



Real-time Monitoring of Carbon Nanotube and Cement Sensor-based Smart Materials Application on Road Traffic Maintenance

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ABSTRACT

Nanomaterials have emerged as a transformative innovation in 21st-century construction technology, offering enhanced performance and sustainability in cement-based materials. Among them, carbon nanotubes (CNTs) have attracted significant attention due to their exceptional mechanical strength, electrical conductivity, and nanoscale reinforcement capability. This study investigates the mechanical and functional performance of CNT-reinforced cement composites prepared using a compaction-shear dispersion technique to ensure uniform fiber distribution.

The primary objective of this research is to evaluate the influence of varying percentages of carbon nanotubes on the mechanical properties and durability characteristics of cement composites. CNTs were incorporated at weight fractions of 0.51%, 0.84%, 1.68%, 3.36%, 5.05%, and 6.02% relative to cement content. The prepared composites were tested for compressive strength, tensile strength, flexural strength, and abrasion resistance to determine the optimum CNT dosage.

The strength test for the six different compositions was evaluated, and it was observed that 5.05% CNT (P5) is the optimized cement composite, where the compressive strength shows a 70.44% increase in percentage compared to the control. The split tensile strength shows a 72.39% increase.

The findings indicate that optimized CNT incorporation significantly improves mechanical performance while enabling self-sensing characteristics, contributing to sustainable and intelligent construction materials. This research provides a pathway for developing next-generation cement composites with enhanced durability, energy efficiency, and real-time monitoring capability.

Keywords: Carbon nano tube; Cement composite; Hydration; Road traffic maintenance; Road health assessment.

1. INTRODUCTION

The convergence of nanotechnology with civil engineering is redefining infrastructure by enhancing material performance, enabling intelligent monitoring, and promoting long-term sustainability through advanced nano-engineered solutions (Firoozi *et al.* 2025). As per industrial survey, research in the field of nanomaterials in civil infrastructure is still scattered. Most of the research has been narrowed to isolated experimental assessments with specific nanocomposite systems rather than integrated, large-scale applications (Sujitha *et al.* 2024; Goel *et al.* 2022). Nanomaterials such as nano-silica and nano-TiO₂ are widely used in transportation systems as a medium in cement composites that are responsible for the atomic-scale modifications of materials used. The nature of civil works

incorporated in this composition bears superior strength, durability, functionality, and environmental performance beyond conventional construction methods (Zhange *et al.* 2023).

Intelligent transportation systems are modern sensor-based detection technologies that comprise round-the-clock and 360-degree roadway monitoring systems. Advancements in this sector have encouraged the improvement of recognition through microwave radars, infrared sensors, and video picture processors. Limitations are due to their capital investment and the need for additional escalating structures, followed by time-consuming measurements (Bolshakov *et al.* 2017, Robert *et al.* 2019). In this investigation, we research self-detecting carbon nanotube (CNT)/concrete composites for traffic stream estimation by identifying the change in electrical resistance of the composite when

subjected to the pressure of a vehicle (Abeer, 2017; Drossel *et al.* 2018; Shashi *et al.* 2020). Being a basic aspect of the asphalt with solid mechanical quality, this new traffic sensor will give a few favourable circumstances over the inductive loop indicators, for example, simple installation and maintenance, long service life with low maintenance cost, wide identification region, and potential applications for, say something movement estimation (Sunjung *et al.* 2015, Shuaichao *et al.* 2020). The field of nanotechnology is quickly developing into a prolific and interdisciplinary research area from which new smart materials can be created (Giuseppe *et al.* 2011). Carbon nanotubes (CNTs) have been widely utilized for a variety of applications due to their magnificent physical properties (Mohamed *et al.* 2019; Josef *et al.* 2016). Table 1 and 2 highlights the importance of this work.

