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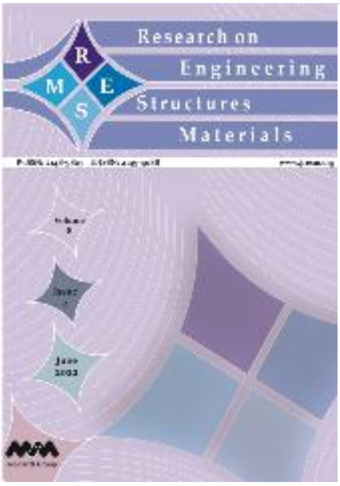

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C. Arvind Kumar, Panga Narasimha Reddy, S.A. Aejaz, Prathik Kulkarni

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Research Article

Self-sensing concrete with recycled coarse aggregates and multi-walled carbon nanotubes: A sustainable and effective method

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Abstract

This study explores the production of self-sensing concrete using recycled coarse aggregates and Multi-walled Carbon Nanotubes (MWCNTs) in varying dosages. The objective is to reduce the usage of natural coarse aggregates and to develop an environmentally friendly and sustainable material for the future generation. The self-sensing concrete was also self-compacting (SCC), which enhances its ability to fill complicated molds without the need for external vibration. The fresh properties of the self-sensing concrete were tested, and the mix proportions with varying dosages of MWCNTs were within the prescribed limit as per European Federation of National Associations Representing for Concrete (EFNARC) code. The mechanical properties of the self-sensing concrete were also evaluated, and it was observed that incorporating MWCNTs into the concrete enhanced its strength. Incorporating MWCNT into concrete increased its strength, seen in higher compressive and split tensile strengths. Adding 0.05%, 0.1%, and 0.15% of MWCNT resulted in compressive strength increases of 1.51%, 3.21%, and 4.72%, respectively. Likewise, the inclusion of 0.05%, 0.1%, and 0.15% of MWCNT led to split tensile strength increases of 1.54%, 3.31%, and 4.82%, respectively. The SEM images of specimens with different MWCNT dosages show a random yet uniform dispersion within the concrete matrix. The initial electrical resistance plot demonstrates the transformation from conventional to self-sensing concrete, with the resistance dropping significantly from 400k-ohms to 37k-ohms. This plot establishes the critical threshold level for self-sensing at 0.10% MWCNTs. Furthermore, the study examined the stress sensing ability and crack detection properties of the self-sensing concrete, and it was found that during cyclic loading, the concrete's stress sensing ability improves with increasing MWCNT dosage. The most favorable similarity plot between stress and FCR is seen at 0.15% MWCNT. However, considering economic reasons, a dosage of 0.1% MWCNT can be considered the best option since it doesn't show a significant difference for both stress and crack detection property.

1. Introduction

Throughout the world, there is a huge demand for concrete, and the current structures are often referred to as "concrete jungles." This demand is considered a sign of development, but from a sustainability point of view, the materials such as coarse aggregate and fine aggregate used to produce concrete are continuously depleting as they are naturally occurring resources. On the other hand, some buildings are continuously being dismantled

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due to various reasons, and disposing of the demolished waste can be challenging. Therefore, using recycled aggregate from this waste can help solve the problem of depleting natural resources and disposing of the waste. In this study, recycled concrete was utilized to produce self-sensing concrete instead of using new coarse aggregate.

The seismic event that recently occurred at the boundary of Turkey and Syria had devastating effects, claiming the lives of more than 40,000 individuals. While natural disasters like earthquakes are beyond human control, utilizing structural health monitoring (SHM) techniques can be effective in mitigating the loss of both life and property. SHM involves the use of different methods to detect potential weaknesses in structures, enabling preventive measures such as repairs or demolition to be taken within time. This can help prevent the structures from being easily compromised during earthquakes, consequently reducing casualties. Embedding sensors in concrete or attaching them to the external surface are among the different techniques available for SHM [1]–[4], where they are used to measure parameters such as strains, deflections, and stresses. It is clear that there is an urgent need to implement SHM to minimize the losses that may result from such events in the future. On the other hand, the conventional SHM approach using external or internal sensors provides information only for the specific locations where the sensors are attached and not for the entire structure. To overcome this limitation, a new technique called SHM using self-sensing concrete (SSC) has been developed. This innovative method involves turning the concrete into a sensor itself, rather than relying on attaching external or internal sensors.

The concept of SSC was discovered by DDL Chung in the early 1990s, who found that the addition of electrically conductive carbon fibers to cement enabled the resulting material to sense external loads[5]–[8]. The sensing ability of the material was measured by monitoring the electrical resistance of the specimen. This groundbreaking technique offers the potential to monitor the entire structure continuously, allowing for timely interventions that could save lives and property during natural disasters like earthquakes. DDL Chung's discovery of the sensing ability of electrically conductive carbon fibers added to cement marked the birth of self-sensing concrete. Since then, a plethora of studies have been carried out to further explore this concept. Researchers have experimented with various materials to enhance the sensing capabilities of self-sensing concrete. The various materials like carbon fibers [9], [10], single walled nano tubes [11] multi-walled carbon nanotubes (MWCNT). [12]–[15], carbon black[16], [17], combined carbon fibers with MWCNT[18]–[20]. Dehghani and Aslani [21] also conducted a study using a blend of steel fibers and carbon fibers. These various studies have contributed significantly to the development and potential applications of self-sensing concrete.

In their research, Suchorzewski, et al. [22] discovered that adding multi-walled carbon nanotubes (MWCNT) to high-performance concrete (HPC) improves both its mechanical and self-sensing properties. The researchers studied the concrete's ability to detect stress during cyclic compression and found that even a small amount of MWCNT (0.05% and 0.10%) improved stress detection and allowed for the monitoring of micro cracking. This study highlights the potential benefits of using MWCNT in HPC to improve the sensing capabilities of the material, which could lead to more effective and accurate monitoring of structures for potential damage or failure. Song, Niu, and Zhong conducted a study to investigate the dynamic mechanical properties of carbon nanotube reinforced concrete when subjected to freeze-thaw cycles. Their results revealed that, with an increase in freeze-thaw cycles, the peak stress of the concrete sample gradually decreased under the same impact pressure, while the corresponding strain increased slightly. Furthermore, the stress-strain curve shifted downwards and to the right as a whole. These findings suggest that the addition of carbon nanotubes to concrete may have a positive effect on its dynamic mechanical properties and ability to withstand environmental stressors like freeze-thaw cycles.

