Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Enhancing Mechanical and Electrical Properties of Hot Mix Asphalt Using Self-Sensing Technology and Graphite Powder

Ahmed Wasfi Obaid, Ali Al-Dahawi, Khawla k. kawther

Department of Civil Engineering, University of Technology, Baghdad, Iraq
Email: bce.22.48@grad.uotechnology.edu.iq

The present study will design self-sensing asphalt mixtures that can detect the applied load; thus, it gives a lead toward more sustainable infrastructure by means of real-time pavement monitoring, hence optimized maintenance with less environmental impact. These are points which scientists have been trying to enhance in the mixes of asphalt concrete from in terms of the mechanical properties; though traditionally, monitoring asphalt surfaces was highly expensive and inaccurate. These monitoring systems provide useful data related to pavement condition assessment, design, and cost estimation for the execution of the maintenance programs. Recent development in technologies, especially the self-sensing technology, has provided new avenues toward improving asphalt mixtures. The purpose of this research is to incorporate conductive materials into hot mix asphalt for enhancing the electrical and mechanical properties, aiming at developing an electrically conductive mixture able to perform self-sensing of the applied loads. The experimental work included the Marshall tests with 40-50 penetration-grade asphalt and aggregate mixtures prepared according to the Iraqi specifications. Graphite powder was added to the asphalt blend as a filler in order to investigate its effect on the performance of the asphalt blend. Electrical resistance changed significantly because the mixture was sensitive to the applied load. Besides, the stability of modified asphalt was increased according to the Marshall test. Indeed, these have improved the watched conditions of the pavement with enhanced operational efficiency and service life.

Keywords: Graphite powder; Electrical resistivity; Multifunctional asphalt concrete mixtures; Self-sensing; Marshall test; Electrical conductivity.

1. Introduction

Modern society depends on the broad range of infrastructures engineered for life support: highways, airport pavements, bridges, subway systems, dams, wastewater plants, coastal structures, and buildings. These facilities serve key components in people's lives, yet they are under constant attack from degradation and deformation resulting from various types of loadings and environmental attacks. Therefore, determining the degree of their respective damages is crucial in risk mitigation, ultimately for the protection of the public. Regular inspections are key to maintaining the safety and functionality of transportation systems [1].

Highways, to be more precise, form the connecting links between cities and large towns, ensuring easier and more possible transportation hence economic development. It is, therefore, indispensable in human life and development. With the international focus on road safety, road research methodologies have ensured scientific evaluation for reliability, validity, and accuracy of results. A major objective of pavement systems involves ensuring that the passage of traffic is safe, efficient, and economical [2,3,4]. Continuous internal monitoring of the stress and displacement within pavement structures provides valuable information on developing strategies for maintenance and construction quality assurance to detect early signs of deterioration to ensure preventive measures in extending pavement lives. The new approach thus offers great potential to optimize pavement performance and safety [5].

Structural health monitoring represents the continuous on-site monitoring of infrastructure in regard to its effectiveness. By applying SHM techniques, the life of the structure can be elongated, safety to public enhanced, and cost of restoration minimized. In addition, to the above advantages, the SHM will provide the real-time status evaluation and thus allow early detection of problems besides providing an opportunity for timely remedial action against catastrophic failure [6]. The SHM techniques, through condition-based maintenance, can provide improved structural safety for the civil infrastructure with reduced frequency of maintenance [1,7].

There are different forms of deterioration that have attacked asphalt concrete on the highway in Iraq [8], and pavement deterioration due to traffic congestion and environmental conditions is indicated by cracking and rutting in flexible asphalt pavement [9,10,11], and such deformations are caused by accumulated stress due to repetition of vehicle load [11]. To assess damage, data from weigh-in-motion (WIM) systems can be used to track traffic loads, providing insights into the impact of heavy vehicles and fatigue on pavement performance [12,13]. Overestimating pavement service life due to underestimating traffic usage can result in unexpected structural failures [14,15].

With increasing traffic volumes, it is crucial to explore materials that enhance the quality and durability of asphalt [16]. Failure to address pavement deterioration can lead to a disruption of the transportation networks, leading to increase costs for drivers, the public, in addition to authorities [17]. The ability to detect stress, strain, and cracks in real-time enables timely warnings about infrastructure degradation, helping to mitigate damage.

Traditional traffic detection systems are often expensive, lack sensitivity, have limited lifespans, and may not be durable enough for long-term use [18-23] . Additionally, asphalt is highly sensitive to temperature fluctuations, becoming brittle in cold weather and soft in hot conditions, which further accelerates its deterioration.

