coatings

MDPI

Article

Encapsulation for Sensing Element and Its Application in Asphalt Road Monitoring

Chuanyi Ma [1], Xue Xin [2,*], Ning Zhang [1], Jianjiang Wang [2], Chuan Wang [1], Ming Liang [2,*], Yunfeng Zhang [2] and Zhanyong Yao [2]

[1] Shandong Hi-Speed Group Co., Ltd., Jinan 250014, China
[2] School of Qilu Transportation, Shandong University, Jinan 250002, China
* Correspondence: xinxue@mail.sdu.edu.cn (X.X.); ming.liang@sdu.edu.cn (M.L.); Tel.: +86-1866-1628-291 (X.X. & M.L.)

Abstract: The internal pavement structure is a "black box"; an accurate strain response for the pavement interlayer structure under vehicle load is hard to obtain by conventional road surface detection methods. This is due to the true strain field of the pavement structure, which means that the service state of the pavement cannot be accurately evaluated. This paper proposes an innovative strain sensor based on a carbon nanotube and epoxy (CNT/EP) composite to solve the current strain monitoring problem in asphalt pavement health monitoring. The CNT/EP composite encapsulation method was proposed, and the I-shaped strain sensor for asphalt pavement structure was developed. The strain–resistance response characteristics of the self-developed sensor were further investigated using a universal testing machine. The encapsulated sensor was used to monitor the strain of the asphalt mixture by means of a laboratory asphalt concrete beam and a practical pavement field. The results showed that the encapsulation method proposed in the study is suitable for CNT/EP material, which could guarantee the survivability and monitoring effectiveness of the self-developed sensor under the harsh environment of high temperature and pressure of asphalt mixture paving. The resistance of encapsulated sensor presents a linear relationship with strain. The laboratory and practical paving verified the feasibility of the self-sensor for strain monitoring of asphalt pavement. Compared to other post-excavating buried sensors, the self-developed sensor can be embedded in the pavement interlayer as the asphalt mixtures paving process, which can obtain the real strain response of pavement structure and reduce the perturbation of the sensor to the dynamic response of the pavement.

Keywords: pavement health monitoring; CNT/EP composites; embedded strain sensor; encapsulation

check for updates

Citation: Ma, C.; Xin, X.; Zhang, N.; Wang, J.; Wang, C.; Liang, M.; Zhang, Y.; Yao, Z. Encapsulation for Sensing Element and Its Application in Asphalt Road Monitoring. *Coatings* **2023**, *13*, 390. https://doi.org/10.3390/coatings13020390

Academic Editor: Andrea Simone

Received: 23 December 2022
Revised: 2 February 2023
Accepted: 5 February 2023
Published: 8 February 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

By the end of 2021, the total mileage of China's road network will have reached 5.28 million kilometers and road maintenance expenditure will be approximately RMB 7.4 trillion [1]. Over the past few decades, approximately 90% of the work has involved the maintenance and upgrading of existing roads. It is expected that more and more roads will need to be maintained and upgraded in the future [2]. Thus, it is necessary to obtain the road structure conditions to judge whether the road needs to be maintained or not. Timely maintenance can help to reduce the maintenance and upgrading costs and extend the life of roads from the view of the full life cycle [3,4]. A prerequisite for obtaining the structure conditions is pavement monitoring. The growth of the traffic volume has forced the world to focus on road surface monitoring and providing a sustainable transportation network [5]. Generally, macroscopic surface investigation and external nondestructive testing techniques are used to evaluate the performance of asphalt pavements. For example, digital image processing techniques are used to assess pavement damage and surface texture [6,7]. A falling weight deflectometer (FWD) is applied to detect road surface

bending and further calculate pavement modulus [8–10]. In addition, ground penetrating radar is used to detect the thickness and density of the pavement. However, pavement structure is a "black box"; the traditional conventional external inspection methods cannot obtain the real strain/stress condition of interlayer structure [11,12], which lacks the actual pavement internal/interlayer structure stress–strain field. As a result, the traditional detection methods from the road surface are not enough to accurately assess the pavement conditions [13,14].

To obtain the interlayer strain/stress of road structures, many researchers proposed embedding sensors in road structures [15–19]. Liu et al. [20] developed a new encapsulated rubber strain sensor for asphalt pavement vertical strain monitoring. Their testing results show that the sensor has good sensing performance, but the sensitivity of the sensor is poor. Wu et al. [21] used a fiber-encapsulated long-range strain sensor with a larger contact surface of the sensing part subjected to temperature, making it more sensitive to temperature and more accurate in monitoring results. Liang et al. [22] used carbon fiber composites to encapsulate the fiber optic sensor, and the results showed that the sensor has good linearity and repeatability. Sohel et al. [23] developed carbon fiber composites for the health monitoring of civil engineering structures, which were found to be highly ductile and greatly prevented the sudden collapse of the structure. However, there is a lack of sufficient information in the literature on the effect of environmental and service conditions on the self-induced properties of the developed composite. Jiang Wei et al. [24] made use of lead zirconate titanate (PZT) powder and PVDF to prepare composite sheet material and then encapsulated the composite sheet material with 3D printed cylindrical packaging structure to prepare a piezoelectric sensing device, which was buried in asphalt mixture and tested the output effectiveness of its sensing signal by simulating vehicle load. These reports indicated the good feasibility of applying sensors for civil structures, and the ideal monitoring effect of the structure service state was obtained. However, the research on asphalt pavement structure monitoring sensors was insufficient. Few studies concentrate on preliminary embedding sensor techniques during the asphalt mixture paving process. The embedded sensor in the asphalt pavement interlayer struggles to survive since the temperature and pressure are high under the mixing, paving, and compaction of the asphalt mixture.

