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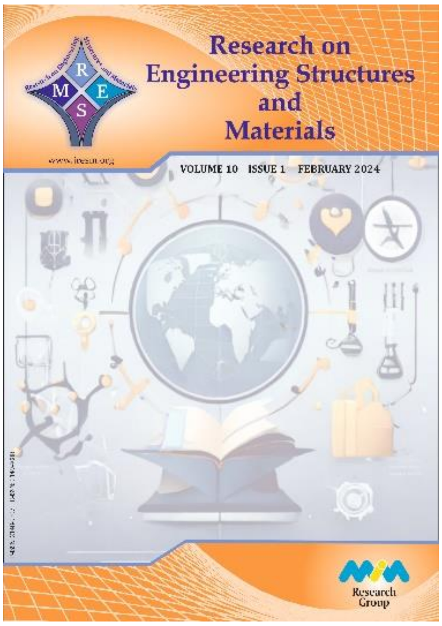

Electrical sensing properties of smart concrete enhanced with nano materials

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Review Article

Electrical sensing properties of smart concrete enhanced with nano materials

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Abstract

The structures have to be assessed for its failures caused by design and construction errors, material deterioration, adverse environment effect hence monitoring the structural health has shown to be a reliable method of assuring the structural integrity. The advanced development of sensor technology and sensing material are the most attractive parts of evaluating structural health. The change in stress, strain, crack formation, temperature variation is measured using fiber optic sensors, piezometers and other sensor types are often utilized in health monitoring systems. Sensors can degrade over time due to exposure to moisture, temperature fluctuations, wearing and tearing or physical impacts. Additionally, installing and maintaining sensors can be costly. These restrictions might be addressed by incorporating sensing technology, such as smart sensing concrete, into concrete structures. This paper explores the piezo resistive properties in concrete by introducing functional fillers like carbon fiber, carbon nano tubes, graphene materials to make electrically conductive concrete that are used to assess its own deformation. This technology could lead to more efficient maintenance and repair processes, ultimately increasing the lifespan of buildings and bridges reduces the wastage of resources leads to sustainability.

1. Introduction

Concrete is a prominent building material, and its performance becomes complex with the high-rise structures. However, the concrete constructions were prone to deformation due to harsh environmental conditions, improper design, materials deterioration, and lack of structural maintenance [1]. To keep structures from being harmed, frequent maintenance and ongoing observation are crucial by monitoring the structures to analyze, localize and damaging conditions are important aspect in structural health monitoring [2,3] which is usually done by visual inspection, Non-destructive testing and sensors. These techniques do have certain limitations for complex civil buildings, for instance, visual inspections are often subjective and may fail to detect inner damage, whereas other methods, like NDT, require specific equipment and skilled operators. Furthermore, the sensors used in conventional SHM systems may become less resilient with time, especially when exposed to unfavorable weather conditions. The requirement for routine maintenance and calibration of sensors may result in a rise in the overall cost and complexity of the monitoring system [5,6]and thus leads to the development of smart sensing concrete by inducing functional fillers were used to detect the variation in electrical resistivity of structures during damage or deformation. Electrical resistivity, the inverse of electrical conductivity, detects damage by measuring the change in stress and strain. Concrete with functional fillers such as 1.5 weight percent carbon fiber shows improved compressive strength of 33 MPa in addition with FCR 2.2% [8], the same proportion of carbon fiber in geopolymer concrete also shows sensing properties [7] hybrid combination of 0.4 weight percent carbon fiber 0.5 weight percent carbon

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nanotubes shows excellent electrical capabilities it creates significant negative potential shift caused by the applied electric current, steel rebars were protected effectively [9]. Concrete mixes containing 0.5% steel fibers lowers electrical resistance, with a gauge factor more than 20 times greater than that of typical strain gauges [10], then mortar with 5 % graphite powder shows 60% decrease in electrical resistivity during compression [11], under uniaxial compression, the electrical resistivity of nickel particles based mortar decreases by 62.61*% in the elastic regime [12] According to the filler concentration, functional fillers form a conductive network within the concrete [4,7] and transforming the concrete into a conductive material. Functional fillers can fill the micropores in the concrete matrix and improve the connection between individual particles. This allows concurrent monitoring of structural health through the detection of cracks and stresses, improving overall safety and longevity of the structure. Simultaneously, the addition of functional fillers in concrete also boosts up its mechanical properties like compressive strength, tensile strength and flexural strength [8-13] and makes the structure durable and resistant against environmental factors as compared with traditional sensors [6].

Sensing concrete plays an essential role in structural durability by investigating reinforcement corrosion [14]. Real-time monitoring of traffic patterns and structural integrity is made possible by this cutting-edge technology, which also provides important information for maintenance and safety enhancements [15]. Furthermore, by automatically recognizing and reacting to ice conditions, sensing concrete used in anti-icing applications reduces accidents and extend the life of the infrastructure [16]. As a result, sensing concrete is more consistent, efficient and cost effective as compared with traditional sensors.

