Materials Research Proceedings **23** (2022) 255-268 https://doi.org/10.21741/9781644901953-29

Structural Health Monitoring of Infrastructures using Sensors as Smart Materials– Review and Perspective

A. Dinesh[1,a,*], A. Karthick[2,b], S. Ramkumar[3,c]

[1] Department of Civil Engineering, Sri Ramakrishna Engineering College, Coimbatore - 641022, India

[2]Department of Civil Engineering, K. Ramakrishnan college of technology, Trichy, India

[3]Department of Civil Engineering, M. Kumarasamy college of engineering, Karur, India

[a]dinesh.a@srec.ac.in; dinesh.a.civil@gmail.com, [b]karthicka.civil@krct.ac.in, [c]ramkumars.civil@mkce.ac.in

Keywords: Structural Health Monitoring, Sensors, Self-Sensing, Cement Composite, Strain, Corrosion

Abstract. Smart materials with sensors can monitor the structure's performance under external loading circumstances. They may also monitor internal deformations or damages caused by environmental factors such as temperature, humidity, etc. As a result, the sensors are linked to structural health monitoring to create automated systems for structural monitoring, inspection, and damage identification. The formulation of this review article was prompted by a growing interest in structural health monitoring and the need to ensure structure safety to detect problems early and avert collapse. The structure, measurement methods, and potential of sensors such as fiber optic, piezoelectric, corrosion, ceramic, and self-sensing cement composite utilized in the health monitoring of concrete structures are discussed in this review paper. This review also includes a brief and comparative analysis of various sensors, as well as the optimal number and location of sensors. The study exposed that choosing a suitable sensor is critical for accurate sensing and long-term structure monitoring. The sensor can detect physical (stress, strain) and chemical (corrosion) variables that affect the structure's endurance. Despite significant advances in damage monitoring approaches utilizing sensors, the study suggests that efficient sensor deployment remains problematic. The review revealed that the type of parameter to be monitored (stress, strain, humidity, etc.) and the structural and climatic conditions in which the sensor will be used determine the sensor's selection. As a result, a self-sensing cement composite based on carbon nanofiber (CNF) has been developed, which has good durability and compatibility with concrete structures. However, increasing the amount of CNF lowers the composite's compressive and flexural strength due to particle agglomeration. As a result, the review covers several sensors used in structural health monitoring with their measurements, applications, benefits, and limitations.

Introduction

Concrete is the most extensively used building material because of its manufacturing, availability, and strength simplicity. Concrete is widely used to construct buildings, pavements, dams, and other structures. Despite its many advantages, concrete lacks significant strength and durability, which leads to damages [1,2]. To withstand external stresses, several advancements have been made in structural design [3,4] and bracings [5]. Despite significant advancements in structures' ability to endure external loads, assuring the structure's safety remains difficult. As a result, numerous advancements in concrete have been made by altering the materials [6–9] in the same way bricks [10] and soil [8,11] have been changed. Conductive materials like carbon nanofiber [12], carbon

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 license. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under license by Materials Research Forum LLC.

Materials Research Proceedings **23** (2022) 255-268 https://doi.org/10.21741/9781644901953-29

nanotube [13], carbon fiber [14,15], and carbon black [16,17] are used to enhance the strength and durability of concrete. As a result, various concrete types, such as high-strength concrete [18,19], lightweight concrete, and ultra-high-performance concrete, have been developed. Cracking, deformation, and deterioration are inevitable, despite several material advances to enhance concrete's strength capabilities. As a result, concrete performance is monitored during the structure's maintenance and service life.

Structural health monitoring is a technique for monitoring the state of a structure's safety during its service life [20,21]. They are used to monitor the condition of bridges, buildings, and pipelines that are failing due to earthquakes, aging, and other risks. Accelerometers [22], acoustic emission sensors [23], ceramic sensors [24], corrosion sensors [25], electrochemical sensors [26], fiber optic sensors [27], shape memory alloys [28], and strain gauges [29] are among the sensors used to analyze and monitor the structure. These sensors are used for preventative maintenance, which helps to improve living conditions while preventing financial losses. The two kinds of sensors accessible are wired and wireless sensors. Wired sensors, such as fiber optic, piezoelectric, and ultrasonic sensors, are expensive and have a high chance of intrusion failure. The wireless sensor, which includes an acoustic sensor, can detect flaws across vast distances with the assistance of humans. The requirements for structural health monitoring, which include dependability, robustness, and cost-effectiveness, limit the use of sensors.

The study's main objective is to explore the need for health monitoring of structural components and the method for monitoring structural health using sensors. The following part compares the use of a wireless strain sensor, a ceramic sensor, and a corrosion sensor in structural health monitoring.

Sensors for Structural Health Monitoring

Structural health monitoring is becoming more significant because of the time-consuming and costly manual evaluations performed at predetermined intervals. Sensor and sensing technology has advanced to the point that they can now be integrated into concrete structures, overcoming these constraints. Many studies have been conducted in the field of structural health monitoring utilizing a variety of sensors, including fiber optic sensors [30], accelerometers [31], acoustic emission sensors [23], electrochemical sensors [32], wireless sensors [33], and self-sensing cement composite [34]. The choice of sensor is determined by the structural and environmental conditions in which the sensor will be used and the type of parameter to be monitored (stress, strain, humidity, etc.). [35]. Fig. 1 depicts the numerous sensors, structural specifications, and potential in measuring external parameters.