It basically deals with the development of asphalt mixtures to avoid a number of pavement distresses such as bending, reflection cracking, fatigue cracking, and moisture damage [24]. Conductive fiber-reinforced asphalt concrete with steel and carbon fibers is researched in recent times, mainly for electro-thermal applications [25]. Minsk in 1968 was the first to first introduce the idea of electrically conductive asphalt concrete, he has gained significant attention in the past decade. Research has focused on using conductive asphalt to melt snow and ice through electrical heating [26]. Additionally, electric heating in conductive asphalt is expected to improve self-healing by reducing recovery time. The piezoresistivity of conductive asphalt—its ability to change electrical resistance under mechanical stress—also opens up opportunities for strain sensing [27].

Self-sensing technology allows asphalt to autonomously detect and monitor damage, such as strain and deformation, without relying on embedded sensors. This method enhances asphalt durability and sustainability by allowing continuous monitoring of pavement conditions [28,29]. Unlike traditional sensors, self-sensing materials are cost-effective, stable, and maintain their mechanical properties over time [30]. Embedded sensors can reduce the mechanical efficiency of pavement and require intrusive repairs, whereas self-sensing materials eliminate these drawbacks [31].

This research deals with the piezoresistive mechanism of the electrically conductive asphalt concrete (CAC) in terms of how the addition of carbon fiber and graphite-modified asphalt contributes to achieving the self-sensing capability of CAC. A model was developed illustrating the self-sensing behavior of CAC [32]. The research work deals with the study of the mechanical and self-sensing properties of carbon nanotubes in composite materials according to the degree of the conductive network by different ratios of carbon nanotubes [33].

Another study examined the effect of conductive materials on the indirect tensile strength (ITS) of asphalt mixtures, finding that high amounts of graphite can reduce the adhesive strength of asphalt due to thinning of the mastic layer [34]. Many studies confirm that the type and quantity of conductive additives can significantly influence the electrical and mechanical properties of asphalt [35,36]. Monitoring key structural characteristics, such as stress and strain, is crucial for designing, maintaining, and servicing asphalt pavements. Recently, the self-sensing property has emerged as a groundbreaking method for detecting pressure on flexible pavements.

This study aims to develop and test a hot mix asphalt sample with electrically conductive materials, measuring changes in electrical resistance when loads are applied. Marshall stability and flow values for the modified asphalt samples will be compared to a control sample. To the authors' knowledge, this is the first study of its kind to explore the sustainability of self-sensing asphalt.

2. Materials and Experimental Work

2.1 Materials

2.1.1 Asphalt: The asphalt used in this study was a (40–50) penetration grade asphalt cement produced by AL-Daurah Refinery. The physical properties of the asphalt are detailed in Table 1. All test results align with the specifications set by the State Commission on Roads and Bridges (SCRB) [37].

Table (1): Characteristics of Asphalt binder

Test	Test condition	ASTM designation	Results	Iraqi Specification's Standard Limits (SCRB/R9,2003)
Penetration	100 g, 25 C, 5 s, (0.1mm).	D-5	46.5	(40-50)
Viscosity	135 C, c.p. 165C, c.p.	D-4402	613 156	Min. 400 ---------
Specific gravity	25 C	D-70	1.031	---------
Flash point	---------	D-92	318	Min. 232
Ductility	25 C, 5 cm/min	D-113	142	>100
Softening point	(4 ± 1) C/min	D-36	53	--------

After thin-film oven ASTM D1754

Penetration of residue	--------	37	55^+
Ductility of residue	--------	108	25^+
Loss in weight	163 C, 50 g,5 h	0.3	--------

2.1.2 Aggregate

Crushed quartz aggregate from the Al-Nibaie quarry was used in this study. Both coarse and fine aggregates were sieved and mixed in the specified ratios to meet Type IIIA mixture requirements for the wearing course, as shown in Figure 1 [37] and Table 2. Routine evaluations of the aggregate's physical properties were conducted. The fine aggregates ranged from 4.75 mm (No. 4) to 0.075 mm (No. 200) sieve, with minimal clay, loam, and other impurities.