In recent years, the development of composite materials with self-sensing properties has provided a new idea to address the above-mentioned limitations of traditional strain sensors. Smart composite material is a new type of functional material that has self-perception of external factors such as force, deformation, temperature, humidity, etc. Composite materials could obtain information about the strain, stress, and other mechanical parameters of the measured structure by means of establishing a correlation between external factors and the electrical signal output of the composite smart material [25]. However, the composite material would be limited according to its application environment. For example, the harsh construction environment makes the survival rate of ordinary composite smart-material-based sensors greatly reduced in the field of civil engineering monitoring. In addition, the temperature and humidity of the environment in which the sensor's work environment varies greatly, which also has a greater impact on the accuracy of sensor signal monitoring [26,27].

For the harsh monitoring environment of asphalt pavement, the authors have carried out a series of related research in the development of new sensors for pavement [28–31]. Smart-material-based strain sensing elements have been developed, and the high accuracy, as well as viability of the sensing elements, were verified. On the basis of our previous research work, the encapsulation technique of smart composite materials and the shape design of the resulting sensor were emphasized in this paper. Afterward, the response of strain with resistance was measured by a universal testing machine. The encapsulated smart composite materials-based sensor was used on a road construction site in order to verify the viability and stability of the developed sensors. It is expected that this work will

provide a new approach to asphalt pavement service state monitoring. The flowchart about this paper's methodology and the expected results, please see as Figure 1.

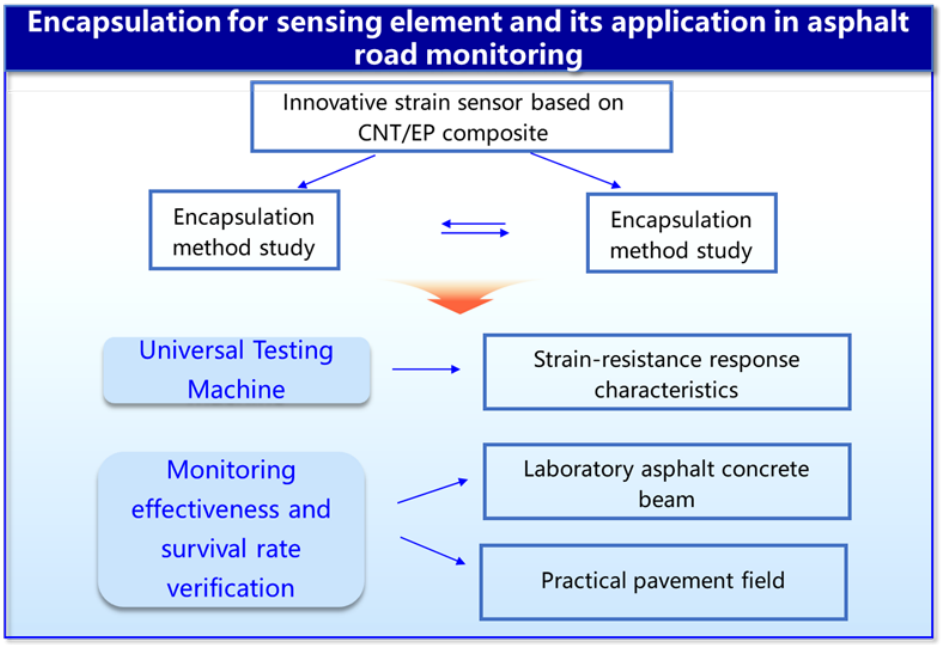


Figure 1. Flowchart about this paper's methodology and the expected results.

2. Preparation and Encapsulation of Smart Material-Based Strain Sensors

2.1. Preparation of Carbon Nanotube/Epoxy Resin (CNT/EP) Composites

Epoxy resin/multi-walled carbon nanotube (MWCNT) composites were prepared in the study as the sensing materials. MWCNT is obtained from high-temperature cracking of acetylene catalyzed by nickel-based catalysts. The selected MWCNT is of 95 wt% purity, with a specific surface area greater than 165 m^2/g. It is noteworthy that the MWCNT shows excellent electrical conductivity of 200 s/cm, which is expected to be beneficial to the conductivity sensitivity. The epoxy resin is bisphenol A type epoxy resin with an epoxy value of 0.48–0.54 eq/100 g and a viscosity of 12,000 mPa.s.

In order to form an effective conductive network, the MWCNT should be uniformly dispersed in the epoxy polymer matrix. The authors' studies have shown that the dispersion degree of CNT plays a key role in the response of strain–resistance [22]. Therefore, in order to overcome the non-uniform dispersion phenomenon of MWCNT caused by the van der Waals forces due to their huge specific surface area and nanoparticle size, the MWCNT were firstly ground in an agate mortar for 30 min in this study, followed by thorough mixing with the dispersant of N,N-Dimethylformamide(DMF). The MWCNT/DMF mixtures were mixed with mechanical stirring for 20 min, and then sonicated for 1 h with an ultrasonic disperser. After that, the mixed MWCNT/DMF suspension was added to the epoxy resin and continued to be sonicated for 1 h. The MWCNT/DMF/EP mixture was put in a vacuum drying oven for 1 h at 80 °C for DMF evaporation. Finally, the curing agent was added and stirred for 10 min to produce MWCNT/EP composites. The strain–resistance response of the composites was tested on equipment shown in Figure 2 (equipment parts: a—strain console, b—developed MWCNT/EP composite rod, c—strain gauge, d—resistance measuring device, e—electrical resistance recorder, and f—strain gauge recorder).