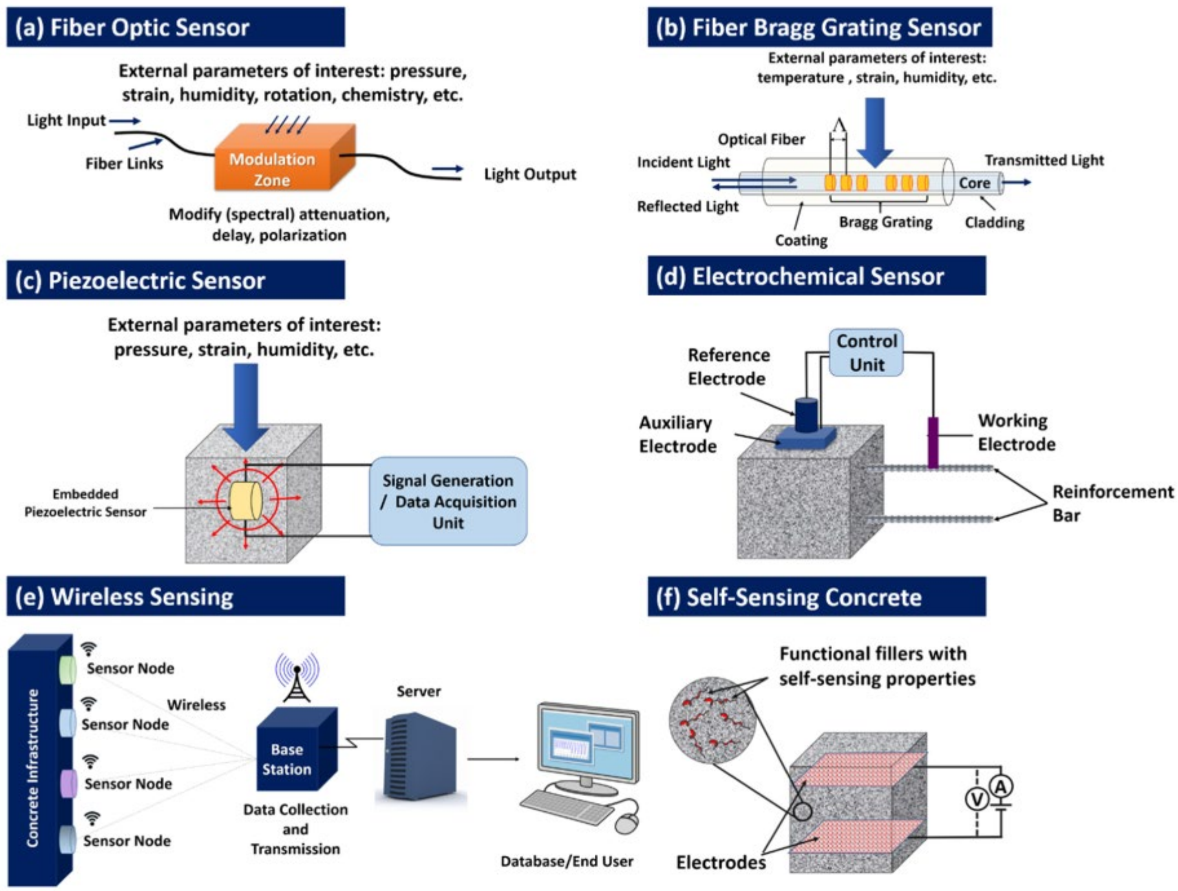


Fig. 1. Demonstration of sensors used in the health monitoring of concrete structures [36]

Self-sensing cement composite

Because of the evolution of interdisciplinary research and the application of nanomaterials in concrete, many new studies have been developed in cement composite. Researchers are quite interested in the field of intelligent concrete with self-sensing capabilities [13]. Nanomaterials such as steel fiber [37], graphite powder [38], carbon black [16], carbon nanofiber [12], carbon nanotube [13], and others are used to create self-sensing capacity in cement composites. The composite will develop piezoresistive properties by incorporating these nanoparticles, transforming them from a traditional cement composite into a self-sensing cement composite. When nanoparticles are included in a composite, they form a conductive network that modifies the composite's resistivity/conductivity as stress/strain varies [13]. Before being placed in the compression testing equipment, the composite is connected to a power supply (LCR meter) and a multimeter to analyze compressive strength and conductivity simultaneously, as shown in Fig. 2 [12]. When the load is applied, the area changes along with the voltage, which may be measured using a multimeter. The fractional change in resistance and sensitivity of the composite is evaluated, as illustrated in Fig. 2. The property that changes resistivity with change in stress is piezoresistivity of the composite, and many researchers have investigated piezoresistivity of the composite with various implanted conductive materials [12,13,39,40]. Scanning electron microscopy (SEM), and X-ray diffraction spectroscopy (XRD) examinations are used to understand better the internal changes in the composite caused by the embedment of conductive components.

Materials Research Proceedings **23** (2022) 255-268 https://doi.org/10.21741/9781644901953-29

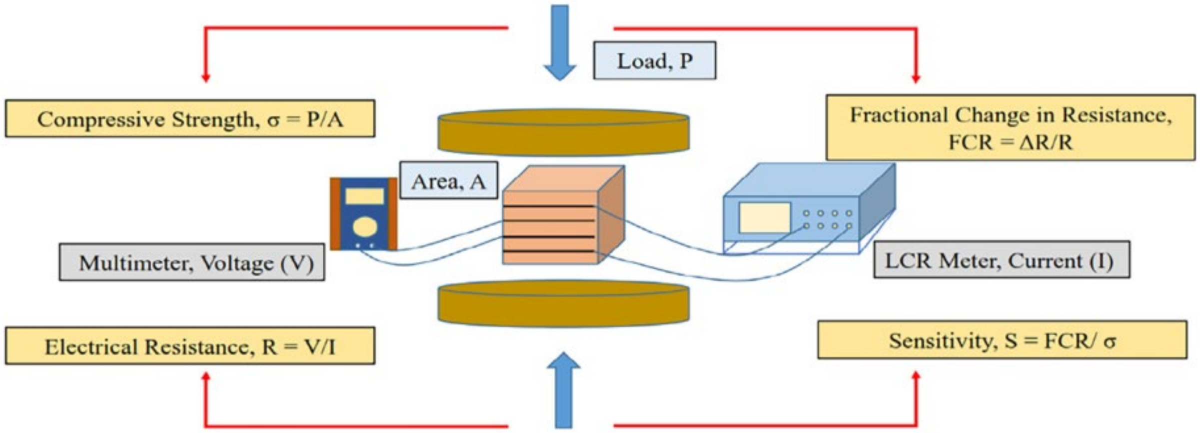


Fig. 2. Schematic diagram depicts methods for analyzing CBS qualities [12]

According to previous studies, the addition of conductive material to a composite greatly impacts the mechanical strength of cement composite. The inclusion of CNF reduces the composite's compressive and flexural strength as the proportion of CNF increases due to particle agglomeration, as seen in fig. 3 [41,42]. When CNF is increased to 1%, the tensile strength of the cement composite is improved to 50 MPa (approx.) due to the high tensile strength (=3800 MPa) of CNF [43].