Table (2): 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): Characteristics of the used aggregate

Property	Coarse aggregate	Fine aggregate	Limits SCRB/2003
Bulk specific gravity (ASTM C-127 AND C128)	2.626	2.569	--
Apparent specific gravity(ASTM C-127 AND C128)	2.613	2.627	--
Percent water absorption (ASTM C-127 AND C128)	0.92	0.93	--
Angularity (ASTM D5821)	95.5%	--	Min. 90%
Toughness (Loss Angeles abrasion)(ASTM C535)	20.17	--	Max. 30%
Soundness (ASTM C88)	3.9 %	--	Max. 12%

Table (4): Chemical composition of the used aggregate

Chemical composition	% Content
Silica, Soi2	82.65
Lime, Cao	5.33
Magnesia, MgO	0.72
Sulfuric anhydride,SO3	2.76

Alumina,Al2O3	0.42
Ferric oxide, Fe2O3	0.68
Loss on lenition	6.67
Total	99.23

Mineral composition

Quartz	80.36
Calcite	10.79

2.1.3 Mineral Filler

As can be seen from Figure 2, Portland cement is utilized in the composition of the mineral filler. The condition describing the ill state is not tight and humid owing to the aggregation of fine particles. Table 5: Mineral filler physical and chemical properties.

Table (5): Physical and chemical properties of the mineral filler

Chemical composition	% Content
Silica, Soi2	21.51
Lime, Cao	62.52
Magnesia, MgO	1.61
Sulfuric anhydride,SO3	5.61
Alumina, Al2O3	3.77
Ferric oxide, Fe2O3	3.35
Loss on lenition	1.36
Total	99.73

Physical properties

%passing sieve No.200 (0.075mm)	97.81
Apparent specific gravity	3.102
Specific surface area (m^2/kg)	356

2.1.4 Graphite powder

Graphite powder possesses characteristics such as being lightweight, flexible, malleable, and compressible. It exhibits good thermal and electrical conductivity, as well as heat resistance. The graphite used is of ’a density of 2.16 g/cm3 and passing the No. 200 sieve (0.075 mm) has a carbon content of 85.6% with electrical resistivity of 10^{-4} Ω .m , Figures 3 and 4 show the graphite powder used for this study.

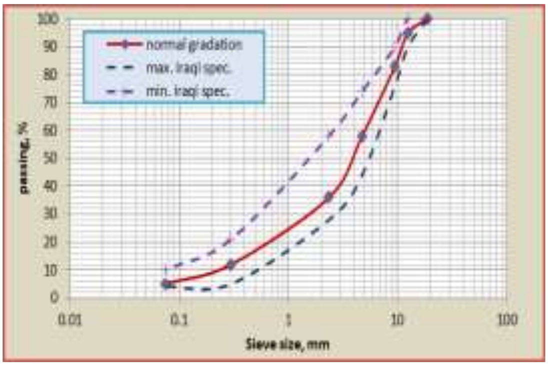

Figure 1. Selected gradations according to SCRB specifications [37]

Figure 2. Portland cement (Filler)

Figure 3. Graphite powder

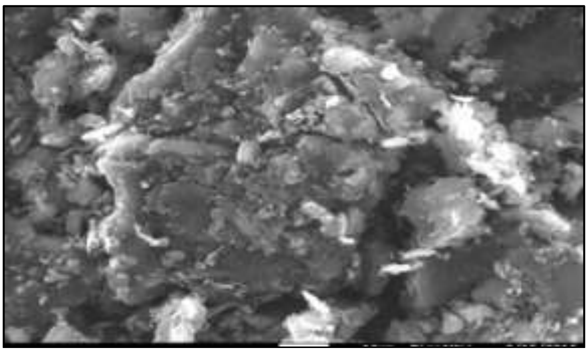

Figure 4. SEM image of graphite powder

2.2 Experimental work

2.2.1 Mix design with graphite powder

The asphalt mixture's conductive components were unable to distribute evenly due to the blending process [39]. Generally, dry conditions are employed to incorporate modifying components into the mixture. Additionally, a technique for achieving homogeneous dispersion of additives in asphalt materials was suggested to assess their impact.

Mixing method: The process involved mixing the fundamental components in a dry form with graphite powder for 10 minutes. Afterward, the asphalt was introduced, and the concoction was subjected to a temperature of 150 ° C and agitated for a minimum duration of 15 minutes. The temperature distribution concept is recognized as a determining factor that impacts the mechanical characteristics of hot asphalt mixture [40].

2.2.2 Marshall Test: O.A.C. of the conventional and the modified asphalt mixtures was determined from a set of Marshall tests -stability, density, and air voids-performed in conformity with ASTM D2726-08.Asphalt concentrations ranged from 4% to 6.5% of the total mixture weight, with 0.5% increments. For each concentration, three samples with a nominal maximum aggregate size of 12.5 mm were prepared. Marshall samples, measuring 2.5 inches in height and 4 inches in diameter, were compacted using a Marshall hammer with 75 blows on each side.