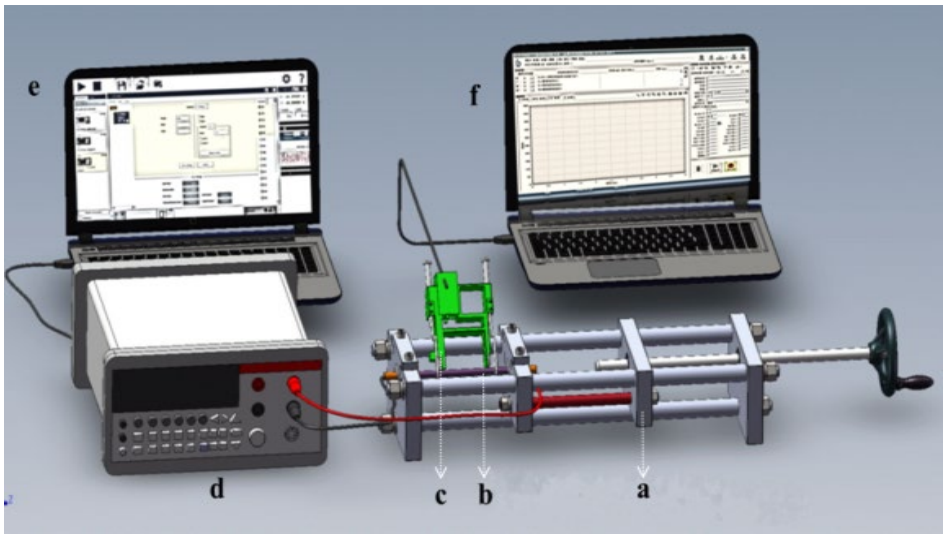


Figure 2. Testing equipment for strain–resistance response of CNT/EP composites.

2.2. Encapsulating MWCNT/EP Composite Rod by Epoxy for Manufacturing Strain Sensing Element

The MWCNT/EP suspensions showed the viscous flow state before curing, and they could be shaped with certain shape characteristics by casting and molding in the mold. The molding and encapsulating procedure of the MWCNT/EP composite rod are shown in Figure 3. The most common forming methods of conductive composite materials include surface conductive film forming method, conductive filler dispersion coating method, conductive material layer method, etc. However, when these methods are used for performance testing after sample preparation, conductive glue such as silver adhesive electrode, aluminum foil adhesive electrode, or the tin welding method is generally used to connect the wires. The material samples prepared by this method may have some shortcomings, such as uneven surface integrity, a long curing period of the conductive adhesive, poor adhesion effect, unstable contact electrical signal, and so on. Moreover, the production process is complex, and the production efficiency is low. So, in the preparation device, conducting wires were embedded in the mold through cap plugs at both ends of the mold. Both sides of the cover plug were provided with a feeding port and a discharge port for the composite self-sensing material to enter and exit. The shape of the cured composite was maintained by means of a fixed tube whose inner diameter was close to the outer diameter of the formed tube.

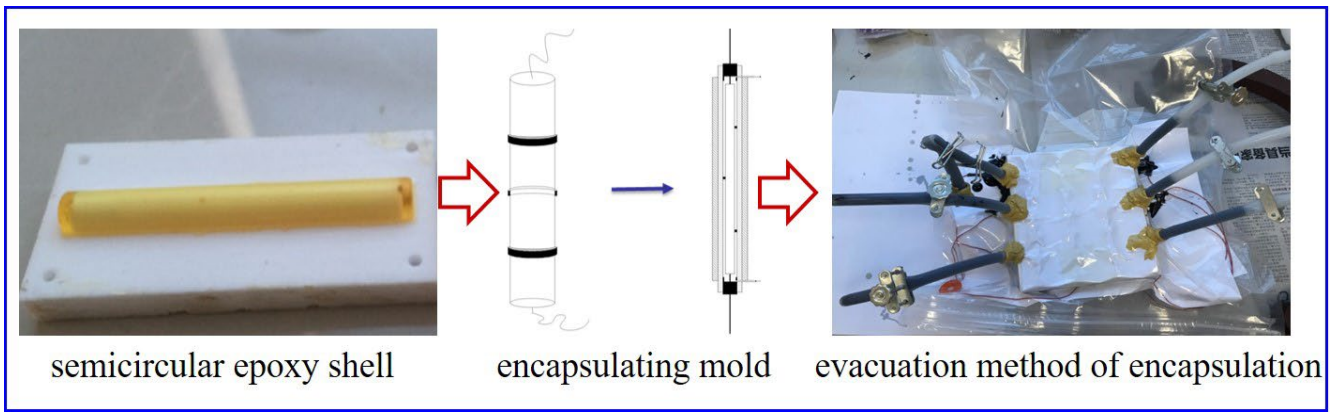


Figure 3. The molding and encapsulating procedure of MWCNT/EP composite rod.