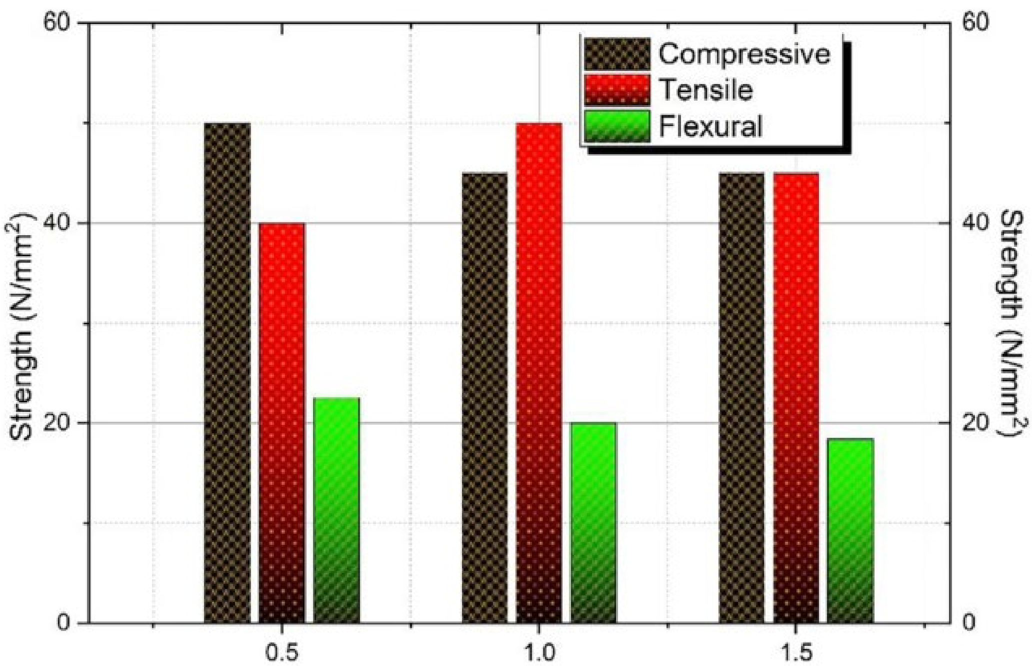


Fig. 3. Compressive, split tensile, and flexural properties of cement composites containing 0.5 %, 1%, and 2% CNF [12]

The electrical conductivity of a composite comprising carbon nanotubes with different electrical characteristics is examined in an analytical study [44]. The effect of aspect ratio (L/D ratio) and its influence on percolation threshold and electrical conductivity is investigated. They

Materials Research Proceedings **23** (2022) 255-268 https://doi.org/10.21741/9781644901953-29

identified that the larger the aspect ratio smaller would be the percolation threshold in the composite. Suppose the quantity of conductive materials incorporated in the composite is less than the threshold volume fraction. In such instances, they have the slightest effect on the electrical conductivity of the composite, as indicated by the spherical model's lower bound. CNT is used to develop self-sensing cement composites in similar analytical models [45,46]. Multiwalled carbon nanotubes (MWCNT) of electrical conductivity > 1250 s/cm are used to prepare epoxy matrix composite for strain monitoring in pavements [47]. They identified that epoxy composite developed with CNT is a suitable cement-based sensor with a gauge factor of 26.04, which is far higher than the gauge factor of conventional metal strain sensors with a gauge factor of 2. Those CNT embedded composites can also measure strain ranging within 1000 με. Similarly, many investigations are done on self-sensing cement composite using CNT [48–51]. Few researches are also focused on the hybrid combination of nanomaterials, including CF/CNT and CF/CB [52,53]. These findings imply that hybrid CNT combinations, rather than individual CNTs, can efficiently improve the flexural strength and electrical conductivity of cement mortars [52]

Ultrasonic sensor

Ultrasonic sensors are used to examine or identify propagating cracks in concrete [6]. The stressed state is used to assess deformation to spot cracks quickly. Fig. 4 (a) shows the DIC values at a tensile stress of 3.2 N/mm^2. Under this load, the correlation factor between the signals sent and received by the embedded ultrasonic sensor is less than 0.8. The dashed lines in Fig 4 (a) show the placement of embedded sensors. The growing surface fracture impacts the signal even if it is not in the wave's direct path. As a result, Fig. 4 (a) depicts the absence of crack formation. The cross-correlation factor fell further in fig. 4 (b) as the tensile stress increased to 3.4 N/mm^2. In the wave path, a crack with a width of 160 μm and a length of 20 mm can be seen. The ultrasonic wave is depicted in Fig. 4 (c) with a tensile strength of 3.8 N/mm^2. The crack development and surface deformation show the spread of the fracture into the direct path of the wave traveling between the implanted sensors. As a result, the study finds that ultrasonic sensors can detect crack propagation in a structure before visible cracks appear on the surface of the concrete.

An ultrasonic sensor based on an autoregressive model (AR) is used to detect structural changes in concrete [7]. This study uses a model to employ an ultrasonic sensor to localize operational changes in massive concrete buildings. When a static force is applied to the top of the sensor, the residual error increases to its maximum value (t=75 minutes). The nonlinearities in the operational change in the structure determine the amplitude of the parameters. The damage-sensitive feature in this system is AR residual error. The level of change in the structure is precisely proportional to the changes in AR parameters. However, the association level appears to vanish if the damage is present with operational and environmental fluctuations. In this study, ultrasonic sensors perform both static and dynamic load tests on reinforced concrete structures. The localized operational changes in the reinforced concrete structures are quantified using an autoregressive model.