The addition of multi-walled carbon nanotubes (MWCNT) to recycled aggregate concrete (RAC) has been the subject of several studies. One such study by Gao [23]. showed that adding 0.1% MWCNT by weight of cement to RAC, made from various waste cementitious materials, and replacing natural aggregates with recycled concrete aggregates (RCA) at rates of 50%, 70%, and 100%, significantly increased the compressive strength of treated RAC samples by approximately 42% compared to untreated RAC samples. In contrast, another study by Song [24] examined the impact of different levels of MWCNT on the interfacial mechanical properties of RAC. They found that the highest shear strength was achieved with the addition of 0.2% MWCNT, resulting in a 53% improvement compared to free-nano mixtures. These studies suggest that the addition of MWCNT to RAC can lead to significant improvements in its mechanical properties and provide insights into the optimal levels of MWCNT for achieving the desired outcomes. Further I. Murali et al. [25] evaluated the impact response of fibrous concrete that incorporated expanded clay aggregate in combination with MWCNT and steel fibers at 0.2% and 2.5% by cement weight, respectively. The study found that 0.2% MWCNT significantly filled nanopores, resulting in a denser concrete matrix.

After conducting a literature review, it was discovered that previous research on self-sensing concrete has been limited to cement, mortar specimens, and conventional concrete. As such, further investigation is required to understand the behavior of concrete with conductive fibers when used in actual site conditions. Furthermore, in the present era, self-compacting concrete (SCC) is being utilized widely in various applications. In the current study, self-sensing concrete was produced by incorporating multi-walled carbon nanotubes (MWCNT) into self-compacting concrete (SCC), which uses recycled coarse aggregate. The aim was to investigate the potential of self-sensing concrete in addressing sustainability concerns. A range of SCC specimens containing varying dosages of MWCNT were produced and tested to assess their mechanical properties, stress-sensing capabilities, crack detection ability under cyclic loading.

2. Experimental Work

2.1. Material Used

For production of self-sensing concrete in present study, Multi Walled Carbon Nano Tubes (MWCNT) obtained from Sun Young Industry, South Korea was used. The MWCNT were completely electrically conductive with an average diameter of 10-20 nm, average length of 5-20 µm, and purity greater than 95%. The properties of the MWCNT used in the study are shown in Table 1.

To ensure adequate dispersion of the MWCNT and produce self-compacting concrete (SCC), a high-range water-reducing super plasticizer with a density of 1.08 g/ml and based on polycarboxylate ether (PCE) was used. Tap water with a pH of 7.2 was used for mixing and curing the concrete. The coarse aggregate used in the study was obtained by screening and cleaning concrete waste from nearby demolished structures, with a size of 10 mm and a specific gravity of 2.75 after cleaning and sieving. River sand with a specific gravity of 2.65 and a fineness modulus of 2.8 was used as the fine aggregate. Cement with a specific gravity of 3.14 and a grade of 43 was used to produce the SCC. The Physical properties and Chemical composition of cement are shown in Table 2.

Table 1. Properties of MWCNT's

Property	Value
Purity	>94%
Colour	Black
Length	6-16 μm
Inner Diameter	5-10 nm
Outer Diameter	40-60 nm
True Density	~2.2 g/cm3
Bulk Density	~0.12 g/cm3
Specific Surface Area	45-600 m2/g
Pore Volume	081cm3/g

Table 2. Physical properties and Chemical composition of cement

Physical Characteristics	Values
Fineness	9%
Density	3080.2 kg/m3
Specific Gravity	3.13
Normal Consistency	31%
Chemical Composition	Values in %
CaO	61.2
SiO2	21.5
Al2O3	5.45
SO3	3.21
Fe2O3	3.57
MgO	2.54

2.2. Mix Proportion

In this study, self-compacting concrete (SCC) mixes were produced using different dosages of MWCNT ranging from 0% to 0.15% by weight of cement, with increments of 0.05%. The mix proportions of materials used are presented in Table 3.

Table 3. Material proportions and slump flow results

Specimen ID	Materials used in kg/m^3							Slump flow test in mm	
	MWCNT		Cement	Fine aggregate	Coarse aggregate	Water	Super Plasticizer (1.55%)	Experimental	Range as per EFNARC
	%	kg							
Ref.	0	0	460	950	880	186	7.13	760	600-850
SCC-0.05	0.05	0.26	460	950	880	186	7.13	732	600-850
SCC-0.1	0.1	0.52	460	950	880	186	7.13	706	600-850
SCC-0.15	0.15	0.78	460	950	880	186	7.13	690	600-850

A compressive strength of 40N/mm2 was chosen for the SCC mix after conducting several trials to ensure that both the fresh and hardened properties satisfied the code European Federation of National Associations Representing for Concrete (EFNARC) [26] requirements.

The European Guidelines for Self-Compacting Concrete. The material proportions for the SCC without MWCNT, which was used as the reference mix after conducting adequate trials, are shown in Table 3 with the label "Reference". The table also shows the flow properties of the different mixes after adding MWCNT. The slump flow of all mixes fell within the prescribed limits and was measured using the slump flow test specified by the EFNARC code

2.3. Specimen Preparation

In order to disperse the MWCNTs in water, initially a solution was prepared by mixing 50% of the water required for concrete preparation with Sodium Dodecylbenzene Sulfonate (SDBS) powder, in a concentration of 0.18% by weight of the nano tubes. The MWCNT were added to this solution, and the mixture was agitated using a mechanical churner for 15 minutes to ensure proper dispersion of the nano tubes in water. This dispersed solution was then added to the concrete mixer containing dry cement, fine aggregate (FA), and coarse aggregate (CA), along with a solution containing the remaining 50% of the water and the superplasticizer. The mixture was further mixed in the concrete mixer until self-compacting concrete was obtained. The complete mix procedure is depicted in Fig. 1.