To ensure the co-axiality of the MWCNT/EP composite rod and its covered epoxy shell, the semicircular epoxy was first pre-casted in the PTFE mold. The semicircular

mold is designed to ensure that the semicircular epoxy has the same internal diameter as the semicircular epoxy and the same thickness as the packaging layer to ensure that the composite rod is at the center of the packaged sensing element. Three semicircular epoxy parts were used to support the MWCNT/EP composite rod along the axial direction. The two ends of the black rod prepared by MWCNT/EP were set with a cap plug with a hole in the middle and, thus, the viscous epoxy could inject into one hole and outflow in another hole through the cap plug with holes. The cap plug can be connected to the mold to ensure the sealing effect. After the forming inner tube was installed, the lead outlet, sample injection hole, sample outlet hole, cap plug, and the forming inner tube were sealed by a vacuum sealant so as to prevent the packaging material from flowing out of the gap resulting in an uneven surface of the sample. Lastly, the encapsulating epoxy materials were injected into the hole and cured into shape to complete the sensor encapsulation. After the sensor was assembled with the molding mold, it was put into the sealed vacuum bag and connected to the vacuum pumping device. Then the vacuum pump was opened, and the packaging material flowed through the injection hole on the cap plug structure. Under the vacuum negative pressure condition, the gas inside the mold cavity was removed, and the packaging material was driven to flow, infiltrate, and finally fill the entire cavity. In the process of injection of packaging materials, the whole sensor and part of the electrode wires at both ends were sealed in the air-tight packaging material through the molding mold and the vacuum device so as to ensure that the sensor itself is completely isolated from the influence of the external environment.

The encapsulation process, with the help of mold, makes the integrated sensing element with the electrode wires at both ends within the encapsulation material. This encapsulated structure could ensure the sensing element is completely insulated from the influence of moisture from the external environment. The excellent waterproofness and airtightness of the encapsulated materials can help to prevent the sensor from being eroded by the harsh external environment during service, thus solving the problems of low sensor survival rate, short survival period, the drift of the received electrical signal, and undesirable measurement accuracy.

After curing at room temperature for 24 h, the encapsulated MWCNT/EP composite sensor in the mold was placed in an oven and cured for 2 h at 80 °C. The strain sensor can be obtained after removing the cap plugs and protective sleeves at both ends. In addition, the thickness of the covered epoxy film can be adjusted, and the multilayer of encapsulated materials can be used based on the same method, which improves the high-temperature resistance characteristics and reduces the humidity sensitivity of the sensor. When the sensing element was manufactured, the I-shaped aluminum accessories were installed on the bottom of the encapsulated cylindrical sensing element, and thus the I-shaped sensor was obtained (shown in Figure 4).



Figure 4. The self-developed I-shaped strain sensor made by encapsulated cylindrical MWCNT/EP composite.

3. Strain–Resistance Response Characteristics of the Self-Developed I-Shaped Sensor

3.1. Embedding Process of Sensor in Asphalt Concrete Slab

In order to figure out the adaptability and survivability of the self-developed strain sensor (Figure 4) in asphalt pavement and its resistance to high temperature and pressure during the asphalt mixture paving process, the self-developed strain sensor was embedded in the bottom of the double-layer asphalt concrete slab (size of 300 mm × 300 mm × 100 mm) in a laboratory. Two holes were set on the two sides of the mold to prepare the double-layer asphalt concrete slab, and to ensure the wire of the sensor could go through. The sensors were placed on the bottom of the asphalt mixture mold, and they needed to be firstly covered by part of the asphalt mixture that was further compacted. Afterward, the asphalt mixtures that had been calculated in volume and quantity were added into the mold, which was compacted for 50 rolls in each direction by a wheel mill to ensure that the asphalt mixture reached the specified compaction level. Subsequently, the mold was removed, and the asphalt concrete slab was cut into 10 cm lengths per beam according to the area where the sensor was located. The embedding process of the sensor in asphalt concrete slab is shown in Figure 5. All the embedded strain sensors have been proven to survive effectively in a laboratory. It is concluded that the sensor can withstand high temperatures and pressure during the asphalt mixture compaction. Thus, it is reasonable to deduce that the self-developed I-shaped strain sensor made by encapsulated MWCNT/EP composite is of good adaptability and survivability, which can adapt to the harsh environment of asphalt pavement construction. The accuracy and durability of the sensor need to be further studied.

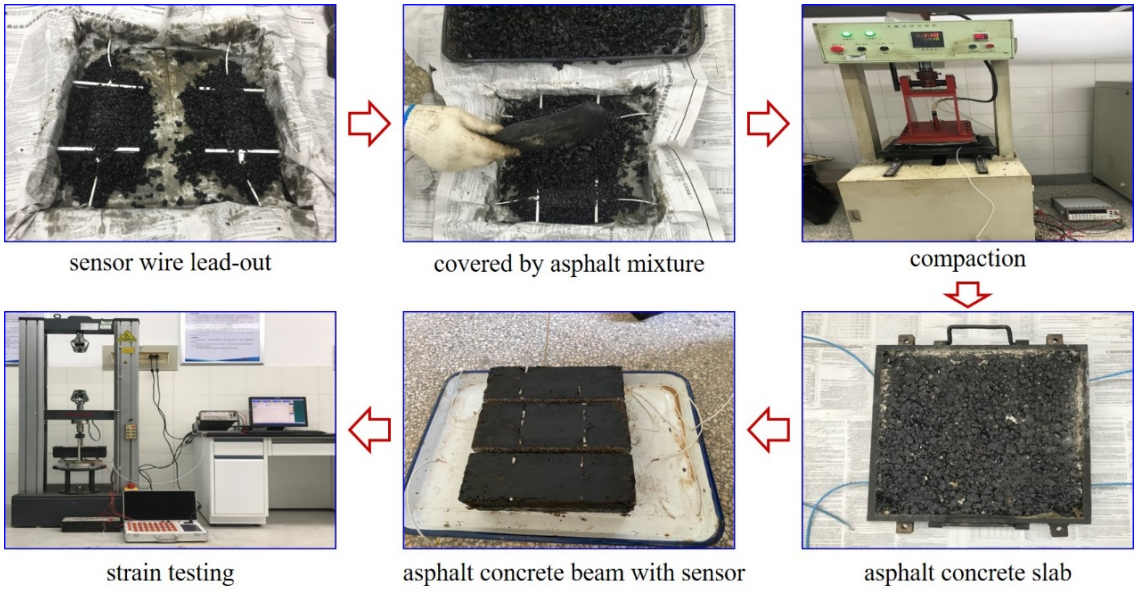


Figure 5. Embedding process of sensor in asphalt concrete slab.