Table 1. Physicochemical and mechanical properties of carbon nanotubes

S. No.	Property	Value
1	Diameter	Inner 5-23, Outer 21-43 (nm)
2	Length	8-46 (μm)
3	Purity	>93%
4	Surface area	241-294 (m^2/g)
5	Density	2.21 (g/cm^3)
6	Agglomeration	181-449 (μm)
7	Young Modulus	>1 TPa
8	Tensile Strength	About 144 GPa
9	Apparent Density	46-144 kg/m^3
10	Thermal Conductivity	2999/W(mK)
11	Electrical Conductivity	Up to 10^7 (Ωm) ⁻¹
12	Electrical resistivity	0.05-0.16 (Ω/cm)
13	Weight Ash content	9-23 (%)

Table 2. Amount of CNT and cement-based composite weight percentage used by various researchers

Researcher	CNT/Cement (%) by Weight	Mix Ratio	Strength Increase (%)	
			Compressive	Flexural
(Xu <i>et al.</i> 2009)	0.02	Mortar	15.9	20.7
(Cwirzen <i>et al.</i> 2008)	0.04	Paste	-	10
(Xun and Eil, 2009)	0.1	Paste	7	-
(Li <i>et al.</i> 2005)	0.5	Mortar	19	25
(Nochaiya <i>et al.</i> 2008)	1	Paste	17	-

Designing the cement mix ratio with CNT and Cement weight percentage decides the efficiency of the sample. Table 2 displays different weight percentages of CNT and cement in the form of mortar or paste. In both cases, the variations in strength have been observed in terms of compressive strength and flexural strength.

Based on the above literature review, the objectives and methodologies are framed.

2. NATURE OF SMART MATERIALS

The nature of self-sensing composites and their classifications are displayed in Figure 1, in which the carbon nanofibers and carbon nanotubes are the predominant cement mixes. Simultaneously, the structure of carbon nano fibers is displayed in Figure 2.

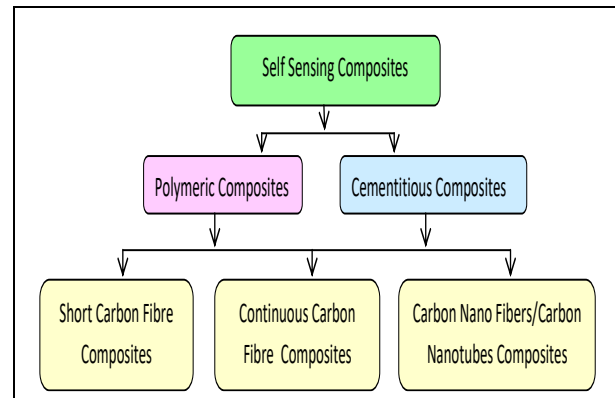


Fig. 1: Categorization of self-sensing composites

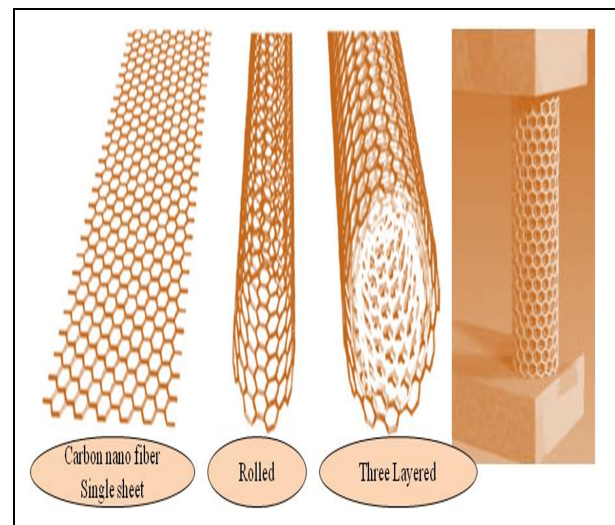


Fig. 2: Structure of carbon nanofiber

The structure of carbon nanofibres gives promising strength to the concrete, which incorporates all the mechanical properties. In cement composite applications, the properties of the carbon nanofibres show significant conductivity in both the thermal and electrical phases. It also has significant mechanical strength, including an elastic modulus of 590 GPa, tensile strength of 8.5 GPa, and also allows for the rate of change of chemical reaction.

3. METHODOLOGY

The carbon nanotube and cement mix ratio itself acts as a sensor using the piezoresistive principle.