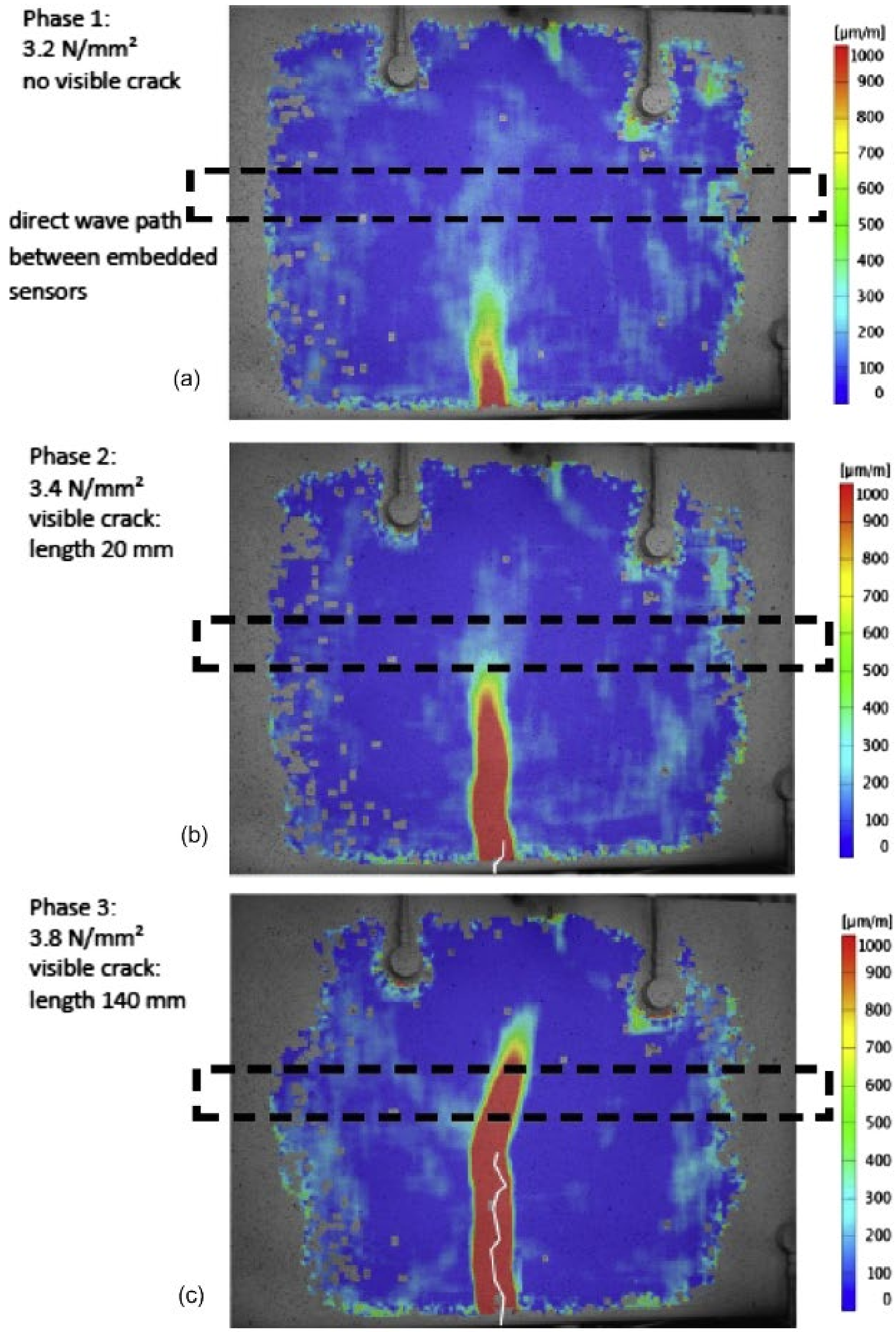


Fig. 4. Tensile stress-causing surface deformation (a) 3.2 N/mm^2 (b) 3.4 N/mm^2 and (c) 3.8 N/mm^2 respectively.

The influence of composite age on ultrasonic wave transmission and reflection coefficients in the concrete-steel-concrete contact is investigated [8]. The structure in question is a multilayer structure with two elastic and isotropic layers with different physical properties. In sand concrete (= 40.65 MPa), conventional concrete (= 45.89 MPa), and high-performance concrete (= 81.02 MPa), the wave propagation velocity is determined. Aging generates a substantial variability in

Materials Research Proceedings **23** (2022) 255-268 https://doi.org/10.21741/9781644901953-29

the longitudinal coefficient (TL) in high-performance concrete, as shown in Fig. 5 (a), and sand concrete, as shown in Fig. 5 (c). The evolution of the transverse transmission (TT) coefficient is depicted in Figures 5 (b) and (c). The TT coefficient drops initially, then climbs dramatically before stabilizing at a specific angle. When comparing the effect of concrete age on sand concrete from the fifteenth day to high-performance concrete and regular concrete, the sand concrete exhibits a more substantial influence. Fig. 5 (d) depicts the behavior of ultrasonic waves that characterize the interface's longitudinal reflection coefficient RL. The curve has a falling and then climbing shape. There is a noticeable drop in the coefficient RL during the measuring interval of 0 to 15 days, which is minimal compared to conventional and high-performance concrete. According to both computational and experimental research, the age of concrete and the inner concrete structure directly impact the acoustic properties and angle of incidence.

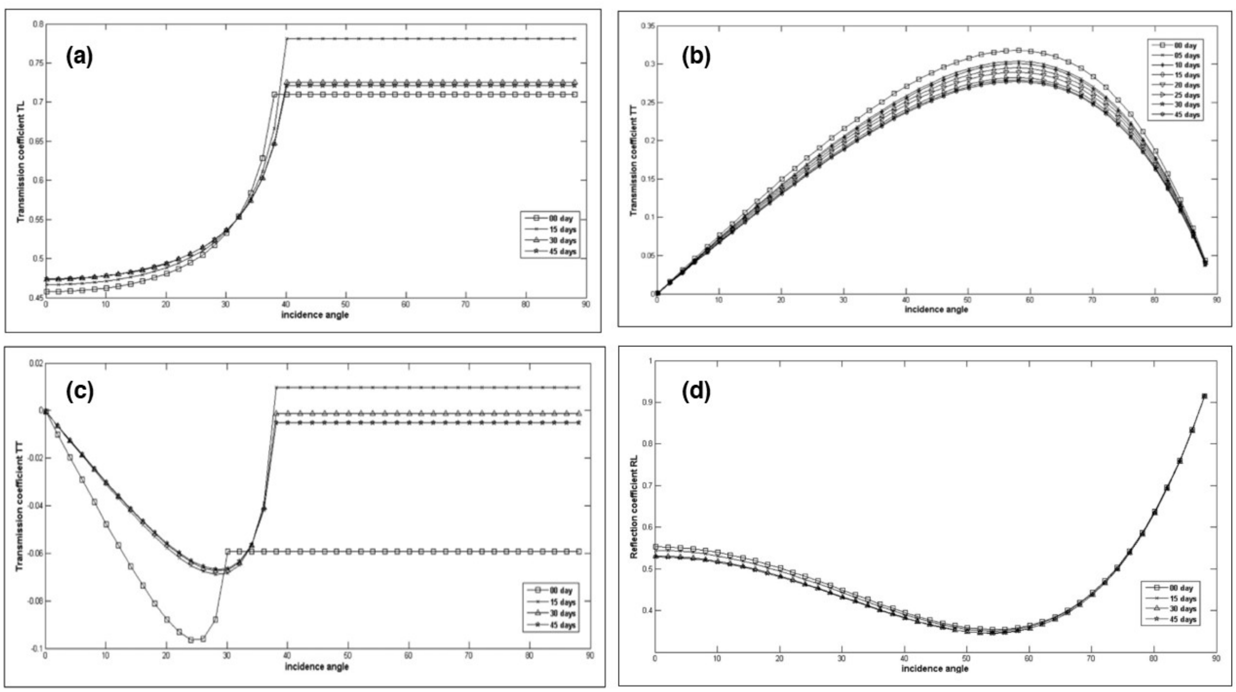
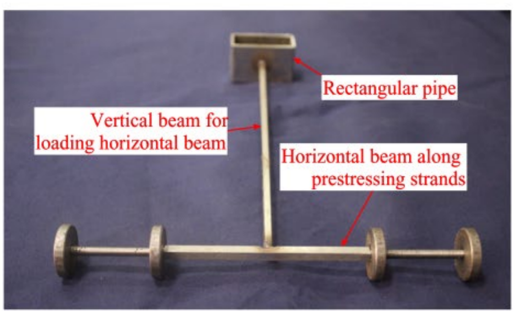