3.2. Strain Monitoring Effectiveness of the Sensor in Asphalt Concrete

The monitoring effectiveness of deformation, the viability of monitoring elements, and so on are the key indicators of monitoring sensors, which could provide guidance on the embedding design and process of the sensor in asphalt pavement. When the asphalt concrete slab embedded with a self-developed sensor was prepared, the sensor reliability and monitoring effectiveness of deformation were analyzed by a universal testing machine. The commercial metal foil strain gauge was pasted on the bottom of the asphalt concrete beam with an embedded strain sensor to compare the difference in deformation strain at the same position of the beam. The asphalt beam was placed on the universal testing machine to conduct the three-point bending test. The resistance of the sensor was acquired

synchronously by connecting a data acquisition instrument during strain loading (shown in Figure 6).

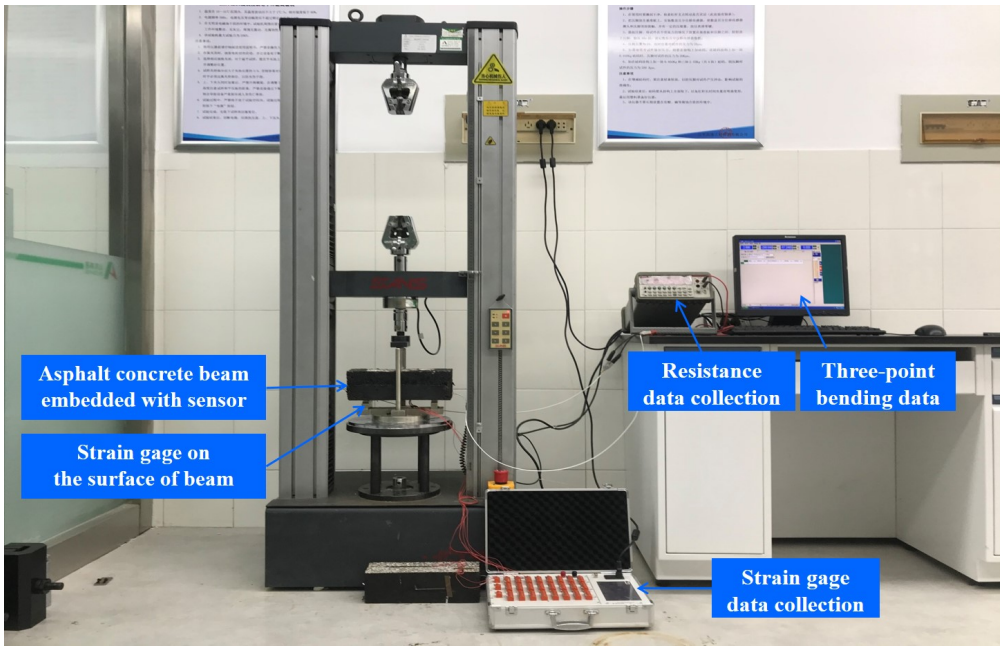


Figure 6. Strain monitoring calibration test of sensor on universal testing machine.

The strain control mode on the universal testing machine takes the program displacement control and the loading speed is 0.02 mm/min. When the displacement reaches 0.2 mm, it is maintained for 10 s. Then, the loading continues to 0.4 mm and the displacement is maintained for 10 s. Repeat the step until the displacement reaches 3.0 mm. The loading curve is shown in Figure 7.

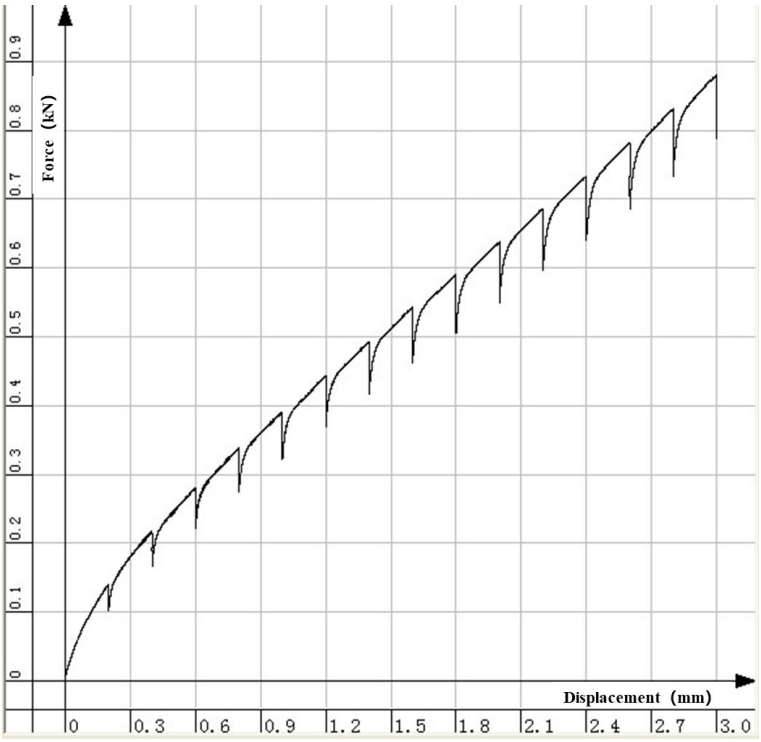


Figure 7. Strain control loading method.