Addition of carbon nanofiber in cement mix obviously limits the spread of microcracks. When this composite material shrinks or is damaged, naturally the contact between cement and fillers changes, which has an effect on electrical resistance. Using a resistivity meter, the stress, strain, crack, and damage are directly measured. In this research work, the experimentation is conducted by fixing the mix ratio as the primary task. The next part of the execution is focused on casting and curing. Further, with the samples, the traffic monitoring works are investigated. As per standard procedure, all experiments are conducted. The schematic diagram of the entire methodology is highlighted in Figure 3, where the consistency of the completed work has been explained in detail in the discussion part.

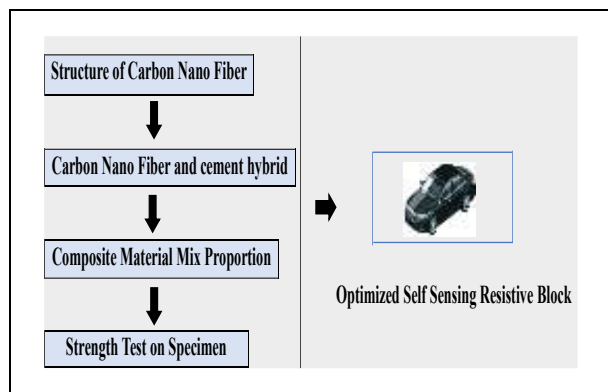


Fig 3: Schematic diagram of the methodology

The composition of carbon nanotube proportion used for this experimentation is prepared using a carbon nanofiber single sheet that has been arranged in a compressed mode that frames a strong layer. The layer of CNT is normally mixed with Cement particles in batch mode, which is further subjected to a cement-carbon nanofibre hybrid with a consistent curing period. A self-sensor to track location, weight, and speed of the vehicle has been incorporated in the model, after optimization of hybrid composite material identification.

Experimental procedure: The experimental procedure is carried forward in four stages: preparing the mix design, specimen preparation, curing, and testing. Mix design is prepared with ordinary Portland cement, water, large stone aggregate, carbon nanotube, carbon nanotube-to-cement ratio, and plasticizer. The details have been displayed in Table 3. The cement and carbon nanotube composite samples of various proportions are tabulated, and the prototypes have been named as 0.51 P1, 0.84 P2, 1.68 P3, 3.36 P4, 5.05 P5, and 6.02 P6. To minimize agglomeration, compaction is done on the sample, where plasticizer is used to improve workability.

Specimen Casting and Curing: The prepared mixes were cast in specimens of 150x150x150 mm in size, as the tolerance limit is 2 mm. To avoid air voids, proper compaction was performed. After casting, the specimens were demolded after 24 hours and subjected to water curing for 7, 14, and 28 days.

Table 3. Different proportions of composite material mix ratio fixation

Indication	Cement (kg)	Water (kg)	LSA (kg)	Aggregate (kg)	CNTs (g)	CNT/Cement (%)	Plasticizer (g)
Control	18	9.4	36	42	0	0	176
0.51% P1	18	9.4	36	42	10	0.51	176
0.84% P2	18	9.4	36	42	16	0.84	176
1.68% P3	18	9.4	36	42	32	1.68	176
3.36% P4	18	9.4	36	42	64	3.36	176
5.05% P5	18	9.4	36	42	96	5.05	176
6.02% P6	18	9.4	36	42	121	6.02	176

Testing equipment: The compressive strength test has to be evaluated using a calibrated Universal Testing Machine (UTM). The tensile strength has to be evaluated using a split tensile testing setup.

Experimental condition: All experimental conditions are carried out under ambient laboratory temperature, approximately 27°C. The Electrical Resistivity (Self-Sensing Test) is measured using a resistivity meter. The piezoresistive behavior is observed through electrical resistance before and during loading. The accuracy is maintained by balancing appropriate environmental conditions.