The samples were tested in a water bath at 60°C for 60 minutes with a loading rate of 50.8 mm/min. The Marshall parameters, including bulk specific gravity, air void volume, Marshall stability, and flow values, were optimized based on the results. Figure 5 illustrates the procedure used in the Marshall test.

Figure 5. Procedures for the stages of the Marshall test

2.2.3 Measurement of electrical resistivity using the Marshall Test: To assess the electrical resistivity, graphite powder was added to the asphalt mixture, and copper electrodes were embedded to ensure conductivity. The samples were electrically insulated from the Marshall apparatus using nylon wraps. Wires connected to the electrodes allowed for the measurement of electrical resistance while the Marshall test was conducted.

A measuring device, equipped with a video camera, was used to record stability, flow, and resistance values over time. This setup allowed for real-time monitoring of changes in electrical resistivity as loads were applied to the samples. Figure 6 shows the procedure for measuring electrical resistivity.

Figure 6. Procedures for the stages of measuring electrical Resistivity

3. Results and Discussion

3.1 Marshall Test Results (Mechanical Properties)

The optimal asphalt content (O.A.C.) for the (40–50) penetration grade asphalt mixture was determined by analyzing a series of samples prepared with varying asphalt contents ranging from 4% to 6%, with 0.5% increments. The Marshall test results, including stability, density, and air voids, were used to identify the O.A.C., which was found to be 4.91% for both conventional and modified mixtures. These results were consistent with previous studies on similar asphalt grades, where O.A.C. typically ranges between 4% and 5% .

When replacing 5%, 10%, 15%, 20%, 25%, and 30% of the filler with graphite powder, the Marshall stability values increased from 9.0 kN (0% graphite) to a peak of 10.1 kN at 10% graphite content, before decreasing to 6.1 kN at 30% graphite content, as shown in Table 6 and Figures 7 and 8. This increase in stability aligns with earlier research by Wu et al. (2011), which demonstrated that conductive fillers like carbon fibers improve the mechanical properties of asphalt concrete up to an optimal content, beyond which mechanical performance declines due to particle agglomeration and loss of cohesion .

The increase in Marshall flow values from 3.2 mm (0% graphite) to 5.2 mm at 30% graphite is also comparable with studies by Pan et al. (2015), where the addition of conductive materials such as graphite and carbon fibers led to a similar trend in flow values. The observed rise in flow can be attributed to the graphite particles’ interference with the aggregate’s interlocking mechanism.

Table 6: Marshall Test Results for Unmodified and Modified Mixtures

Asphalt Mixture	Graphite Powder (%)	Marshall Stability (kN)	Flow (mm)
Unmodified	0%	9.0	3.2
Modified	5%	9.6	3.303
Modified	10%	10.1	3.62
Modified	15%	8.7	3.73
Modified	20%	8.2	3.82
Modified	25%	7.4	4.6
Modified	30%	6.1	5.2