The relationship between strain and resistance changing rate collected simultaneously under the step-by-step loading is shown in Figure 8. It can be seen that the resistance changing rate $\Delta R/R_0$ shows an increasing trend accordingly with the gradual increase in the deformation of the asphalt mixture beam. Furthermore, the strain–resistance changing response curve is plotted using the strain gauge data from the bottom of the asphalt mixture beam as the calibration strain of the embedded sensor. It can be seen that the resistance changing rate $\Delta R/R_0$ of the strain sensor shows a good linear relationship with the strain, and the fitting linear equation can be obtained.

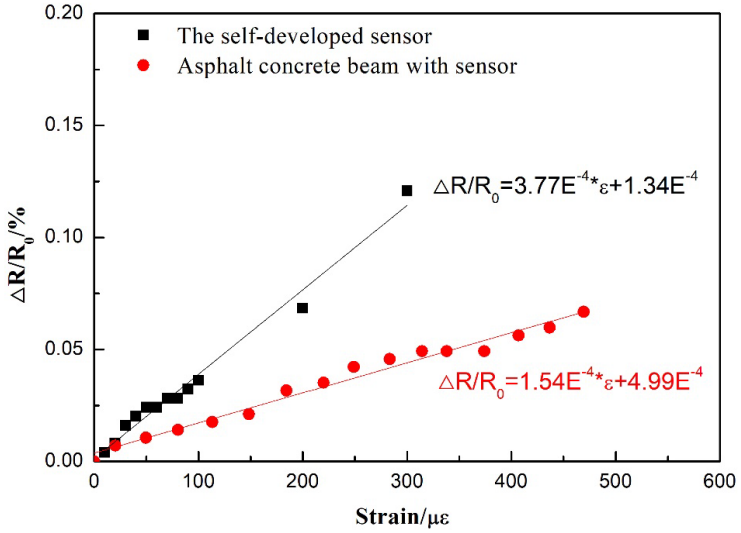


Figure 8. Force–electric response during step-by-step loading.

The strain sensor has good effectiveness in monitoring the deformation of the asphalt mixture beam. By comparing the fitted curves of sensor response before and after embedding, it can be seen that the value of $\Delta R/R_0$ for the embedded sensor is about 0.65 times that before embedding at the experimentally selected depth and loading rate. Therefore, the embedded strain sensors in asphalt pavement can be calibrated by multiplying the correction factor on the sensor room calibration results for practical engineering applications. The strain calibration test of asphalt concrete beam embedded with a sensor also verified that the self-developed I-shaped strain sensor made by encapsulated MWCNT/EP composite has stable sensing characteristics when employed for pavement strain monitoring, although it suffered the high temperature and pressure during asphalt mixtures compaction.

3.3. Application of Self-Developed Sensor in Practical Pavement Interlayer Strain Monitoring

On the basis of laboratory strain monitoring effectiveness of the sensor in asphalt concrete, the self-developed sensor was applied in practical pavement construction, aiming to verify its engineering performance [32,33]. The engineering field application of the self-developed sensor is shown in Figure 9. The position of the sensor in the lane should be accurately located in practical pavement engineering in order to make it coincide with the road lane wheel tracks. Then, the distance between every sensor needs to be determined, and the location of each sensor is coded. The sensors were pre-installed and positioned according to the location marker, and the wire was led through the curbstone gap. The hot asphalt mixtures were taken out from the truck and used to cover the installed sensor. The covered asphalt mixtures were further compacted using a rubber hammer. Eventually, as the paving truck moved, the sensor was buried in the interlayer of the asphalt pavement structure. After compaction, the monitoring results verified the good survivability and monitoring effectiveness of the self-developed sensor. Compared to other post-excavating buried sensors, the self-developed sensor can be embedded in the pavement interlayer as the asphalt mixtures paving process, which can obtain the real strain

response of pavement structure and reduce the perturbation of the sensor to the dynamic response of the pavement. It also provides the possibility of significantly simplifying the strain sensor embedding process.