Fig. 5. (a) Variation of the TL coefficient with concrete age (high-performance concrete–steel contact) (b) Variation of the TT coefficient with concrete age (steel–high-performance concrete interface) (c) Variation of the TT coefficient with concrete age (sand concrete–steel contact) and (d) Variation of the RL coefficient with concrete age (steel–sand concrete interface).

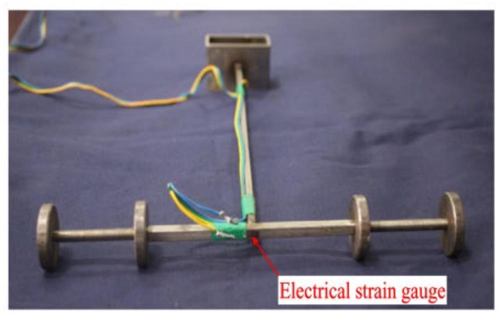
Strain gauge

Due to the time-consuming and challenging sample surface preparation and strain gauge adhesion, traditional strain gauges such as electric resistance strain gauges, demec mechanical strain gauges, and compressometers have limited applications in SHM. As a result, the automatic digital image correlation (ADIC) optical strain gauge was developed as practical and cost-effective monitoring of concrete parameters [9]. The ADIC significantly broadens the convergence range and can accurately measure the concrete strain caused by an autonomous searching approach. After obtaining the strain, the concrete stress-strain curve is drawn using the load to determine the elastic modulus of the concrete. According to the research, the produced optic strain gauge has good accuracy, convenience, and reliability when compared to the electronic strain gauge, compressometer, and demec mechanical strain gauge. For C20, C40, and C60 concrete cubes and cylinders, the optic strain gauge has a standard deviation of 0.37, 0.44, and 0.58, which is lower than the electronic strain gauge (0.42, 0.34, and 0.94), compressometer (0.64, 0.43, and 0.71), and Demec mechanical strain gauge (1.96, 1.41, and 1.33).

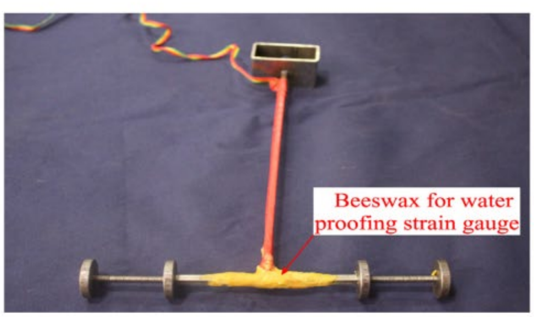
Strain gauges are also embedded in concrete members to measure the prestressing force in concrete beams and slabs [10]. Vibrating beam strain gauges (VBSG) are similar to vibrating wire strain gauges in that they work on the same principles. The VBSG test frame setup is shown in Fig. 6. The steel bar is extended at both ends and tightened with a circular plate, as shown in Fig. 6 (a), to guarantee that the strain in the VBSG steel bar matches the strain in the concrete at the steel bar level. The strain gauge is positioned in the center of the steel bar, as shown in Fig. 6 (b). Beeswax is applied to the strain gauge to make it water-resistant, as shown in Fig. 6 (c). A PVC pipe with water sealant is installed above the strain gauge, as shown in Fig. 6 (d), to prevent water from entering into the pipes from the cement paste. The current strain in the VBSG can be calculated by comparing the frequency data of the stretched part with static strain measured with electrical strain gauges. The average inaccuracy in calculating the prestressing force is 1.9% from frequency measurements and 1.4% from static strain data. Because both strain and frequency yield precise results, the prestressing force in the structure may be calculated by anyone. The error associated with using a vibrating wire strain gauge is 1.4% to 1.9%, which is slightly higher than the error associated with using a VBSG (around 0.5%). VBSG, on the other hand, can analyze the state of prestressed concrete buildings with pinpoint accuracy.



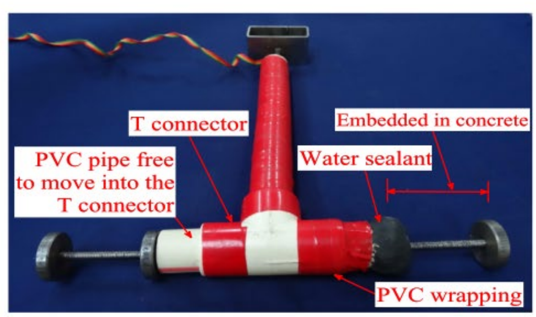
(a) Frame structure of vibrating beam strain gauge.



(b) Strain gauge location in VBSG.



(c) Water proofing the strain gauge.



(d) Clear cover for movement of VBSG using PVC pipes.

Fig. 6. Vibrating beam strain gauge [54]

At the start of corrosion, the concrete behavior is studied using strain gauges, SEM, and EDS [11]. They were particularly interested in the penetration of rust agents into pores and the measurement of stresses and strains in the concrete around the rebars when corrosion first began. An analytical model is also proposed to calculate the crack width at the time of cracking. The method is applied to two concretes with different porosity networks and corrosion current densities to analyze the reinforcement corrosion process and discover cracks in the surrounding concrete. SEM and EDS are used to investigate the corrosion advancement and rust layer growth on prismatic samples with a base of 50 X 50mm^2 that includes rebar, as shown in Fig. 7. The researchers discovered that placing the strain gauge close to the rebar provided more information on the circumferential strain in the concrete.