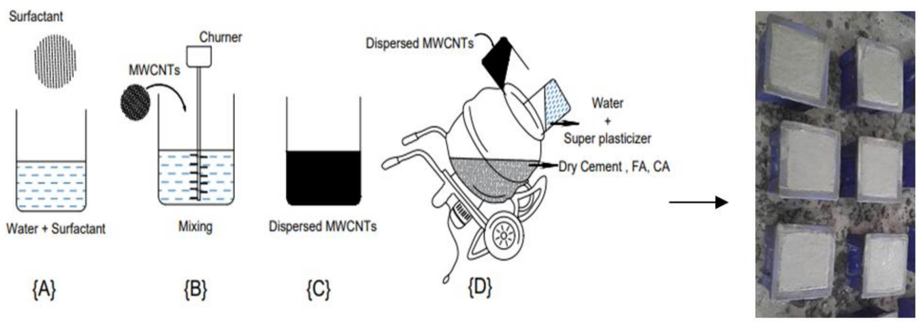


Fig. 1. Mixing procedure for production of self sensing concrete

The freshly prepared self-compacting concrete (SCC) mix was evaluated for its fresh properties using the slump flow test [26]. Subsequently, the mix was poured into steel molds of cubes and cylinders. The cube molds had dimensions of 150 x 150 x 150 mm3, while the cylinder molds had a diameter of 150 mm and a length of 300 mm. The filled molds were then allowed to dry at room temperature for 24 hours. After the drying period, the molds were carefully demoded, and the specimens were placed in fresh water for curing over a period of 28 days. Each SCC mix was used to create five cubes and three cylinders.

2.4. Testing Procedure

2.4.1. Compressive and Split Tensile Strength

After 28 days of curing, the self-sensing concrete specimens were removed from the water and underwent testing to determine their load carrying capacity under both compression and tension using a Universal Testing Machine (UTM). To determine the ultimate load carrying capacity in compression, a set of three cubes were loaded gradually using the UTM until failure occurred. The average stress value of the three specimens was then calculated and recorded. Similarly, the split tensile strength of the SSC was evaluated by subjecting the cylinders to a transverse load using the UTM until they reached failure. The split tensile strength value was then calculated using the codal formula and included in the results section.

2.4.2. Electrical Resistivity Measurements

In order to achieve consistent and reliable measurements of electrical resistance in the specimens, an electrically conductive paint is used to coat the periphery of each cube, and copper wire is wrapped over the paint at a distance of 10mm from the top and bottom edges, as depicted in Fig. 2. A digital multimeter (DMM) is used to measure the electrical resistance at the top and bottom ends of the copper wires, both during non-loading and loading situations. Prior to any loading, the sensor's sensing capability is tested by measuring the initial electrical resistance. The stress sensing ability is then evaluated by measuring the resistance during both loading and unloading in a cyclic manner.

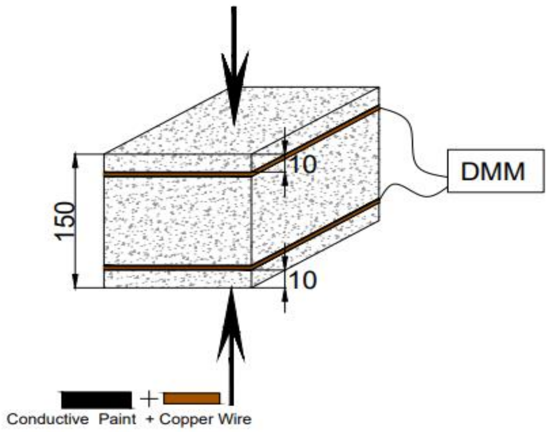


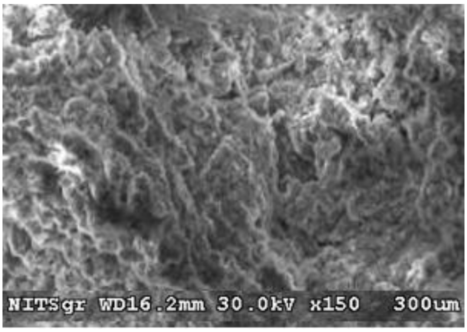
Fig. 2. Specimen details for stress sensing test

3. Results and Discussion

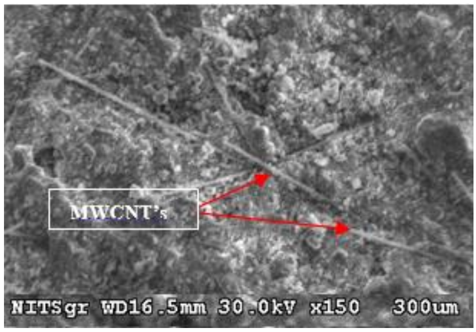
3.1. Dispersion of MWCNT's

Various samples, each containing different dosages of Multi-Walled Carbon Nanotubes (MWCNT's), underwent testing using a Hitachi 3600 N Scanning electron microscope (SEM) with a 5 axis motorized stage. These tests involved examining the SEM images of hardened concrete powder obtained from broken cube specimens after 28 days of curing during compressive testing.

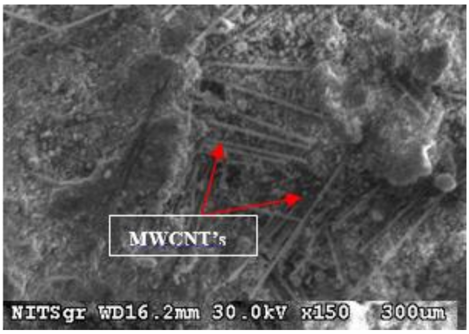
In Fig. 3, the SEM images depict the concrete with varying dosages of MWCNTs. All the sample dimensions were almost kept uniform of 16.2mm with zooming of X150 resolution for SEM imaging. From the obtained images SEM images, it becomes evident that as the dosage of nano-tubes increases within the concrete, their visibility improves. Additionally, the images reveal that the nanotube fibers have been uniformly and randomly dispersed throughout the concrete matrix.