Sensing Performance Evaluation

The self-sensing capability of the composites was evaluated based on the change in electrical resistivity under applied load. The relationship is given by:

$$\text{Change in resistivity} = (pt - po) / po \quad \dots (1)$$

po = Initial resistivity (Before loading)

pt = Resistivity at time of loading

4. RESULTS AND DISCUSSION

The even dispersion of carbon nanofiber and concrete blend over a wide territory of the structures is shaped through van der Waals principles (Naqi *et al.* 2019). The capacity of carbon nanotubes and concrete is shown with an SEM picture in Figure 4. The schematic perspectives on concrete particles are envisioned as dispersed grains; furthermore, the particles were spread over a wide territory with the impact of carbon nanotubes. The mixture composite material developments are soaked by providing a satisfactory

concrete-to-water ratio that supports retention (Han *et al.* 2011).

Carbon nanotubes act as a crack bridging component, which normally contributes to the toughening mechanism. The microstructure faces uniform distribution of nanoparticles that eventually delivers efficient stress transfer. These parameters are monitored in each sample individually and are highlighted in Figure 4.

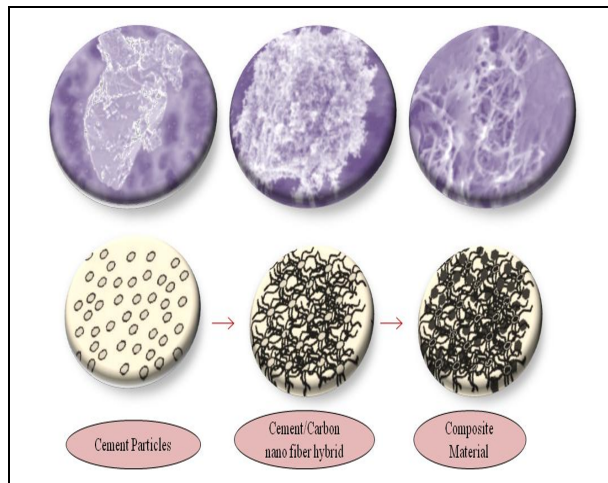


Fig. 4: Carbon nano fiber and cement hybrid

From the exploratory outcome, it is seen that the ideal measurement of carbon nanotube with concrete is 5.05 P5, with higher quality and strength. In Figure 5, the X-axis represents Control, 0.51 P1, 0.84 P2, 1.68 P3, 3.36 P4, 5.05 P5, and 6.02 P6 (CNT/Cement wt%), and the Y-axis represents compressive strength (MPa). For this situation, the chart speaks to the compressive strength of the cementitious materials compared to the control (Syed *et al.* 2017). Similarly, the composites show indications of around 40%, 67%, 60%, and 70% higher compressive strength at 3, 7, 14, and 28 days, which are displayed in Table 4.

From the observation, it is clear that the blend of CNT/Cement composite achieved significantly higher 28-day compressive strength, when compared with the control. This is because of the adjustment in concrete hydration properties related to carbon nanotubes (Catarina *et al.* 2019).

Figure 6 compares the outcome on split elasticity (MPa) in the Y pivot relating to (CNT/Cement wt %) in the X hub. For this situation, the split rigidity values range from 2 to 4 (MPa). Table 5 clarifies the rate of expansion related to control values, and the outcomes are higher for the 5.05 P5 proportion among the various proportions.

The strength of hybrid nano composite mixed with cement proportion shows significant improvement

in multiple interacting mechanisms. During the tensile loading conditions, the CNT acts as a crack-bridging medium and naturally enhances the strength. The highest split tensile strength is observed at 5.05 wt% (P5) CNT dosage. After this dosage, the 6.02% P6 loading shows a drop in performance, which is due to CNT agglomeration. This may be due to strong van der Waals attractions that naturally lead to weak interfacial zones that delay stress transfer. In this case, the maximum improvement attained at 5.05 wt% in a 3-day curing period shows 84.95%, 7 days is 86.26%, 14 days is 82.52%, and 72.39% in 28 days.