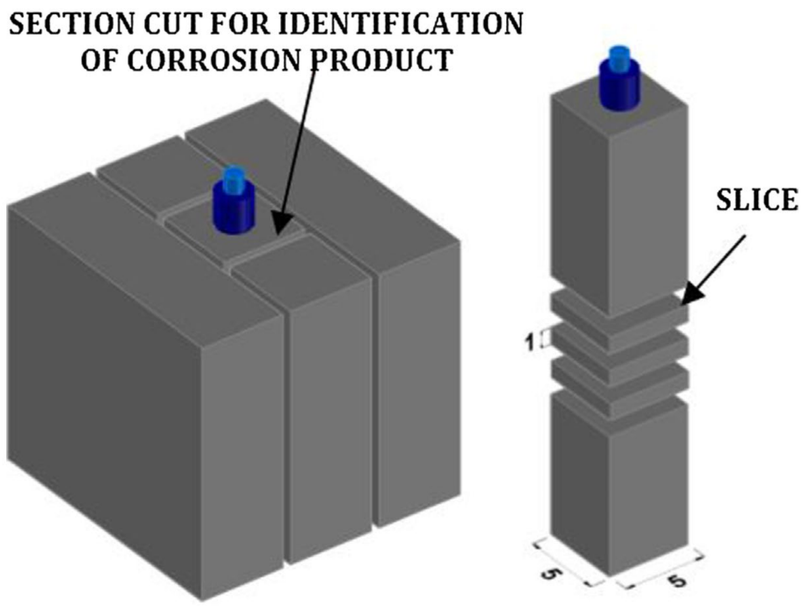


Fig. 7. The cutting technique for the specimens for SEM observations [55]

Conclusions

Thus, the article reviews the different sensors, working, and monitoring vital infrastructure status. Monitoring criteria such as sensor sensing capabilities in detecting mechanical (displacement, strain, vibration, fractures) and durability (corrosion, chloride ion concentration) features of the concrete structure are also carefully examined. Through this review, the following conclusions are revealed

1. The type of parameter to be monitored (stress, strain, humidity, etc.) and the structural and climatic circumstances in which the sensor will be utilized decide the selection of the sensor.
2. In self-sensing cement composite, because of particle agglomeration, increasing the proportion of CNF reduces the compressive and flexural strength of the composite.
3. Researches identified that the higher the aspect ratio, the lower the percolation threshold of the composite. They found that an epoxy composite containing CNT is an excellent cement-based sensor, with a gauge factor of 26.04, which is much greater than the gauge factor of typical metal strain sensors, which is 2.
4. In conventional sensors, the research finds that ultrasonic sensors may detect fracture propagation in a structure before visible cracks appear on the surface of the concrete. The

localized operational changes in the reinforced concrete structures are quantified using an ultrasonic sensor with an autoregressive model.

5. According to both computational and experimental research, the age of concrete and the inner concrete structure directly influence the acoustic properties and angle of incidence.
6. The standard deviation of the optic strain gauge is 0.37, 0.44, and 0.58, which is lower than the electronic strain gauge (0.42, 0.34, and 0.94), compressometer (0.64, 0.43, and 0.71), and Demec mechanical strain gauge (0.42, 0.34, and 0.94). (1.96, 1.41, and 1.33). VBSG, on the other hand, can analyze the state of prestressed concrete buildings with good accuracy.
7. The researchers discovered that placing the strain gauge close to the rebar provided more information on the circumferential strain in the concrete.

Thus, the study demonstrates that self-sensing cement composites, ultrasonic sensors, and strain gauges have promising concrete structure health monitoring applications.

Acknowledgments

The authors would like to thank the Management, Sri Ramakrishna Engineering College, Coimbatore, for their support. The authors would like to express their gratitude to the management of PSG College of Technology in Coimbatore for their assistance in carrying out this study.

References

[1] R. Capozucca, Damage to reinforced concrete due to reinforcement corrosion, Constr. Build. Mater. 9 (1995) 295–303. https://doi.org/10.1016/0950-0618(95)00033-C.

[2] K. Kovler, V. Chernov, Types of damage in concrete structures, Woodhead Publishing Limited, 2009. https://doi.org/10.1533/9781845697037.1.32.

[3] A. Professor, Analytical study on the behaviour of cold formed steel double channel beam sections, n.d. www.ripublication.com/ijaer.htm.

[4] A. Dinesh, R. Prasanth Kumar, S.R. Abijith, Experimental investigation on bubble deck concrete using plastic waste, 2020. https://doi.org/10.1007/978-981-15-0990-2_14.

[5] P. Eswaramoorthi, P. Magudeaswaran, A. Dinesh, PUSHOVER ANALYSIS OF STEEL FRAME, n.d.

[6] A. Professor, Study on Strength properties of High performance concrete, n.d. www.ripublication.com/ijaer.htm.

[7] K. Sathish Raja, Dinesh. A, Study on Self Compacting Concrete – A Review, Int. J. Eng. Res. V5 (2016). https://doi.org/10.17577/ijertv5is020349.

[8] A. Professor, Stabilization of soil by using solid waste-A Review, © 2017 IJEDR |. 5 (2017). www.ijedr.org.

[9] A. Dinesh, S. Harini, J.P. Jasmine, J. Jincy, J. Shagufta, International journal of engineering sciences & research technology experimental study of blast furnace slag concrete, Int. J. Eng. Sci. Res. Technol. 6 (2017) 42–50. https://doi.org/10.5281/zenodo.345692.

[10] D. Sellakutty, A. Professor, UTILISATION OF WASTE PLASTIC IN MANUFACTURING OF BRICKS AND PAVER BLOCKS, 2016. https://www.researchgate.net/publication/303273892.

[11] A. Dinesh, S. Indhumathi, Moorthi Pichumani, Performance assessemnt of copper slag and sawdust ash in stabilization of black cotton soil, 2021.https://doi.org/10.1007/978-981-33-

4590-4_21.

[12] A. Dinesh, B. Abirami, G. Moulica, Materials Today : Proceedings Carbon nanofiber embedded cement composites : Properties and promises as sensor – A review, Mater. Today Proc. (2020). https://doi.org/10.1016/j.matpr.2020.10.526.