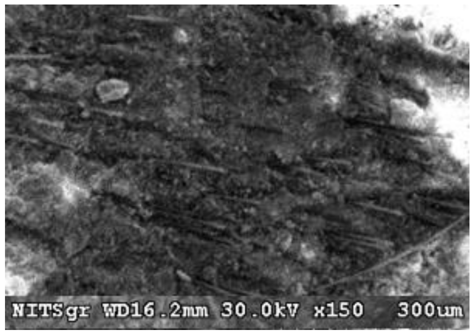
(a) No MWCNT's



(b) 0.05% MWCNT's



(c) 0.1% MWCNT's



(d) 0.15% MWCNT's

Fig. 3. SEM images of hardened samples

3.2. Mechanical Properties

3.2.1. Compressive Strength

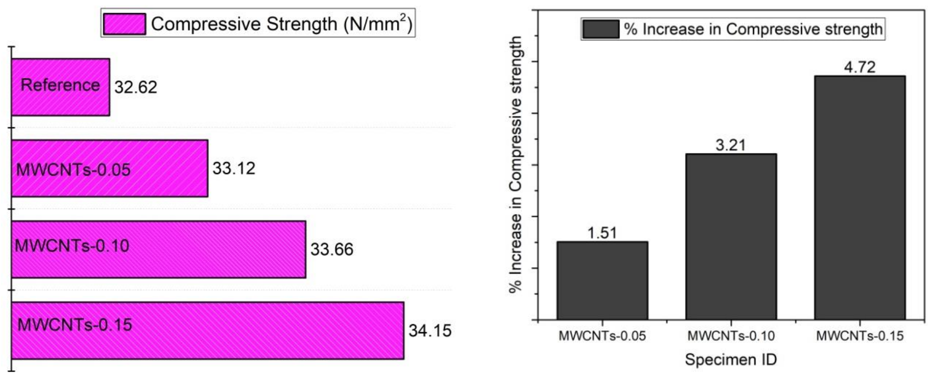
To evaluate the influence of MWCNT on concrete strength, the ultimate load carrying capacity was determined. For each MWCNT dosage, three sets of cubes were subjected to a Universal Testing Machine (UTM) with a 1000kN capacity, and gradually loaded at a constant speed of 5.2kN/sec until failure. The maximum load carrying capacity was recorded for each set, and the average value for each MWCNT dosage was presented in Table 4 for both compressive and split tensile strength.

Table 4. Compressive and Split tensile strength results

Specimen ID	Compressive Strength			Split Tensile Strength		
	Ultimate Load (kN)	Compressive Stress (N/mm^2)	% Increase in stress	Ultimate Load (kN)	Stress (N/mm^2)	% Increase in stress
Ref.	733.95	32.62	-	200.06	2.83	-
SCC-0.05	745.21	33.12	1.51	202.86	2.87	1.54
SCC-0.1	757.35	33.66	3.21	206.40	2.92	3.31
SCC-0.15	768.37	34.15	4.72	209.23	2.96	4.82

From these results, it can be inferred that the MWCNT dosage plays an important role in enhancing the compressive strength of self-compacting concrete. The increase in compressive strength for sample containing 0.05% of MWCNT's is 1.51% when compared to reference sample. Similarly, the increase in compressive strength for samples congaing 0.01% and 0.15 % MWCNT's is 3.21 and 4.72% respectively when compared to reference samples.

In a parallel investigation conducted by Ali Naqi and Naseem Abbas[27], which focused on cement paste blended with silica fume, the inclusion of 0.01% Multi-Walled Carbon Nanotubes (MWCNTs) led to notable enhancements in compressive strength. Compared to the reference specimens, the concrete samples with 0.01% MWCNTs exhibited 4.4%, 9.7%, and 12.4% higher compressive strengths at 1, 3, and 7 days, respectively. Also Morsy et al. [28] demonstrated an 11% improvement in compressive strength by adding 0.02 wt.% CNT and 6 wt.% nano metakaolin. Similarly, Cwirzen et al. [29] achieved a significant 50% increase in compressive strength by adding 0.045% MWCNTs compared to the reference samples. It is important to note that in present study, there is a limit to the increase in compressive strength, and the dosage of MWCNT cannot be increased indefinitely. The optimal dosage range for MWCNT addition appears to be between 0.1% and 0.15% by weight of cement. Beyond this range, the increase in compressive strength may not be significant or may even decrease due to issues related to agglomeration of the nano tubes. Overall, the results indicate that the addition of MWCNT in self-compacting concrete can lead to an improvement in the compressive strength, which can result in the production of more durable and long-lasting structures.



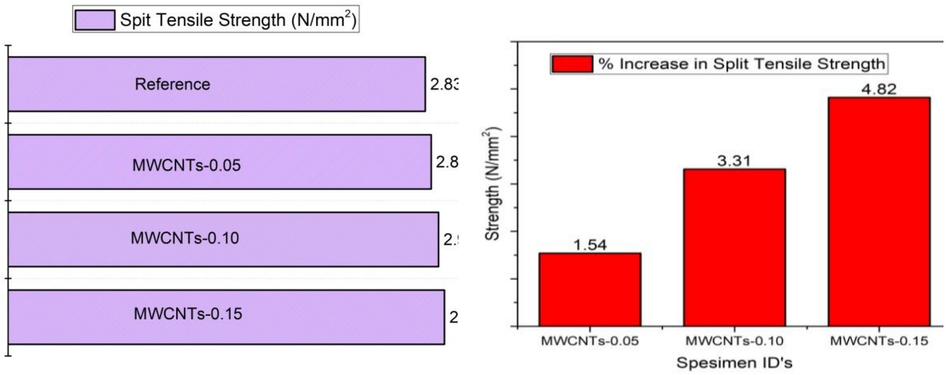
(a) Compressive strength (b) Increase in compressive strength

Fig. 4. Increase in compressive strength

The figure presented in Fig. 4 (a) graphically represents the compressive strength and Fig.4 (b) represent shows increase in compressive strength resulting from the addition of MWCNT to the concrete mix. The increase in compressive strength is attributed to the ability of MWCNT to fill pores within the concrete structure, making it denser due to its small size. Furthermore, the fibers contribute to bridging small cracks in the concrete, which ultimately increases the strength of the material. However, it is worth noting that the increase in strength is relatively small despite the positive impact of MWCNT on concrete strength.

3.2.2. Split Tensile Strength

Based on the results of split tensile strength shown in Fig. 5, it is observed that the addition of MWCNT has a positive impact on split tensile strength, and the increase in strength is proportional to the dosage of MWCNT added to the mix. The increase in split tensile strength for 0.05, 0.1 and 0.15% dosage of MWCNT's is 1.51, 3.21 and 4.72% respectively. Similar research conducted by Baban Singh and Sushmita[31], observed that incorporating Multi-Walled Carbon Nanotubes (MWCNTs) into concrete resulted in significant improvements in split tensile strength. Concrete specimens containing 0.015%, 0.030%, and 0.045% MWCNT content demonstrated higher values of split tensile strength compared to conventional concrete. The enhancement in split tensile strength was measured at 30.83%, 45.38%, and 66.3%, respectively, for the mentioned MWCNT content levels. The increase in split tensile strength can be attributed to the bridging effect of the MWCNT in the concrete matrix, which enhances the tensile strength. Moreover, the smaller size of MWCNT compared to traditional fibers enables them to penetrate and fill the small voids in the concrete, making it denser and hence more resistant to cracking as said earlier.