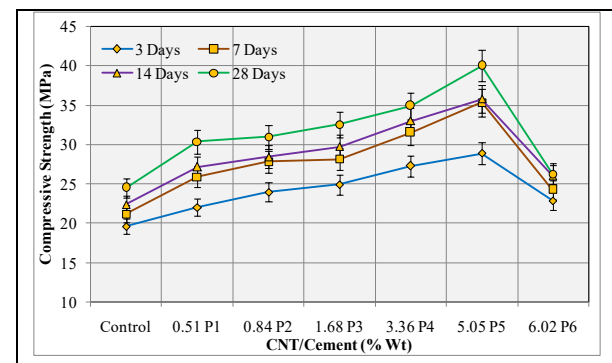


Fig. 5: Graphical representation of the impact of compressive strength on specimens

Table 4. Increase in percentage of compressive strength compared with control

Days	0.51 P1	0.84 P2	1.68 P3	3.36 P4	5.05 P5	6.02 P6
3	6.91	16.29	21.06	32.49	40.32	11.09
7	22.37	31.41	33.02	48.82	67.08	14.62
14	21.33	27.10	32.78	47.41	59.84	16.23
28	29.39	32.00	38.69	48.68	70.44	11.90

The rate increments in flexural qualities are displayed in Figure 7. The lower concentrated composites, 0.51 P1 and 0.84 P2, are better in flexural quality, while the higher amount shows reasonable difference. The blend ratio 5.05 P5 shows noticeable variation in performance, which suggests being the improved proportion (Annibale *et al.* 2013).

The applied stress was applied to the projected model as a compressive load at a frequency ranging from 0.2 to 0.6 Hz (Shilang *et al.* 2015). The model was tested for its detecting property using CNT/Cement weight rate proportions. Typically, damage in common development occurs through typhoon, tempest, and tremor, in which the effect is estimated in the range of 0 to 5.0 Hz (Sohel *et al.* 2016).

The variation in flexural strength with CNT dosage is presented in Figure 7. The results indicate that lower CNT concentrations (0.51% P1 and 0.84% P2)

provide moderate improvements over the control mix, while a substantial increase in flexural strength is observed with increasing CNT content up to the optimal level of 5.05 wt% (P5). Beyond this dosage, the improvement becomes less significant.

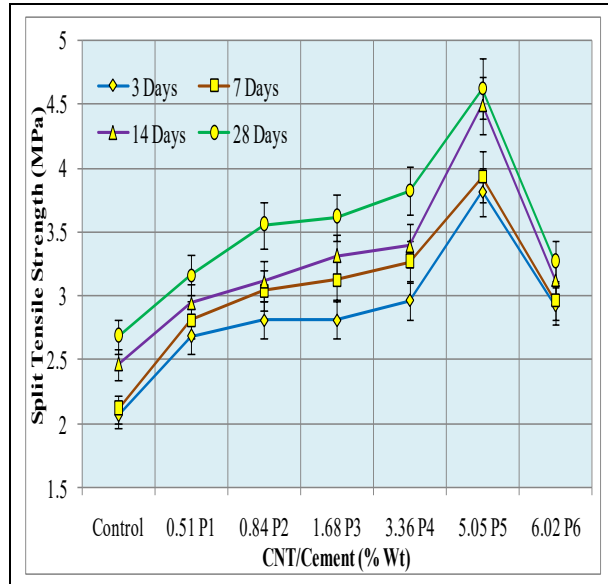


Fig. 6: Graphical representation of the effect of split tensile strength on specimens

Table 5. Increase in percentage of split tensile strength compared with control

Days	0.51 P1	0.84 P2	1.68 P3	3.36 P4	5.05 P5	6.02 P6
3	30.10	36.41	36.41	43.69	84.95	41.75
7	33.18	44.08	47.87	54.50	86.26	40.28
14	19.51	26.42	34.55	37.80	82.52	26.83
28	17.91	32.46	34.70	42.54	72.39	21.64