[13] A. Dinesh, S.T. Sudharsan, S. Haribala, Self-sensing cement-based sensor with carbon nanotube: Fabrication and properties – A review, Mater. Today Proc. (2021). https://doi.org/10.1016/j.matpr.2021.02.722.

[14] S. Wen, D.D.L. Chung, Strain-Sensing Characteristics of Carbon Fiber-Reinforced Cement, (2006) 2006.

[15] W. Wang, S. Wu, H. Dai, Fatigue behavior and life prediction of carbon fiber reinforced concrete under cyclic flexural loading, Mater. Sci. Eng. A. 434 (2006) 347–351. https://doi.org/10.1016/j.msea.2006.07.080.

[16] A.O. Monteiro, P.B. Cachim, P.M.F.J. Costa, Electrical Properties of Cement-based Composites Containing Carbon Black Particles, Mater. Today Proc. 2 (2015) 193–199. https://doi.org/10.1016/j.matpr.2015.04.021.

[17] Y. Ding, G. Liu, A. Hussain, F. Pacheco-Torgal, Y. Zhang, Effect of steel fiber and carbon black on the self-sensing ability of concrete cracks under bending, Constr. Build. Mater. 207 (2019) 630–639. https://doi.org/10.1016/j.conbuildmat.2019.02.160.

[18] M. Aboubakar, Y. Sato, K. Niitani, Experimental investigation of monotonic behavior and stress-strain models of AE and non-AE high strength concrete with BFS fine aggregates under freezing and thawing, Constr. Build. Mater. 249 (2020) 118679. https://doi.org/10.1016/j.conbuildmat.2020.118679.

[19] J. Zhu, J. Chen, T. Chan, Analytical model for circular high strength concrete filled steel tubes under compression, Eng. Struct. 244 (2021) 112720. https://doi.org/10.1016/j.engstruct.2021.112720.

[20] P.C. Chang, A. Flatau, S.C. Liu, Review paper: Health monitoring of civil infrastructure, Struct. Heal. Monit. 2 (2003) 257–267. https://doi.org/10.1177/1475921703036169.

[21] J. Paek, K. Chintalapudi, R. Govindan, J. Caffrey, S. Masri, A wireless sensor network for structural health monitoring: Performance and experience, Second IEEE Work. Embed. Networked Sensors, EmNetS-II. 2005 (2005) 1–10. https://doi.org/10.1109/EMNETS.2005.1469093.

[22] K. Chilamkuri, V. Kone, Monitoring of varadhi road bridge using accelerometer sensor, Mater. Today Proc. 33 (2020) 367–371. https://doi.org/10.1016/j.matpr.2020.04.159.

[23] N. Beheshtizadeh, A. Mostafapour, S. Davoodi, Three point bending test of glass/epoxy composite health monitoring by acoustic emission, Alexandria Eng. J. 58 (2019) 567–578. https://doi.org/10.1016/j.aej.2019.03.006.

[24] V. Agarwal, A. Shelke, B.S. Ahluwalia, F. Melandsø, T. Kundu, A. Habib, Damage localization in piezo-ceramic using ultrasonic waves excited by dual point contact excitation and detection scheme, Ultrasonics. 108 (2020) 106113. https://doi.org/10.1016/j.ultras.2020.106113.

[25] L. Xie, X. Zhu, Z. Liu, X. Liu, T. Wang, J. Xing, A rebar corrosion sensor embedded in concrete based on surface acoustic wave, Meas. J. Int. Meas. Confed. 165 (2020) 108118. https://doi.org/10.1016/j.measurement.2020.108118.

[26] G.T. Parthiban, T. Parthiban, R. Ravi, V. Saraswathy, N. Palaniswamy, V. Sivan, Cathodic protection of steel in concrete using magnesium alloy anode, Corros. Sci. 50 (2008) 3329–3335. https://doi.org/10.1016/j.corsci.2008.08.040.

[27] A. Barrias, J.R. Casas, S. Villalba, Fatigue performance of distributed optical fiber sensors in reinforced concrete elements, Constr. Build. Mater. 218 (2019) 214–223. https://doi.org/10.1016/j.conbuildmat.2019.05.072.

[28] S. Abouali, M. Shahverdi, M. Ghassemieh, M. Motavalli, Nonlinear simulation of reinforced concrete beams retrofitted by near-surface mounted iron-based shape memory alloys, Eng. Struct. 187 (2019) 133–148. https://doi.org/10.1016/j.engstruct.2019.02.060.

[29] S.Z. Chen, G. Wu, D.C. Feng, Damage detection of highway bridges based on long-gauge strain response under stochastic traffic flow, Mech. Syst. Signal Process. 127 (2019) 551–572. https://doi.org/10.1016/j.ymssp.2019.03.022.

[30] K.T. Lau, C.C. Chan, L.M. Zhou, W. Jin, Strain monitoring in composite-strengthened concrete structures using optical fibre sensors, Compos. Part B Eng. 32 (2001) 33–45. https://doi.org/10.1016/S1359-8368(00)00044-5.

[31] S. Mahjoubi, R. Barhemat, Y. Bao, Optimal placement of triaxial accelerometers using hypotrochoid spiral optimization algorithm for automated monitoring of high-rise buildings, Autom. Constr. 118 (2020) 103273. https://doi.org/10.1016/j.autcon.2020.103273.

[32] A.S.E. Belaidi, B. Benabed, H. Soualhi, Physical and mechanical properties of concrete repair materials in dry and hot-dry environment, J. Adhes. Sci. Technol. 29 (2015) 543–554. https://doi.org/10.1080/01694243.2014.998001.

[33] Z. Herrasti, I. Gabilondo, J. Berganzo, I. Val, F. Martínez, Wireless Sensor Nodes for Acceleration, Strain and Temperature Measurements, Procedia Eng. 168 (2016) 1659–1662. https://doi.org/10.1016/j.proeng.2016.11.484.

[34] M.S. Konsta-Gdoutos, C.A. Aza, Self sensing carbon nanotube (CNT) and nanofiber (CNF) cementitious composites for real time damage assessment in smart structures, Cem. Concr. Compos. 53 (2014) 162–169. https://doi.org/10.1016/j.cemconcomp.2014.07.003.

[35] C. Maraveas, T. Bartzanas, Sensors for structural health monitoring of agricultural structures, Sensors (Switzerland). 21 (2021) 1–32. https://doi.org/10.3390/s21010314.