(a) Split tensile strength (b) Increase in split tensile strength

Fig. 5. Split tensile strength

It is noteworthy that the split tensile strength showed higher improvement compared to the compressive strength for the same dosage of MWCNT. This indicates that the addition of MWCNT can significantly enhance the tensile behavior of concrete, making it more durable and resistant to cracking, especially under tensile stresses. Therefore, the use of MWCNT can potentially improve the durability and longevity of concrete structures, especially those subject to heavy loads and harsh environmental conditions. The results suggest that the addition of MWCNT improves the tensile strength of concrete to a greater extent than its compressive strength, even when the same dosage is used. This can be attributed to the fact that the concrete tends to develop cracks and separate from each other during tensile loading, whereas the presence of MWCNT acts as a bridge, holding the concrete together and improving its strength.

3.3 Electrical Properties

3.3.1 Initial Resistance

To evaluate the conversion of normal concrete to sensing concrete and its sensing ability, the initial resistance of all specimens with varying dosages of MWCNT was measured by assessing the initial resistance in a dry condition before loading the specimens. Fig. 6 illustrates the measured values of initial resistance for different dosages of MWCNT for all the specimens. It is observed that as the dosage of MWCNT increases, the electrical resistance decreases, indicating that the concrete becomes more sensitive compared to the reference concrete. The initial resistance of the reference concrete was 332 k-ohms, while for 0.05% of MWCNT, it drastically reduced to 48k-Ohms. However, beyond the 0.05% dosage of MWCNT, the change was relatively small. Thus, the addition of MWCNT to the reference concrete converted it to a sensor. In a study conducted by D'Alessandro et al.

[30], it was discovered that the introduction of multi-wall carbon nanotubes (MWCNTs) and carbon fibers (CFs) into concrete led to a significant reduction in the initial electrical resistance. Specifically, when the MWCNT dosage varied between 0% and 1.5%, the initial electrical resistance experienced a remarkable decrease at the 0.75% MWCNT concentration.

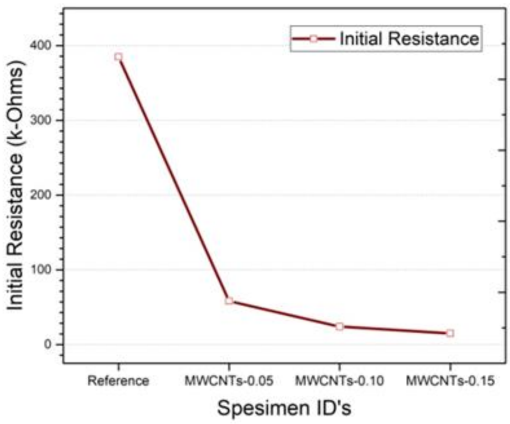


Fig. 6. Initial electrical resistance

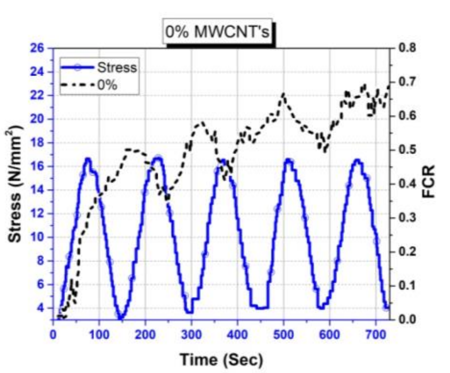
3.3.2 Stress Sensing Test

As previously stated, in order to assess the stress sensing capability of the specimen, it underwent 5 cycles of cyclic loading at a peak load of 382kN. This specific load was selected based on 40% of the maximum load-carrying capacity of the reference sample, and the cyclic load was kept within the elastic limit. Throughout the testing process, the electrical resistance and load were recorded, and a graphical representation of the stress and fractional change in resistance (FCR) was produced which us shown in Fig. 7 The stress was calculated using the load, while the FCR was determined using the equation shown below as Eq. 1.

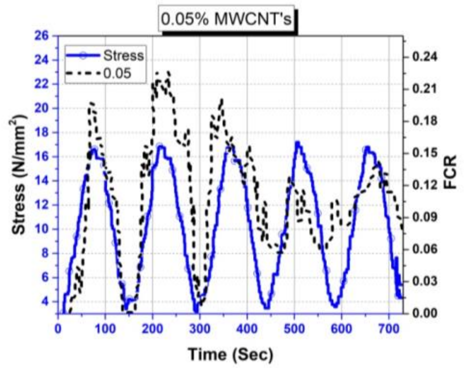
$$FCR = \frac{\Delta R}{R} = \frac{R_x - R_0}{R_0} \tag{1}$$

In the previously provided equation, Rx denotes the electrical resistance of the sample at any point in time during the loading process, whereas R0 signifies the initial resistance of the sample.