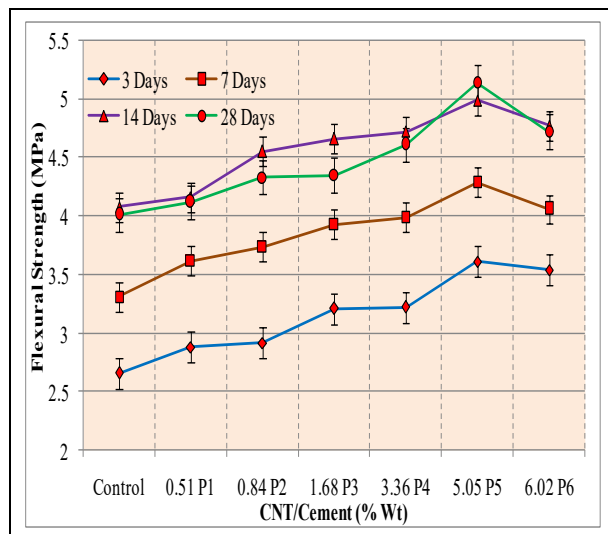


Fig. 7: Graphical representation of the impact of flexural strength on specimen

The enhancement in flexural strength is governed by several interacting mechanisms. Under flexural loading, tensile stresses dominate in the tension zone, making crack initiation and propagation the primary failure modes. CNTs act as effective crack-bridging elements, restricting crack opening and delaying crack propagation. In addition, CNTs promote crack deflection and branching, which increases the energy required for crack propagation. This mechanism enhances the fracture toughness of the composite and contributes to improved flexural performance. The superior performance of the 5.05 wt% (P5) mix confirms that this dosage achieves an optimal balance between dispersion and reinforcement efficiency.

In Figure 8, X hub is (CNT/Cement wt %), Y hub is voltage yield (V) on the right side and resistance on the left side. The diagram shows the voltage output from the composite with 12 MPa tensile loads (Andrea *et al.* 2018).

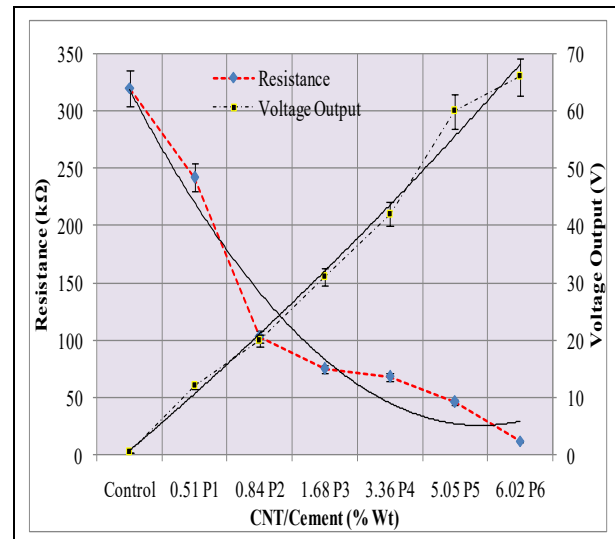


Fig. 8. Effect of resistance and voltage output on composite materials

Smart materials are artificial, manmade intelligent materials that are leading the world in almost all sectors. Effective utilization of nanomaterials is still motivated for application in the field of the construction industry. Electromagnetic protection dominates with the support of mechanical and chemical properties. Conductivity is developed with the support of CNT electrons; thereby, the electric percolation threshold is maintained for a successful conductive system. Concrete acts as a better sensor while facing stress and strain. The support of various concentrations of additives in the mix ratio makes the concrete a novel sensor as composite smart materials applied on the road surface. Applied external load varies with different frequencies that are captured as energy through components. In this case, the stress and strain stimulate the sensing property with respect to resistance in a short time frame. CNT &

Cement composites are used as a diagnostic material in assessing the flow of current that monitors the traffic flow. Commercial equipments is available to measure direct readings that are practiced in urban civil engineering applications.

Figure 9 features the electrical obstruction that is higher in the control test, with an increment in carbon nanotube blend rate, where the composite material detecting property shows reasonable abatement (Barani *et al.* 2020). In any case, when an external load is applied on the skin of the basic part with higher frequency, it stimulates the detecting property regarding resistance in a brief time frame.