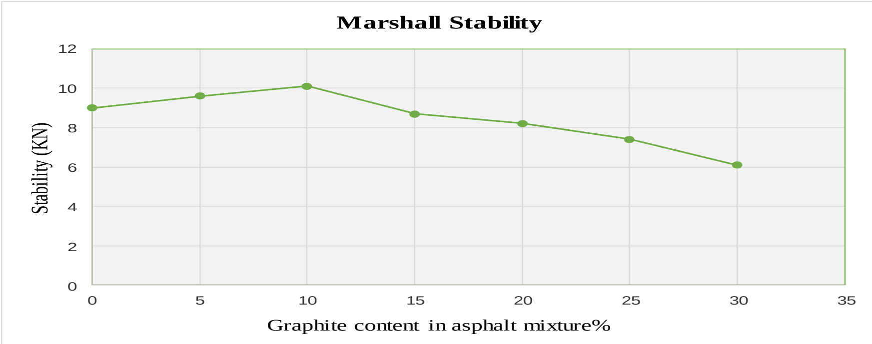

Figure 7. Marshall stability with graphite powder

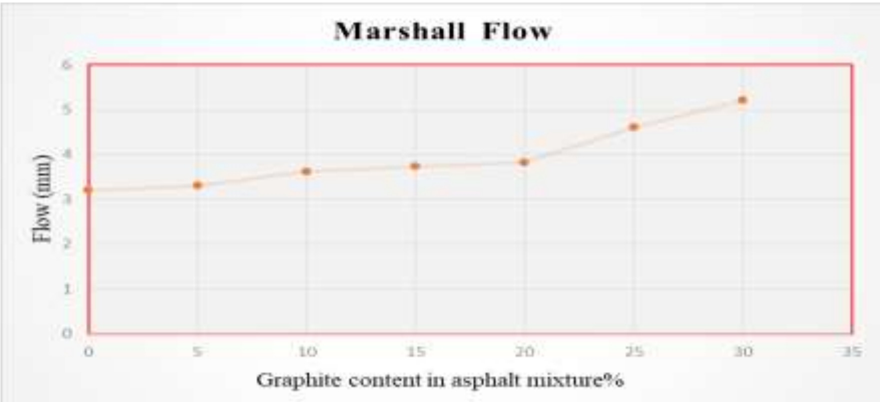

Figure 8: Marshall Flow with Graphite Powder

From these results, it is evident that 20% graphite powder represents the optimal balance between stability and flow, similar to findings in previous research. Studies such as those by Liu and Wu (2009) observed that conductive fillers enhance stability up to a certain threshold, after which the mechanical properties diminish due to increased brittleness and weaker matrix integrity.

3.2 Electrical Resistivity Behavior

To explore the electrical resistivity behavior, copper electrodes were embedded within the asphalt samples containing different proportions of graphite powder (0%, 5%, 10%, 15%, 20%, 25%, and 30%), and real-time resistance measurements were taken during the Marshall test.

The results indicated a clear transition from an insulating state to a conductive state as graphite content increased, with the percolation threshold (Pc) occurring at approximately 20% graphite content. At this point, electrical resistivity dropped from 1×1011 Ω·m1×1011Ω·m to 1.1×106 Ω·m1.1×106Ω·m, as shown in Figure 9. This drastic change in resistivity reflects the formation of a continuous conductive network within the asphalt matrix, similar to findings reported by Xin et al. (2020), who investigated carbon nanotubes as conductive fillers in asphalt and found a comparable percolation threshold.

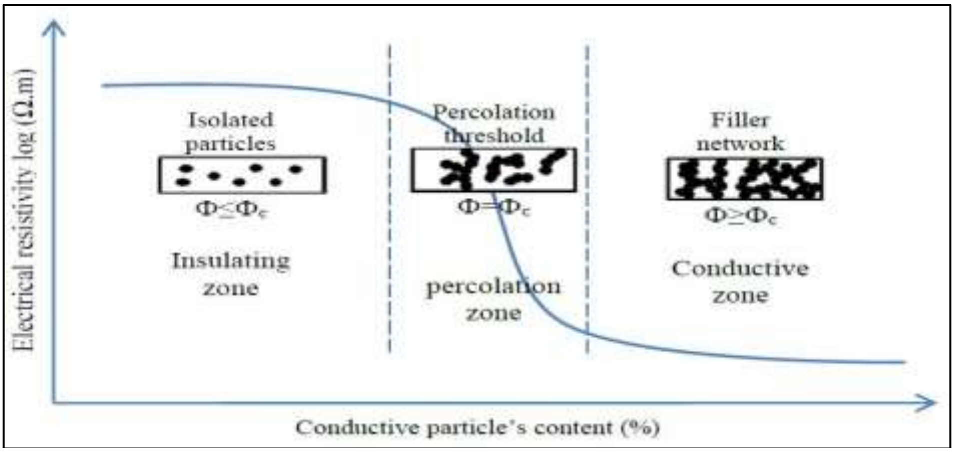

Figure 9: Electrical Phase Transition with Graphite Content

The relationship between the electrical resistivity and graphite content followed closely the S-shaped curve generally followed by conductive materials. Other similar studies by Liu and Schlangen 2010; Wu et al. 2005 also recorded a sharp decrease in the electrical resistance beyond the percolation threshold, substantiating the fact that the Asphalt matrix had now become a conductive material from an insulating one.

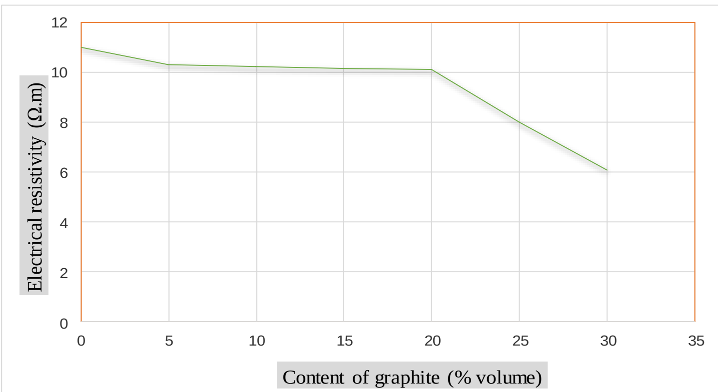

Figure 10: Electrical Resistivity vs. Graphite Content

That is reflected at 20% graphite, where the asphalt mixture showed an optimum electrical conductivity that could detect the applied loads through real-time changes in resistance. The resistivity behaviour noted in this study corroborates the observations of previous studies such as those by Al-Dahawi et al. (2017), who also observed that asphalt mixtures incorporating conductive materials exhibited self-sensing properties under applied stress. Because the graphite particles have a close molecular arrangement, charge could flow freely within the mixture, hence the ability to show self-sensing capability.