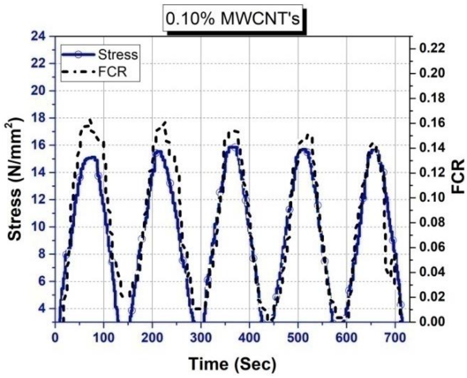
The plot depicted in Fig. 7 portrays time on the x-axis and FCR and stress on the y-axis (2 YY axis plot). Throughout the cyclic loading process, both the stress and FCR were computed and graphed. As demonstrated by the results presented in Fig. 7 (a), there was no significant fluctuation in FCR measurements during the cyclic loading of the reference sample. In addition, Fig. 7 (a) demonstrates that the FCR readings steadily rise without any correlation with stress. This is due to the lack of MWCNT in the specimen, which prevented it from transforming into a sensor and exhibiting any sensing capabilities under external loading. Conversely, Fig. 7 (b) showcases the specimen containing 0.05% MWCNT, revealing an enhancement in the FCR plot when compared to the reference specimen. The FCR plot depicted in Fig. 7 (b) displays fluctuations both during the increase and decrease in loading, indicating that the addition of MWCNT induces sensing capabilities to external loading. Although the variation observed is not as precise as that of cyclic stress, it is still noticeable. Additionally, the correlation between stress and FCR improves as the amount of MWCNT added increases. As the loading increases, the FCR tends to rise, whereas it decreases with a decrease in load. Galao[31] and Chung [32] observed a similar trend in cement cubes, varying the dosage of carbon nano fibers (CNF) from 0 to 2% by weight of the cement. As the CNF percentage increased, the cubes exhibited enhanced self-sensing, detecting structural changes. In contrast, cement composites without conductive admixtures lack self-sensing behavior, and any observed behavior is non-reversible and non-repeatable. The findings highlight the importance of incorporating conductive materials like carbon nano fibers for improved structural health monitoring and concrete durability. This is because the MWCNT dispersed in the concrete specimen move closer to each other during loading, which in turn reduces the electrical resistance and increases conductivity.



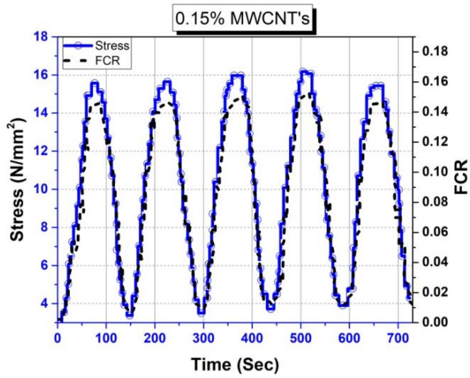
a) 0% MWCNT



b) 0.05% MWCNT



c) 0.10% MWCNT



d) 0.15% MWCNT

Fig. 7. Plot of Stress and FCR against time

Likewise, when the specimen is unloaded, the fibers move apart due to the decrease in load, leading to a reduction in ion flow and an increase in resistance. For a dosage of 0.1%, Fig. 7 (c) illustrates that the FCR plot displays even greater enhancement in stress sensing when compared to the reference and 0.05% MWCNT specimens. This is due to the increased sensing ability caused by the greater dispersion of nanotubes within the concrete specimen as more MWCNT is added. Additionally, the FCR plot fluctuates in a very similar manner to the stress plot and overlaps with it. The stress sensing ability of the specimen improves with the addition of 0.15% MWCNT, as indicated by the plot Fig.7 (d), but it is not considerably distinct from the plot for 0.1% MWCNT, as depicted in Fig. 7 (c).

As a result, for economic considerations, it can be inferred that a dosage of 0.1% MWCNT would be sufficient for the production of self-sensing concrete.

It can be concluded that self-sensing concrete has the potential to transform the approach to stress and damage monitoring of structures. Real-time stress measurement without requiring the dismantling of structures can contribute to enhanced infrastructure safety and maintenance. Self-sensing concrete can facilitate continuous Structural Health Monitoring (SHM) across the entire structure, eliminating the necessity for attaching or inserting sensors at specific locations. This could potentially enhance the overall safety and durability of structures by enabling the timely detection and addressing of any stress or damage.

3.3.3 Crack Detection Test

This test aims to determine the effectiveness of self-sensing concrete in detecting crack formation in a concrete specimen. The test involves subjecting the specimen to cyclic loading, where the stress is incrementally increased to 4N/mm^2 for each cycle. Initially, the load is applied until the specimen reaches a stress level of 15kN and is then unloaded back to zero stress. In the next cycle, the load is increased to reach a stress level of 19kN (15+4), and in the subsequent cycle, the stress level is raised to 23N/mm2 (19+4). The stress level is increased to 27 N/mm^2 in the following cycle, and after that, the load is applied until the specimen fails. In this test, the load was measured using a data logger, while changes in resistance were recorded using a DMM, as was done in the stress sensing test. The load measurements were used to calculate stress, and a plot of FCR and stress was generated, as shown in Fig. 8.

