. (2020) found that when the steel fibers increase, the electrical resistivity increases [28].

3.2.2. Graphite Effect

Graphite is scattered randomly in the mixture. When graphite amounts increase until they reach a determined quantity, graphite particles gather together and constitute a continuous and electrically conducting access. The contact strength between graphite particles governs the resistivity. The air gap inside the asphalt concrete mixture diminishes progressively under external force and the inside becomes more compact. This increases contact between particles and graphite and constitutes an electrically conducting access. Consequently, test tube conductance will increase and electrical strength will decrease. As shown in Figure 14, the resistivity of asphalt concrete that contains graphite decreases progressively with graphite content as it increases. Resistivity drop occurs between 20 and 25% of the mixture volume, something that can be considered as a percolation threshold. Then, resistivity decreases progressively from 5.31×10^{11} to $2.15 \times 10^5 \Omega \cdot m$ when graphite content increases. In our case, asphalt concrete with graphite remains nonconductor with a maximum volume amount of 35%. Graphite could slightly decrease asphalt and aggregate adherence.

When graphite amount increased to 30 %, asphalt concrete resistivity had already reached relatively a low level of $2.24 \times 10^7 \Omega \cdot m$. It can also remark that resistivity variation, in mixtures containing steel fibers, follows a similar profile to that of asphalts with graphite. It seems that steel fiber has a very higher efficiency than graphite to improve mixture conductivity. A sufficiently low electrical resistivity can be obtained by adding enough graphite or steel fiber. For example, by assuming a situation where asphalt concrete roads are heated for auto-cure or de-icing, these roads resistivity have to be controlled rightly to guarantee safety and good energy efficiency.

Asphalt concretes with steel fiber have higher tensile strength, dissipated energy, and ductility compared to asphalt concretes with graphite powder. Asphalt concrete's electrical conductivity could be improved by adding steel fiber or graphite. According to previous studies by Liu et al. (2021), Hasan et al. (2021) and Xiaoming et al. (2011), the conductivity of asphalt is proportional to the percentage of graphite powders [29, 30, 32]. Electrical resistivity increases reversibly with tensile strength, dissipated energy, and ductility increases by adding steel fibers (Figure 15). As to graphite adding, when electrical resistivity increases, tensile strength and dissipated energy increase, but ductility decreases (Figure 16).

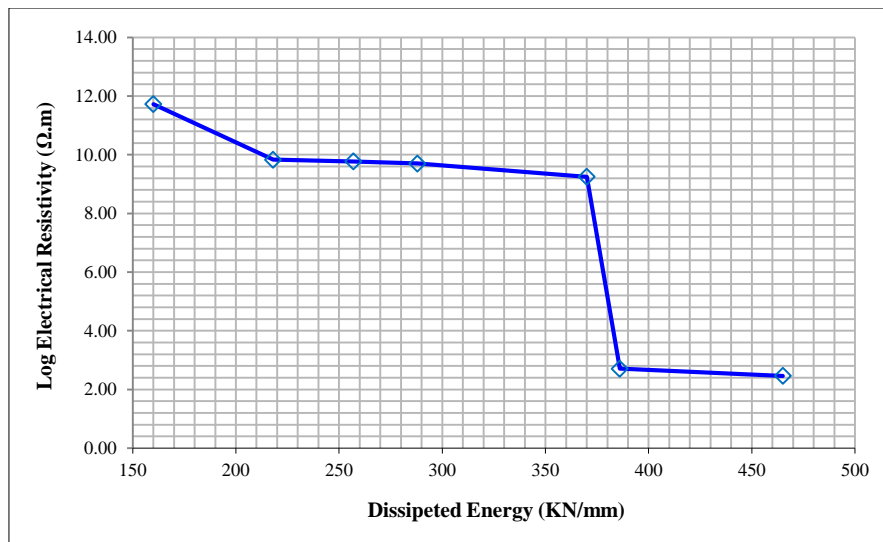


Figure 12. Asphalt Concrete Electrical Resistivity in terms of dissipated energy of different percentages of steel fibers

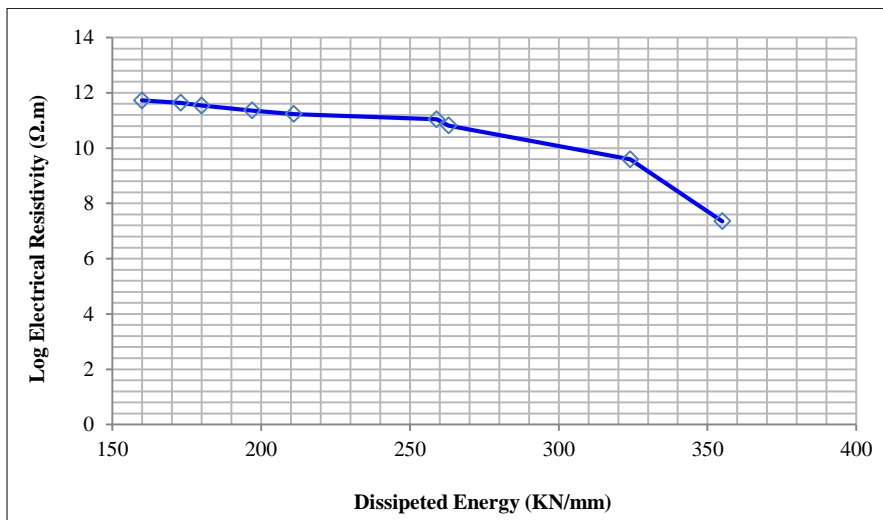


Figure 13. Asphalt Concrete Electrical Resistivity in terms of dissipated energy of different percentages of graphite powder

4. Conclusion

Asphalt concrete's electrical conductivity could be improved by adding steel fibers or graphite. In the measurement of the electrical resistivity of conductive asphalt concrete with steel fibers, the percolation threshold is reached. In the case of graphite powder, the asphalt concrete is not conductive because it has not reached the percolation threshold. It is much more efficient to reach the desired conductivity with steel fibers $5.06 \times 10^2 \Omega.m$ rather than with graphite powder $2.15 \times 10^5 \Omega.m$. Steel fibers 1% are made asphalt concrete a conductor, and they are an efficient means to improve asphalt concrete tensile strength, dissipated energy, and ductility module. With increasing graphite percentage, direct tensile strength and dissipated energy increase, but the ductility module decreases. The additives such as steel fibers and graphite powder increase the cracking resistance of asphalt concrete, which is indicated by a high level of dissipated energy. Steel fibers in asphalt concrete behave in a good way in terms of mechanical and electrical performance. Asphalt concrete with graphite powder is an advantage for increasing mechanical proprieties. But this additive, at 35%, is not suitable to make conductive asphalt concrete. The authors intend to work on a conductor that combines steel fibers and graphite and can improve the electrical and mechanical properties of asphalt concrete in future research.

5. Declarations

5.1. Author Contributions

M.M., B.G. and O.A. contributed to the conception and design of the study; M.M. performed the experimental tests and analyzed the data; M.M. wrote the first draft of the manuscript; B.G. and O.A. guided and supervised the research

work and commented on the previous version of the manuscript. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in article.

5.3. Funding

The authors thank the DGRSDT (Direction Générale de la Recherche Scientifique et du Développement Technologique) for funding this work.

5.4. Acknowledgements

The authors thank the team from Technical University of Catalonia (Barcelona) because they give the authorization to use the Fénix test in our university.

5.5. Conflicts of Interest

The authors declare no conflict of interest.

6. References

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