The results obtained in this study generally complement the findings obtained in prior research into conductive asphalt mixtures in both their mechanical and electrical properties. Incorporating graphite powder as a conductive filler enhanced the Marshall stability; such phenomena were also presented by Pan et al. (2015) in the study of conductive fillers, which showed increased stability up to an optimum content. Beyond 20% graphite, it lost stability because of brittleness in material nature, which agrees with the findings of Wu et al. 2011 using carbon fibers.

Electrical behavior: The outcome repeated some of the previous works from Xin et al. 2020 and Liu and Wu, 2009, where a quite clear percolation threshold-around 20% content-had been found in asphalt mixtures filled by conductive additives such as carbon nanotubes and fibers. These among present works ensure that at the percolation threshold, inside the matrix conductive pathways are formed that reduce radically resistivity, enabling the real-time monitoring of the mechanical loads.

Besides, the traced self-sensing ability agreed with those works of Al-Dahawi et al., 2017; Schlangen et al., 2010, who independently indicated that the conductive asphalt composite is in a position to detect stress and strain through the change in electrical resistance-that can be regarded as an opening towards smart pavement fabrication, which would thus provide real-time conditions of the road, hence better maintenance and prolonging its lives.

4. Conclusions

This study explored the use of graphite powder as a conductive filler in hot mix asphalt to enhance both its mechanical properties and self-sensing capabilities. Based on the laboratory experiments and analysis, the following key conclusions can be drawn:

- Marshall Stability Improvement: As a general trend, the measured stability values by Marshall have been increased drastically when adding graphite powder in asphalt mixture; the highest value of stability reported was at 10.1 kN for 10% graphite content. The stability values started to decrease beyond 20% of graphite contents since the graphite is brittle and it affected the integrity of asphalt matrix.

- Marshall Flow Behavior: Similarly, the values of Marshall flow continued to increase with the increase in the percentage of graphite powder and reached a maximum value of 5.2 mm at 30% graphite content. Such increase in flow was believed to be due to the reduction in cohesion among the aggregate particles since the graphite particles interfered in the interlocking mechanism of the asphalt matrix.

- Optimum Graphite Content: A graphite powder content of 20% was found to be optimum in achieving mechanical strength and complying with the SCRB standards of 2003. Such content can depict a quite appropriate balance in stability and flow parameters of the asphalt mixture for practical consideration.

- Electrical Conductivity and Self-Sensing: With increasing graphite content in the asphalt mixture, its electrical resistance was reduced more and more considerably until it attained a percolation threshold with the addition of 20% graphite content. While pure asphalt behaves like an electrical insulator, a mixture of asphalt and graphite immediately becomes electrically conductive just after the addition of graphite. Such a transition allows for real-time monitoring of the applied load, pointing to the possibility of self-sensing in pavements.

- Self-Sensing Capability: The results indicated that under load, the electrical resistance of asphalt mixture reduced, hence it could self-sense the applied stress and deformation, and will be able to make use of continuous pavement monitoring in gathering useful data related to traffic volume and road condition without embedded or attached sensors.

- Practical Implications: These results can show that graphite powder blended into asphalt is going to provide enhancement not just in mechanical properties but also to facilitate smart pavements due to their enabling of detections of traffic volume and pavement stress. This technology is inexpensive and going to improve infrastructure quality, which is both existing and newly constructed roadways.

The overall trend of the present study shows that the addition of conductive materials, such as graphite, during the production of multifunctional asphalt mixtures, is very promising for applications with combined needed mechanical and self-sensing properties and thus for much more sustainable and intelligent infrastructure systems.

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.

Statements and Declarations

Funding and/or Conflicts of interests/Competing interests. Also, I declare that the manuscript was done depending on the personal effort of the author, and there is no funding effort from any side or organization, as well as no conflict of interest with anyone related to the subject of the manuscript or any competing interest.