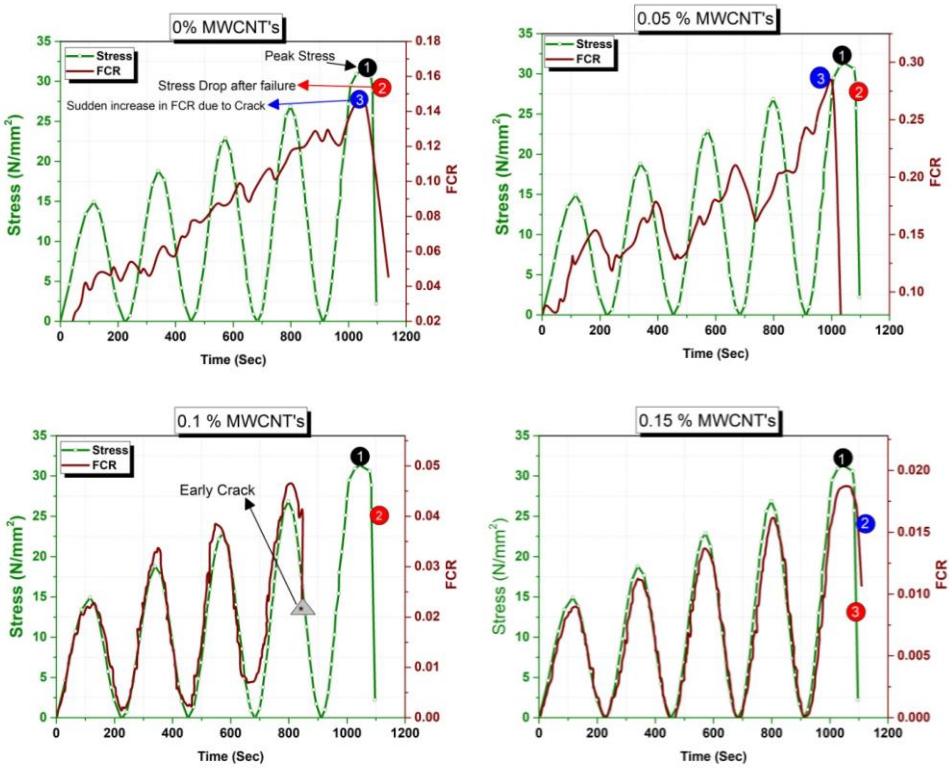


Fig. 8. Results of crack detection test

The results indicate that all specimens exhibited crack detection properties. However, it is important to note that the stress sensing ability improved with increasing dosages of MWCNTs. The sudden drop in the FCsR plot observed in all graphs indicates the formation of cracks within the specimens. The sudden drop in FCR is due to the formation of cracks in the concrete specimen at the peak load. Galao's[31] research investigated the impact of incorporating carbon nano fibers (CNF) at a 2% dosage in cement paste. The study revealed that this addition made the cement paste highly sensitive to its own structural damage, enabling successful crack detection. On a similar note, Arvind[33] conducted a study involving self-compacting concrete (SCC) reinforced with CNF. Their findings indicated that the damage sensing capacity of SCC increased proportionally with the CNF content, ranging from 0 to 2%. Both studies highlight the promising potential of carbon nano fibers in enhancing the structural health monitoring of cement-based materials, leading to the development of more durable and self-aware construction elements. The crack creates a gap between the specimen, which interrupts the flow of electrons and discontinues the FCR measurements, resulting in a drop in FCR.

In all graphs Fig.7, the value "1" indicates the peak stress capacity, “2” indicates stress drop due to failure, while the value "3" indicates the sudden drop in FCR plot due to crack formation in the specimen. The specimen with 0.1% MWCNTs showed an early drop in FCR before reaching the peak load level, indicating the presence of cracks in the specimen at an earlier stage. The results suggest that whenever there is a crack in the specimen, the FCR plot drops suddenly, indicating the formation of cracks. Therefore, it can be concluded from the results that self-sensing concrete can be used for both stress sensing and crack detection in concrete.

4. Conclusions

From the results of this study, the following conclusions can be drawn:

- The maximum critical buckling load was achieved in specimen having 0o rowing orientation angle.
- The specimens having small cutout diameter were showed the maximum strength against to buckling. So that, the maximum critical buckling load was achieved in specimen with 2 mm cutout diameter.
- The utilization of recycled coarse aggregate in the manufacturing of self-sensing concrete can lessen the requirement for natural coarse aggregate. Additionally, the addition of MWCNT did not have a significant impact on the fresh characteristics of self-compacting concrete.
- Incorporating MWCNT into concrete resulted in an enhancement of its strength, as demonstrated by the elevation of both compressive and split tensile strength. The addition of 0.05%, 0.1%, and 0.15% of MWCNT resulted in an increase of 1.51%, 3.21%, and 4.72%, respectively, in compressive strength. Similarly, incorporating 0.05%, 0.1%, and 0.15% of MWCNT led to an increase of 1.54%, 3.31%, and 4.82%, respectively, in split tensile strength.
- The SEM images of specimens containing varying dosages of MWCNTs provide evidence of a random yet uniform dispersion of MWCNTs within the concrete matrix. Additionally, the initial electrical resistance plot clearly illustrates the transformation of conventional concrete into self-sensing concrete, as the initial resistance of the sample significantly decreases from 400k-ohms to 37k-ohms. Moreover, this plot establishes that the critical threshold level of MWCNTs required for creating a self-sensing sample is 0.10%.
- During cyclic loading, the stress sensing ability of concrete improves as the dosage of MWCNT increases. The best similarity plot between stress and FCR is observed

at 0.15% MWCNT. However, for economic reasons, a dosage of 0.1% MWCNT can be considered the best option as it does not show a significant difference.

- During the crack detection test, it was observed that the specimen containing MWCNTs was able to detect crack formation within the specimen at any point of loading, regardless of the dosage of MWCNTs, all the specimens have shown the damage sensing property with improved sensing ability with dosage increase of MWCNTs.
- In comparison to the current methods used for structural health monitoring (SHM), the self-sensing concrete developed using recycled aggregate has shown more efficient stress-sensing capabilities. This new material has the potential to revolutionize the field of SHM by providing real-time and continuous monitoring of structures, leading to better safety and maintenance practices.

References

[1] Gómez J, Casas JR, Villalba S. Structural Health Monitoring with Distributed Optical Fiber Sensors of tunnel lining affected by nearby construction activity. Automation in Construction. 2020 Sep; 117: 103261. https://doi.org/10.1016/j.autcon.2020.103261

[2] Reddy PN, Kavyateja BV, Jindal BB. Structural health monitoring methods, dispersion of fibers, micro and macro structural properties, sensing, and mechanical properties of self-sensing concrete—A review. Structural Concrete. 2021 Apr;22(2):793-805. https://doi.org/10.1002/suco.202000337

[3] Cholker AK, Kavyateja BV, Reddy PN. Influence of Carbon Fibers on Strain and Damage Sensing of Self Compacting Concrete under External Applied Forces. I2M. 2019 Dec 30;18(6):559-65.https://doi.org/10.18280/i2m.180607

[4] Di Nuzzo F, Brunelli D, Polonelli T, Benini L. Structural Health Monitoring System with Narrowband IoT and MEMS Sensors. IEEE Sensors J. 2021 Jul 15;21(14):16371-80. https://doi.org/10.1109/JSEN.2021.3075093

[5] Chen, P. W., & Chung, D. D. Carbon fiber reinforced concrete for smart structures capable of non-destructive flaw detection. Smart Materials and Structures, 1993; 2(1); 22. https://doi.org/10.1088/0964-1726/2/1/004

[6] Fu X, Chung D. Self-monitoring of fatigue damage in carbon fiber reinforced cement. Cement and Concrete Research. 1996 Jan;26(1):15-20. https://doi.org/10.1016/0008-8846(95)00184-0

[7] Chung D. Self-monitoring structural materials. Materials Science and Engineering: R: Reports. 1998 Mar;22(2):57-78. https://doi.org/10.1016/S0927-796X(97)00021-1

[8] Fu X, Ma E, Chung D, Anderson W. Self-monitoring in carbon fiber reinforced mortar by reactance measurement. Cement and Concrete Research. 1997 Jun;27(6):845-52. https://doi.org/10.1016/S0008-8846(97)83277-2

[9] Cholker AK, Tantray MA. Strain-sensing characteristics of self-consolidating concrete with micro-carbon fibre. Australian Journal of Civil Engineering. 2020 Jan 2;18(1):46-55. https://doi.org/10.1080/14488353.2019.1704206