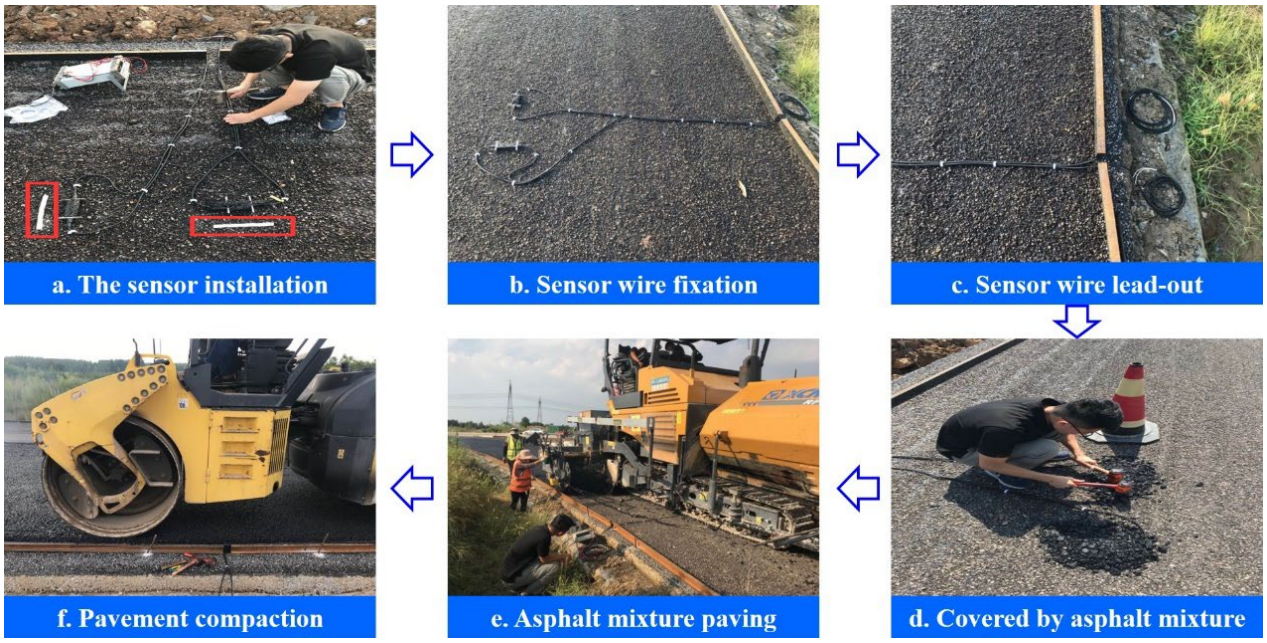


Figure 9. Engineering field application validation of strain sensors.

4. Conclusions

In order to solve the problem of direct monitoring of the internal strain response of the asphalt pavement, this study innovatively developed a strain sensor based on MWCNT/EP composite materials. The encapsulation techniques of MWCNT/EP composite rod by epoxy, the embedding process of the sensor in asphalt concrete, the strain monitoring effectiveness of the sensor in asphalt concrete, and the application of a self-developed sensor in the practical pavement were investigated systematically. The conclusions are summarized as follows:

- The self-developed embedded strain sensor can detect the strain changes in the asphalt pavement structure. When it is subjected to an external load, the conductive path is changed accordingly in conductive MWCNT/EP composite material, causing changes in the resistance of the sensor.
- The strain monitoring effectiveness test showed that the sensor has a high sensitivity to strain, and the resistance value of the sensor is linearly related to the changes in the external strain.
- By comparing with the commercial strain sensor, the self-developed embedded strain sensor has the advantage of deformation coordination and consistency with the road structure because of the encapsulating materials and packaging techniques studied in this paper, which can help to improve the monitoring accuracy.
- The embedding of the sensor in asphalt concrete slab and its application in practical pavement both showed that the sensor could effectively survive after being subjected to high temperature and heavy pressure during asphalt pavement compaction, which verified the feasibility of a self-developed sensor in asphalt pavement strain monitoring.

Author Contributions: C.M., X.X. and M.L.: Data curation, Writing—original draft; Writing—review & editing. N.Z. and J.W.: Data curation; C.W.: Investigation. Y.Z. and Z.Y.: Investigation. We confirm that the order of authors listed in the manuscript has been approved by all named authors. All authors have read and agreed to the published version of the manuscript.