References

1. Al-Dahawi A. Multifunctional Cementitious Composites for Damage-Resistant Highway Structures.
2. Delatte NJ. Concrete pavement design, construction, and performance. CRC Press. Boca Raton, FL, USA. 2014.
3. Al-Rubaee RH, Shubber AA. Assessment of Reasons for Driver Speeding and Estimation of Penalty Probability. InE3S Web of Conferences 2023 (Vol. 427, p. 03012). EDP Sciences.
4. Albayati AH. A review of rutting in asphalt concrete pavement. Open Engineering. 2023 Jun 8;13(1):20220463.
5. Xue W, Wang L, Wang D, Druta C. Pavement health monitoring system based on an embedded sensing network. Journal of Materials in Civil Engineering. 2014 Oct 1;26(10):04014072.
6. Sofi A, Regita JJ, Rane B, Lau HH. Structural health monitoring using wireless smart sensor network–An overview. Mechanical Systems and Signal Processing. 2022 Jan 15;163:108113.
7. Downey A, D'Alessandro A, Baquera M, García-Macías E, Rolfes D, Ubertini F, Laflamme S,

Castro-Triguero R. Damage detection, localization and quantification in conductive smart concrete structures using a resistor mesh model. Engineering Structures. 2017 Oct 1;148:924-35.

8. Zghair HH, Joni HH, Hassan MS. Impact of Mixing process on the physical and Rheological Characteristics of Asphalt Binder Modified with Nano-Silica Powder. InIOP Conference Series: Materials Science and Engineering 2019 Jul 1 (Vol. 579, No. 1, p. 012046). IOP Publishing.
9. Joni HH, Zghair HH. Properties of modified asphalt mixtures with additives of fillers materials. InIOP Conference Series: Materials Science and Engineering 2020 Feb 1 (Vol. 737, No. 1, p. 012120). IOP Publishing.
10. Y Fattah M, S Abdaljabbar A. Analysis of the performance of flexible pavement under the effect of wheel and thermal loads. Engineering and Technology Journal. 2010 Sep 1;28(18):5782-802.
11. Taher ZK, Ismael MQ. Rutting Prediction of Hot Mix Asphalt Mixtures Modified by Nano silica and Subjected to Aging Process. Civil Engineering Journal. 2022 Dec 14;9:1-4.
12. Ghadhban D, Joni HH, Al-Dahawi AM. Carbon Fiber-Based Cementitious Composites for Traffic Detection and Weighing In Motion. Engineering and Technology Journal. 2021 Aug 25;39(8):1250-6.
13. Sujon M, Dai F. Application of weigh-in-motion technologies for pavement and bridge response monitoring: State-of-the-art review. Automation in Construction. 2021 Oct 1;130:103844.
14. Andrle S, McCall B, Kroeger D. Application of weigh-in-motion (WIM) technologies in overweight vehicle enforcement. In3rd International Conference on Weigh-in-Motion (ICWIM3) 2002. Citeseer.
15. Lehman M. The american society of civil engineers' report card on america's infrastructure. InWomen in Infrastructure 2022 Feb 26 (pp. 5-21). Cham: Springer International Publishing.
16. Al-Tuwayyij H, Al-Mukaram N, Musa SS. Impact of Plastic Waste on The Volumetric Characteristics and Resilient Modulus of Asphalt Concrete. Civil Engineering Journal. 2023 Apr 1;9(04).
17. Han B, Wang Y, Dong S, Zhang L, Ding S, Yu X, Ou J. Smart concretes and structures: A review. Journal of intelligent material systems and structures. 2015 Jul;26(11):1303-45.
18. Li GY, Wang PM, Zhao X. Pressure-sensitive properties and microstructure of carbon nanotube reinforced cement composites. Cement and Concrete Composites. 2007 May 1;29(5):377-82.
19. Gupta S, Lin YA, Lee HJ, Buscheck J, Wu R, Lynch JP, Garg N, Loh KJ. In situ crack mapping of large-scale self-sensing concrete pavements using electrical resistance tomography. Cement and Concrete Composites. 2021 Sep 1;122:104154.
20. Wang H, Shi F, Shen J, Zhang A, Zhang L, Huang H, Liu J, Jin K, Feng L, Tang Z. Research on the self-sensing and mechanical properties of aligned stainless steel fiber-reinforced reactive powder concrete. Cement and Concrete Composites. 2021 May 1;119:104001.
21. Armoosh SR, Oltulu M, Alameri I, Mohammed HM, Karacali T. The combined effect of carbon fiber and carbon nanotubes on the electrical and self-heating properties of cement composites. Journal of Intelligent Material Systems and Structures. 2022 Nov;33(18):2271-84.
22. Al-Dahawi A, Öztürk O, Emami F, Yıldırım G, Şahmaran M. Effect of mixing methods on the electrical properties of cementitious composites incorporating different carbon-based materials. Construction and Building Materials. 2016 Feb 1;104:160-8.
23. Celik DN, Yıldırım G, Al-Dahawi A, Ulugöl H, Han B, Şahmaran M. Self-monitoring of flexural fatigue damage in large-scale steel-reinforced cementitious composite beams. Cement and Concrete Composites. 2021 Oct 1;123:104183.
24. Wang H, Jun Y, Gong M, Shi X. Laboratory performance evaluation of high-modulus asphalt