[10] Cholker AK, Tantray M. Electrical resistance-based health monitoring of structural smart concrete. Materials Today: Proceedings. 2021; 43: 3774-9. https://doi.org/10.1016/j.matpr.2020.10.991

[11] Kang J, Al-Sabah S, Théo R. Effect of Single-Walled Carbon Nanotubes on Strength Properties of Cement Composites. Materials. 2020 Mar 13;13(6):1305. https://doi.org/10.3390/ma13061305

[12] Guo Y, Li W, Dong W, Luo Z, Qu F, Yang F, et al. Self-sensing performance of cement-based sensor with carbon black and polypropylene fibre subjected to different loading conditions. Journal of Building Engineering. 2022 Nov; 59: 105003. https://doi.org/10.1016/j.jobe.2022.105003

[13] Li GY, Wang PM, Zhao X. Mechanical behavior and microstructure of cement composites incorporating surface-treated multi-walled carbon nanotubes. Carbon. 2005 May;43(6):1239-45. https://doi.org/10.1016/j.carbon.2004.12.017
[14] Xu S, Liu J, Li Q. Mechanical properties and microstructure of multi-walled carbon nanotube-reinforced cement paste. Construction and Building Materials. 2015 Feb;76:16-23. https://doi.org/10.1016/j.conbuildmat.2014.11.049
[15] Nochaiya T, Chaipanich A. Behavior of multi-walled carbon nanotubes on the porosity and microstructure of cement-based materials. Applied Surface Science. 2011 Jan;257(6):1941-5. https://doi.org/10.1016/j.apsusc.2010.09.030
[16] Dong W, Li W, Wang K, Guo Y, Sheng D, Shah SP. Piezoresistivity enhancement of functional carbon black filled cement-based sensor using polypropylene fibre. Powder technology. 2020;373:184-194. https://doi.org/10.1016/j.powtec.2020.06.029
[17] Li H, Xiao HG, Ou JP. Effect of compressive strain on electrical resistivity of carbon black-filled cement-based composites. Cement and Concrete Composites. 2006;28(9):824-828. https://doi.org/10.1016/j.cemconcomp.2006.05.004
[18] Zuo J, Yao W, Wu K. Seebeck effect and mechanical properties of carbon nanotube-carbon fiber/cement nanocomposites. Fullerenes, Nanotubes and Carbon Nanostructures. 2015;23(5):383-391. https://doi.org/10.1080/1536383X.2013.863760
[19] Hunashyal AM, Tippa SV, Quadri SS, Banapurmath NR. Experimental investigation on effect of carbon nanotubes and carbon fibres on the behavior of plain cement mortar composite round bars under direct tension. International Scholarly Research Notices. 2011. https://doi.org/10.5402/2011/856849
[20] 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;33(18):2271-2284. https://doi.org/10.1177/1045389X221077447
[21] Dehghani A, Aslani F. The effect of shape memory alloy, steel, and carbon fibres on fresh, mechanical, and electrical properties of self-compacting cementitious composites. Cement and Concrete Composites. 2020;112:103659. https://doi.org/10.1016/j.cemconcomp.2020.103659
[22] Suchorzewski J, Prieto M, Mueller U. An experimental study of self-sensing concrete enhanced with multi-wall carbon nanotubes in wedge splitting test and DIC. Construction and Building Materials. 2020;262:120871. https://doi.org/10.1016/j.conbuildmat.2020.120871
[23] Gao C, Huang L, Yan L, Jin R, Chen H. Mechanical properties of recycled aggregate concrete modified by nano-particles. Construction and Building Materials. 2020;241:118030. https://doi.org/10.1016/j.conbuildmat.2020.118030
[24] Song XB, Li CZ, Chen DD, Gu XL. Interfacial mechanical properties of recycled aggregate concrete reinforced by nano-materials. Construction and Building Materials. 2021; 270: 121446. https://doi.org/10.1016/j.conbuildmat.2020.121446
[25] Murali G, Abid SR, Karthikeyan K, Haridharan MK, Amran M, Siva A. Low-velocity impact response of novel prepacked expanded clay aggregate fibrous concrete produced with carbon nano tube, glass fiber mesh and steel fiber. Construction and Building Materials. 2021;284:122749. https://doi.org/10.1016/j.conbuildmat.2021.122749
[26] EFNARC, "Specification and Guidelines for Self-Compacting Concrete," Rep. from EFNARC, vol. 44, no. February, 2002.
[27] Naqi A, Abbas N, Zahra N, Hussain A, Shabbir SQ. Effect of multi-walled carbon nanotubes (MWCNTs) on the strength development of cementitious materials. Journal of Materials Research and Technology. 2019;8(1):1203-1211. https://doi.org/10.1016/j.jmrt.2018.09.006

[28] Morsy MS, Alsayed SH, Aqel M. Hybrid effect of carbon nanotube and nano-clay on physico-mechanical properties of cement mortar. Construction and Building Materials. 2011;25(1):145-149. https://doi.org/10.1016/j.conbuildmat.2010.06.046
[29] Cwirzen A, Habermehl-Cwirzen K, Penttala V. Surface decoration of carbon nanotubes and mechanical properties of cement/carbon nanotube composites. Advances in cement research. 2008;20(2):65-73. https://doi.org/10.1680/adcr.2008.20.2.65
[30] D'Alessandro A, Ubertini F, Materazzi AL, Laflamme S, Cancelli A, Micheli L. Carbon cement-based sensors for dynamic monitoring of structures. In 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC) (pp. 1-4). 2016; IEEE. https://doi.org/10.1109/EEEIC.2016.7555628
[31] Galao O, Baeza FJ, Zornoza E, Garcés P. Strain and damage sensing properties on multifunctional cement composites with CNF admixture. Cement and concrete composites. 2014;46:90-98. https://doi.org/10.1016/j.cemconcomp.2013.11.009
[32] Chen PW, Chung DDL. Concrete as a new strain/stress sensor. Composites Part B: Engineering. 1996;27(1):11-23. https://doi.org/10.1016/1359-8368(95)00002-X
[33] Cholker A, Tantray M. Strain and damage sensing property of self-compacting concrete reinforced with carbon fibers. International Journal of Engineering. 2019;32(11):1577-1583. https://doi.org/10.5829/ije.2019.32.11b.09