Funding: The authors acknowledge the financial support of the Qilu Young Scholars Program of Shandong University, Natural Science Foundation of Shandong Province (CN) (No. ZR2020ME244), Jinan Research Leader Studio (202228101) and National Key R&D Program "Transportation Infrastructure" "Reveal the list and take command" project (2022YFB2603300).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. China Highway Network Website. Available online: http://www.chinahighway.com/ (accessed on 12 November 2022).
2. Di Graziano, A.; Marchetta, V.; Cafiso, S. Structural health monitoring of asphalt pavements using smart sensor networks: A comprehensive review. *J. Traffic Transp. Eng.* **2020**, *7*, 639–651. [CrossRef]
3. Corticelli, R.; Pazzini, M.; Mazzoli, C.; Lantieri, C.; Ferrante, A.; Vignali, V. Urban Regeneration and Soft Mobility: The Case Study of the Rimini Canal Port in Italy. *Sustainability* **2022**, *14*, 14529. [CrossRef]
4. Tiboni, M.; Rossetti, S.; Vetturi, D.; Torrisi, V.; Botticini, F.; Schaefer, M.D. Urban policies and planning approaches for a safer and climate friendlier mobility in cities: Strategies, initiatives and some analysis. *Sustainability* **2021**, *13*, 1778. [CrossRef]
5. Shtayat, A.; Moridpour, S.; Best, B.; Shroff, A.; Raol, D. A review of monitoring systems of pavement condition in paved and unpaved roads. *J. Traffic Transp. Eng.* **2020**, *7*, 629–638. [CrossRef]
6. Du, Z.; Yuan, J.; Xiao, F.; Hettiarachchi, C. Application of image technology on pavement distress detection: A review. *Measurement* **2021**, *184*, 109900. [CrossRef]
7. Mataei, B.; Nejad, F.M.; Zakeri, H. An improved multiresolution technique for pavement texture image evaluating. *Multimed. Tools Appl.* **2023**, *82*, 3007–3031. [CrossRef]
8. Salour, F.; Erlingsson, S. Investigation of a pavement structural behaviour during spring thaw using falling weight deflectometer. *Road Mater. Pavement Des.* **2013**, *14*, 141–158. [CrossRef]
9. Jung, F.W.; Stolle, D.F. Nondestructive Testing with Falling Weight Deflectometer on Whole and Broken Asphalt Concrete Pavements. *Transp. Res. Rec.* **1992**, *1377*, 183–192.
10. Salour, F.; Erlingsson, S. *Impact of Groundwater Level on the Mechanical Response of a Flexible Pavement Structure: A Case Study at the Torpsbruk Test Section along County Road 126 Using Falling Weight Deflectometer*; VTI: Sydney, Australia, 2014.
11. Li, W. A theoretical analysis of the evolution of traffic and transportation structure development. *Water Transp. Manag.* **2000**, *7*, 2–7.
12. Fang, L.; Guo, B.; Zheng, Y.; Zhang, X. Research on intelligent monitoring technology for asphalt pavement construction. *China Meas. Test.* **2022**, *47*, 122–125.
13. Yang, Y.; Wang, L.; Wei, J.; Ma, S. Data collection and analysis of dynamic response of typical pavement structures under heavy load. *Road Traffic Technol.* **2010**, *27*, 11–16.
14. Zeng, J.; Xiao, C.; Li, B.; Xu, T. Study on the effect of temperature on the dynamic response of asphalt pavement under FWD loading. *Highw. Eng.* **2015**, *40*, 107–111, 161.
15. Mustafa, S.; Sekiya, H.; Maeda, I.; Takaba, S.; Hamajima, A. Identification of external load information using distributed optical fiber sensors embedded in an existing road pavement. *Opt. Fiber Technol.* **2021**, *67*, 102705. [CrossRef]
16. Mustafa, S.; Sekiya, H.; Morichika, S.; Maeda, I.; Takaba, S.; Hamajima, A. Monitoring internal strains in asphalt pavements under static loads using embedded distributed optical fibers. *Opt. Fiber Technol.* **2022**, *68*, 102829. [CrossRef]
17. Xiang, P.; Wang, H. Optical fibre-based sensors for distributed strain monitoring of asphalt pavements. *Int. J. Pavement Eng.* **2016**, *19*, 842–850. [CrossRef]
18. Li, Q.; Cary, C.; Combs, S.; Garg, N. Evaluation of asphalt concrete layer response using asphalt strain gauges and fiber optic strain gauges. In Proceedings of the International Conference on Transportation and Development, Houston, TX, USA, 26–29 June 2016; pp. 42–53.
19. Han, M.; Muhammad, Y.; Wei, Y.; Zhu, Z.; Huang, J.; Li, J. A review on the development and application of graphene based materials for the fabrication of modified asphalt and cement. *Constr. Build. Mater.* **2021**, *285*, 122885. [CrossRef]
20. Liu, Y. *Development and Research of Rubber Encapsulated FBG Asphalt Pavement Vertical Strain Sensor*; Harbin Institute of Technology: Harbin, China, 2008.
21. Wu, B.; Lin, Z.; Zeng, Y.; Lin, Z.; Lu, H. Experimental study on the temperature sensitivity coefficient of fiber-encapsulated long-scale strain sensors. *Adv. Laser Optoelectron.* **2022**, *59*, 142–149.
22. Liang, L.; Liu, D.; Li, P. Research on carbon fiber composite encapsulated fiber optic sensors. *J. Wuhan Univ. Technol.* **2008**, *30*, 55–57.
23. Rana, S.; Subramani, P.; Fangueiro, R.; Correia, A.G. A review on smart self-sensing composite materials for civil engineering applications. *AIMS Mater. Sci.* **2016**, *3*, 357–379. [CrossRef]

24. Li, P.; Jiang, W.; Lu, R.; Yuan, D.; Shan, J.; Xiao, J. Design and durability of PZT/PVDF composites based on pavement perception. *Constr. Build. Mater.* **2022**, *323*, 126621. [CrossRef]
25. Hou, S.; Lei, J.; Ou, J. Vehicle load monitoring for asphalt concrete pavement based on smart aggregates. *J. Vib. Shock* **2014**, *33*, 42–47.
26. Zhao, Q.; Wang, L.; Zhao, K.; Yang, H. Development of a Novel Piezoelectric Sensing System for Pavement Dynamic Load Identification. *Sensors* **2019**, *19*, 4668. [CrossRef] [PubMed]
27. Wang, Q. *Research on the Electrical Conductivity and Mechanosensitivity of Carbon Fiber Epoxy Resin Composites*; Chongqing University: Chongqing, China, 2006.
28. 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. *Constr. Build. Mater.* **2020**, *257*, 119404. [CrossRef]
29. Xin, X.; Yu, R.; Su, L.; Qiu, Z.; Yang, C.; Liang, M.; Ji, P.; Zhong, G.; Yao, Z. Dynamic Mechanical and Chemorheology Analysis for the Blended Epoxy System with Polyurethane Modified Resin. *J. Renew. Mater.* **2022**, *10*, 1081. [CrossRef]
30. Xin, X.; Qiu, Z.; Luan, X.; Ding, X.; Liang, M.; Yao, Z.; Li, Y. Novel conductive polymer composites for asphalt pavement structure in situ strain monitoring: Influence of CB/CNT and GNP/CNT nano/micro hybrid fillers on strain sensing behavior. *IEEE Sens. J.* **2022**, *10*, 3945–3956. [CrossRef]
31. Xin, X.; Luan, X.; Su, L.; Ma, C.; Liang, M.; Ding, X.; Yao, Z. The innovative self-sensing strain sensor for asphalt pavement structure: Substitutability and synergy effects of graphene platelets with carbon nanotubes in epoxy composites. *Front. Mater.* **2022**, *9*, 824364. [CrossRef]
32. Guo, L.; Chen, X.; Yu, J.; Tang, Y.; Liu, R.; Rogers, R.; Leidy, J.; Claros, G. Pavement deflection vehicle weighing method with embedded piezoelectric sensor. *SPIE Proc.* **2005**, *5758*, 471–478.
33. Tan, Z.; Li, H.; Xu, X.; Wu, C.; Liu, F. Study on the arrangement scheme of asphalt pavement mechanical response monitoring system. *J. Wuhan Univ. Technol.* **2017**, *41*, 528–532.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.