2. Monitoring of Structures

In general, the planning of the urban infrastructure for a more effective and sustainable future is being completely transformed by the incorporation of cutting-edge materials and sensors into the concrete building process. Sensors are implanted in concrete during and after construction to monitor the health of buildings by collecting data from the sensors. [2]. The sensing methods in structures were indicated in table 1.

2.1. Electric Strain Gauge

Electrical resistance serves as the foundation for the operation of a strain gauge [17]. A material's electrical resistance varies as it expands or compresses. This characteristic is used by a strain gauge to quantify strain by identifying variations in resistance. The strain gauge will sense variations in strain during testing and adjust its electrical resistance accordingly. These variations in resistance cause a voltage differential, which the DAQ system subsequently records [18].

2.2. Accelerometers

Sensors that measure variation in velocity and it measures vibrations in variations of electrical resistance which is concurrently recorded in data logger [19].

2.3. Fiber Optic Sensors

Sensor that uses optical fiber to measure strain, temperature and pressure variations. Fiber Bragg Grating (FBG) sensors is the most commonly used fiber optic sensors. The grating is engraved in to the core of the optical fiber. The grating spacing varies in response to temperature variations or strain on the fiber, which modifies the reflected light's wavelength. The strain or temperature change can be ascertained by measuring this wavelength shift [20].

2.4. LVDT

Transducers that work on the principle of a transduction process are known as inductive transducers. A position sensor that can detect linear movements or vibrations and convert them into electrical signals or a pulsating electrical current is essentially what an LVDT is. The linear movement of the item to which it is linked is converted into a fluctuating electrical signal by the LVDT sensor [21].

2.5. Piezo Electric Sensors

Piezoelectric phenomena are caused by an electric dipole moment. When a piezoelectric material is exposed to an external stress or deformation in a particular direction, it produces electric polarization, which results in opposing bound charges on each side. After the external stress was removed, the polarization disappeared, resulting in the voltage differential. Piezoelectric sensors are widely used to detect dynamic pressure signals which is recorded in data logging system [22].

2.6. Acoustic Emission Sensors

AE sensors is a passive non-destructive testing technique that uses the high-frequency acoustic energy released by a stressed item, such as when corrosion products develop on a corroding rebar and push out onto the concrete around it. Subsequently, the data is recorded [23].

2.7. Eddy Current Sensors

ECT is an NDT technique, ECT probe is activated by an alternating current. The electrical current generates an alternating magnetic field in the area of the ECT probe, which oscillates at the same frequency. The eddy current distribution changes due to variations in the test object's electrical conductivity and magnetic permeability, as well as the existence of defects concurrently changes were recorded [24].

2.8. Electro Chemical Corrosion Sensors

Electrochemical analysis offers a real-time performance evaluation non-destructive estimation of rebar corrosion in existing concrete structures. The mechanism involves in this process is oxidation and reduction reaction [25].

2.9. Humidity Sensor

The term "humidity sensor" describes any apparatus or gadget that may transform humidity into an electrical signal that is simple to detect and records the moisture movement in cracks [26].

2.10. Vibrating Wire Sensors

VWS are widely employed to monitor the strain in structures The working principle of vibrating wire sensors rely on the measurement of the frequency changes of a wire which is placed on the support of the structure depending on the wire specification and the surrounding environment oscillation occurs which is recorded in a data monitoring system [27].

Table 1. Sensing methods and its parameters

Sensing methods	Materials	Measuring parameter	References
Intrinsic	Conductive fillers (carbon fibers, graphene, CNT, steel fibers)	Stress, strain, temperature, crack, moisture movement	[7-11]
Non intrinsic	Electric strain gauge	Strain	[17,18]
Non intrinsic	Accelerometers	Acceleration (to study dynamic behavior of structure)	[19]
Non intrinsic	Fiber optics	Strain, temperature and pressure variations	[20]
Non intrinsic	LVDT	Displacement	[21]
Non intrinsic	Piezo electric sensors	Stress, temperature, crack	[22]
Non intrinsic	Acoustic Emission sensors	Detects stress waves during crack propagation.	[23]
Non intrinsic	Eddy current sensors, crack sensor	Crack growth	[24]
Non intrinsic	Humidity sensors	Moisture content	[25]
Non intrinsic	Electro chemical corrosion sensors	Corrosion	[26]
Non intrinsic	Vibrating Wire sensors	strain	[27]

3. Evolution of Self-Sensing Concrete

The larger subject of smart materials and structures, which started to get substantial attention in the 1980s, is where the idea of self-sensing concrete first emerged. But there are a few significant turning points to track the precise evolution of self-sensing concrete as shown in Fig 1.

3.1. Early Ideas (1990s)

In the early 1990s, the concept of adding sensing capabilities to concrete structures was initially put out. Researchers started experimenting with strain and temperature monitoring using fiber optic sensors implanted in concrete [28]. These early attempts, albeit not specifically self-sensing concrete, set the stage for the eventual integration of sensing capabilities into concrete buildings.