Figure 9 describes the schematic view of the optimized proportion implemented on the road, as these composites can detect pressure modification utilizing voltage yield, which demonstrates that it is conceivable to utilize as sensors for diagnosing the road traffic for periodic support. The executions of carbon nanotubes in concrete composites typically has a reasonable electrical conductivity because of carbon fibers' properties. This acts as an embedded sensor that reveals the electrical resistivity if there is strain or damage among the fibers. Typically, this supports evaluation of damage to the structure. This is utilized as a diagnostic assessment for the wellbeing of real-time road traffic monitoring, which is financially utilized in metropolitan applications.

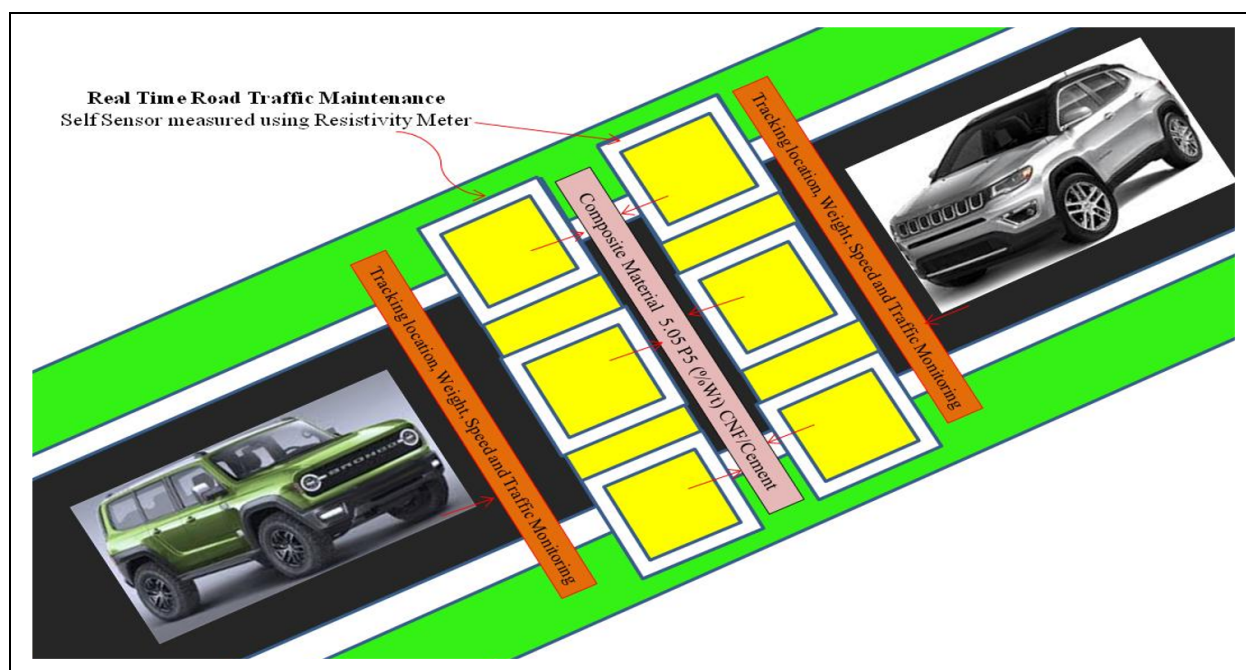


Fig. 9: Schematic view of real time road traffic maintenance using carbon nanofibers

The CNT and cement composite mix forms a smart bridging mechanism adopted in this experimentation process that works without external sensors. When mechanical stress is applied by vehicle load on the optimized dosage 5.05 wt% (P5) composite material, there is a change in electrical resistance, where the road itself becomes a sensor in real-time applications.

5. CONCLUSION

The created self-detecting CNT/concrete composite presents sensitive and stable reactions to repeated compressive loadings and dynamic loadings, and has surprising reactions to vehicular movements. These findings show that the self-detecting CNT/concrete composite has incredible potential for traffic monitoring use. As the cost of nanomaterials is decreasing, there comes the feasibility of utilizing it in large-scale applications. The optimization study predicts that the prototype with 5.05% CNT and a weight of

cement proves to be an effective combination for preparing a remote block for measuring resistivity.

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CONFLICTS OF INTEREST

The author declares that there is no conflict of interest.

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