[36] S. Taheri, A review on five key sensors for monitoring of concrete structures, Constr. Build. Mater. 204 (2019) 492–509. https://doi.org/10.1016/j.conbuildmat.2019.01.172.

[37] F. Köksal, F. Altun, I. Yiğit, Y. Şahin, Combined effect of silica fume and steel fiber on the mechanical properties of high strength concretes, Constr. Build. Mater. 22 (2008) 1874–1880. https://doi.org/10.1016/j.conbuildmat.2007.04.017.

[38] S.H. Liu, M.Q. Wu, M.J. Rao, L.H. Li, H.L. Xiao, Preparation, Properties, and Microstructure of Graphite Powder-Containing Conductive Concrete, Strength Mater. 51 (2019) 76–84. https://doi.org/10.1007/s11223-019-00052-1.

[39] X. Dongyu, C. Xin, H. Shifeng, Investigation of inorganic fillers on properties of 2-2 connectivity cement/polymer based piezoelectric composites, Constr. Build. Mater. 94 (2015) 678–683. https://doi.org/10.1016/j.conbuildmat.2015.07.090.

[40] H. Liu, K. Liu, Z. Lan, D. Zhang, Mechanical and Electrical Characteristics of Graphite Tailing Concrete, Adv. Mater. Sci. Eng. 2018 (2018). https://doi.org/10.1155/2018/9297628.

[41] H. Siad, M. Lachemi, M. Sahmaran, H.A. Mesbah, K.A. Hossain, Advanced engineered cementitious composites with combined self-sensing and self-healing functionalities, Constr. Build. Mater. 176 (2018) 313–322. https://doi.org/10.1016/j.conbuildmat.2018.05.026.

[42] L. Gao, T.W. Chou, E.T. Thostenson, Z. Zhang, A comparative study of damage sensing in fiber composites using uniformly and non-uniformly dispersed carbon nanotubes, Carbon N. Y. 48 (2010) 3788–3794. https://doi.org/10.1016/j.carbon.2010.06.041.

[43] X. Fan, D. Fang, M. Sun, Z. Li, Piezoresistivity of carbon fiber graphite cement-based composites with CCCW, J. Wuhan Univ. Technol. Mater. Sci. Ed. 26 (2011) 339–343. https://doi.org/10.1007/s11595-011-0226-0.

[44] Y. Fang, L.Y. Li, S.H. Jang, Calculation of electrical conductivity of self-sensing carbon nanotube composites, Compos. Part B Eng. 199 (2020) 108314. https://doi.org/10.1016/j.compositesb.2020.108314.

[45] Y. Kuronuma, T. Takeda, Y. Shindo, F. Narita, Z. Wei, Electrical resistance-based strain sensing in carbon nanotube/polymer composites under tension: Analytical modeling and experiments, Compos. Sci. Technol. 72 (2012) 1678–1682. https://doi.org/10.1016/j.compscitech.2012.07.001.

[46] X.F. Sánchez-Romate, J. Artigas, A. Jiménez-Suárez, M. Sánchez, A. Güemes, A. Ureña, Critical parameters of carbon nanotube reinforced composites for structural health monitoring applications: Empirical results versus theoretical predictions, Compos. Sci. Technol. 171 (2019) 44–53. https://doi.org/10.1016/j.compscitech.2018.12.010.

[47] X. Xin, M. Liang, Z. Yao, L. Su, J. Zhang, P. Li, C. Sun, H. Jiang, Self-sensing behavior and mechanical properties of carbon nanotubes/epoxy resin composite for asphalt pavement strain monitoring, Constr. Build. Mater. 257 (2020) 119404. https://doi.org/10.1016/j.conbuildmat.2020.119404.

[48] A. Naqi, N. Abbas, N. Zahra, A. Hussain, S.Q. Shabbir, Effect of multi-walled carbon nanotubes (MWCNTs) on the strength development of cementitious materials, J. Mater. Res. Technol. 8 (2019) 1203–1211. https://doi.org/10.1016/j.jmrt.2018.09.006.

[49] T. Yin, J. Xu, Y. Wang, L. Liu, Increasing self-sensing capability of carbon nanotubes cement-based materials by simultaneous addition of Ni nanofibers with low content, Constr. Build. Mater. 254 (2020) 119306. https://doi.org/10.1016/j.conbuildmat.2020.119306.

[50] X.F. Sánchez-Romate, J. Martín, A. Jiménez-Suárez, S.G. Prolongo, A. Ureña, Mechanical and strain sensing properties of carbon nanotube reinforced epoxy/poly(caprolactone) blends, Polymer (Guildf). 190 (2020). https://doi.org/10.1016/j.polymer.2020.122236.

[51] Alamusi, N. Hu, H. Fukunaga, S. Atobe, Y. Liu, J. Li, Piezoresistive strain sensors made from carbon nanotubes based polymer nanocomposites, Sensors. 11 (2011) 10691–10723. https://doi.org/10.3390/s111110691.

[52] B. Han, L. Zhang, S. Sun, X. Yu, X. Dong, T. Wu, J. Ou, Electrostatic self-assembled carbon nanotube/nano carbon black composite fillers reinforced cement-based materials with multifunctionality, Compos. Part A Appl. Sci. Manuf. 79 (2015) 103–115. https://doi.org/10.1016/j.compositesa.2015.09.016.

[53] J.M. Park, P.G. Kim, J.H. Jang, Z. Wang, J.W. Kim, W. Il Lee, J.G. Park, K. Lawrence

Materials Research Proceedings **23** (2022) 255-268 https://doi.org/10.21741/9781644901953-29

DeVries, Self-sensing and dispersive evaluation of single carbon fiber/carbon nanotube (CNT)-epoxy composites using electro-micromechanical technique and nondestructive acoustic emission, Compos. Part B Eng. 39 (2008) 1170–1182. https://doi.org/10.1016/j.compositesb.2008.03.004.

[54] S. Biswal, A. Ramaswamy, Measurement of existing prestressing force in concrete structures through an embedded vibrating beam strain gauge, Meas. J. Int. Meas. Confed. 83 (2016) 10–19. https://doi.org/10.1016/j.measurement.2016.01.031.

[55] A.M. Bazán, J.C. Gálvez, E. Reyes, D. Galé-Lamuela, Study of the rust penetration and circumferential stresses in reinforced concrete at early stages of an accelerated corrosion test by means of combined SEM, EDS and strain gauges, Constr. Build. Mater. 184 (2018) 655–667. https://doi.org/10.1016/j.conbuildmat.2018.06.195.