mixtures for perpetual asphalt pavements. 2015.
25. Wu S, Pan P, Chen M, Zhang Y. Analysis of characteristics of electrically conductive asphalt concrete prepared by multiplex conductive materials. Journal of materials in civil engineering. 2013 Jul 1;25(7):871-9.
26. Wang X, Yuxing G. Notice of Retraction: Research on the preparation of conductive asphalt concrete for deicing and snow melting. In2010 3rd International conference on advanced computer theory and engineering (ICACTE) 2010 Aug 20 (Vol. 2, pp. V2-381). IEEE.
27. Al-Dahawi A, Yıldırım G, Öztürk O, Şahmaran M. Assessment of self-sensing capability of Engineered Cementitious Composites within the elastic and plastic ranges of cyclic flexural loading. Construction and Building Materials. 2017 Aug 1;145:1-0.
28. Park P, El-Tawil S, Park SY, Naaman AE. Cracking resistance of fiber reinforced asphalt concrete at− 20 C. Construction and Building Materials. 2015 Apr 15;81:47-57.
29. Baranikumar A. Imparting Electrical Conductivity into Asphalt Composites Using Graphite (Doctoral dissertation, Texas A & M University).
30. Liu X, Wu S. Study on the graphite and carbon fiber modified asphalt concrete. Construction and Building Materials. 2011 Apr 1;25(4):1807-11.
31. Ozturk M, Chung DD. Capacitance-based stress self-sensing in asphalt without electrically conductive constituents, with relevance to smart pavements. Sensors and Actuators A: Physical. 2022 Aug 1;342:113625.
32. Liu X, Wu S. Research on the conductive asphalt concrete's piezoresistivity effect and its mechanism. Construction and Building Materials. 2009 Aug 1;23(8):2752-6.
33. Xin X, Liang M, Yao Z, Su L, Zhang J, Li P, Sun C, Jiang H. Self-sensing behavior and mechanical properties of carbon nanotubes/epoxy resin composite for asphalt pavement strain monitoring. Construction and Building Materials. 2020 Oct 10;257:119404.
34. Liu Q, Schlangen E, García Á, van de Ven M. Induction heating of electrically conductive porous asphalt concrete. Construction and Building Materials. 2010 Jul 1;24(7):1207-13.
35. Wu S, Mo L, Shui Z, Chen Z. Investigation of the conductivity of asphalt concrete containing conductive fillers. Carbon. 2005 Jun 1;43(7):1358-63.
36. Huang B, Chen X, Shu X. Effects of electrically conductive additives on laboratory-measured properties of asphalt mixtures. Journal of Materials in Civil Engineering. 2009 Oct;21(10):612-7.
37. SCRB RE. Standard Specifications for Roads and Bridges. Section R/9, Hot-Mix Asphaltic Concrete Pavement. 2003.
38. Vijay R, Singaravelu DL, Jayaganthan R. Development and characterization of stainless steel fiber-based copper-free brake liner formulation: a positive solution for steel fiber replacement. Friction. 2020 Apr;8:396-420.
39. Pan P, Wu S, Xiao F, Pang L, Xiao Y. Conductive asphalt concrete: A review on structure design, performance, and practical applications. Journal of Intelligent Material Systems and Structures. 2015 May;26(7):755-69.
40. Hilal MM, Fattah MY. A model for variation with time of flexible pavement temperature. Open Engineering. 2022 Mar 16;12(1):176-83.
41. Zadri Z, Glaoui B, Abdelkhalek O. Enhancement of electrical and mechanical properties of modified asphalt concrete with graphite powder. Civil Engineering Journal. 2022 Jan 1;8(01).
42. Abdullah RD, Al-Dahawi A, Zghair HH. Mechanical characteristics and self-monitoring technique of smart cementitious mixtures with carbon fiber and graphite powder as hybrid functional additives. Engineering and Technology Journal. 2022 Nov 1;40(11):1537-47.