3.2. Electrically Sensitive Concrete (Late 1990s to Early 2000s)

The creation of electrically conductive concrete was a key step toward complete self-sensing capabilities work on carbon fiber-reinforced cement-based composites with strain-sensing characteristics [29]. This study found that the electrical resistivity of these materials altered in response to applied stress, indicating a route to intrinsic sensing capabilities.

3.3. Piezoresistive Cement Sensors (Late 2000s)

Following on previous work with sensitive concrete, researchers created specialized compositions of cement-based composites with improved piezo resistivity. Han et al. (2015) investigated cement composites containing carbon nano tubes, which showed significant sensitivity to stress and strain. The creation of multifunctional self-sensing concrete, which is capable of monitoring several factors at once, has been the focus of recent advancements in this field [30]. A cement-based composite with enhanced mechanical properties and the ability to detect strain, cracks, and damage was created by many researchers by using various functional fillers such as carbon fiber, carbon nanotubes, steel fiber, graphene nano platelets [4-12]. The current paradigm in research is on the practical application of self-sensing concrete technology at a large scale in real-world structures.

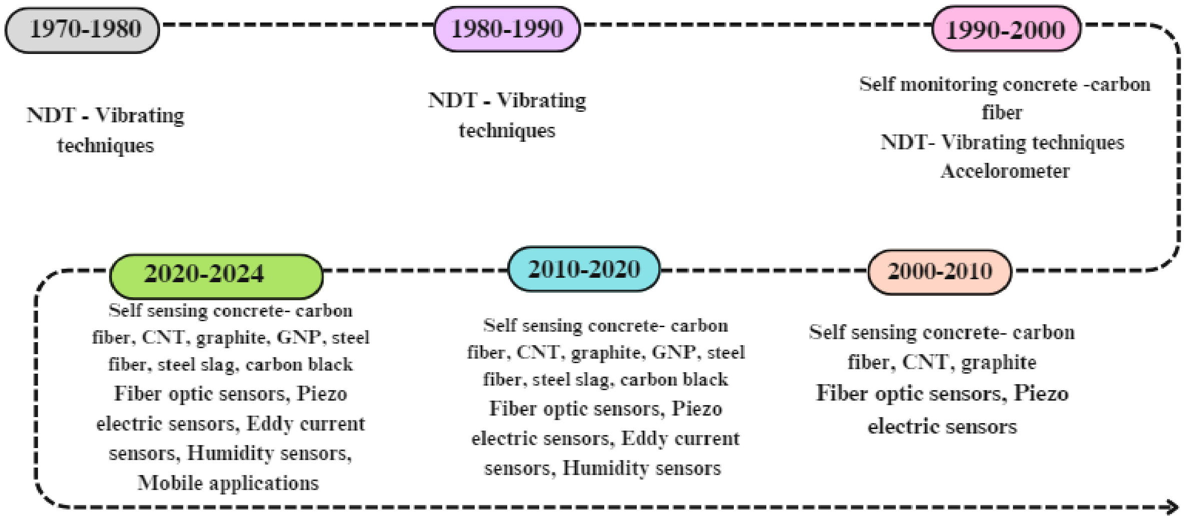

Fig. 1. Evolution of self-sensing concrete

4. Functional Fillers in Concrete

Functional fillers, like metallic fibers, carbon materials, graphene materials, metallic powder, and other conductive materials, that are typically utilized in electrically conductive concrete are indicated in table 2. Carbon black, the by-product of pulverization of waste tires and the amorphous form of carbon decreases the concrete resistivity concurrently increases the sensitivity of concrete [31]. Graphene materials such as graphite coated fibers, aggregates and graphene nano platelets are also proved effective conductive fillers for sensing concrete. The graphite nano platelets (GNP) diminish conductivity with 2.5%, later it enhances with 5% and 7.5% by weight of cement [32]. Graphene powder significantly enhances the conductivity of concrete, simultaneously decreases its workability and makes the mix harsher [11].

Steel slag, obtained from smelting of iron, in the iron industry increases compressive and split tensile strength it also enhances high conductivity in concrete with steel fibers through quantum tunneling. Its use contributes to reduce waste and lower the carbon impact of construction projects. Overall, integrating Steel slag in concrete mixes provide durable, robust, and cost-effective material in construction industry [33]. The short stainless-steel fiber improved electrical conductivity, flexural tension, and energy absorption capacity [10], whereas the inclusion of nano stainless-steel powder reduces dry shrinkage by 12.1% to 39.8% [34].

Table 2. Functional fillers in concrete

Constituents of filler	Functional fillers	Function of fillers	Cost Comparison
Carbon based fillers	Carbon fiber	Enhances electrical conductivity to monitor strain and improves tensile strength.	High
	Carbon nano tubes	Improves piezo resistive property and self-heating.	Very high
	Carbon black	Reduces resistivity, improves compressive strength.	Low
	Activated carbon	Reduces resistivity, improves compressive strength and reduces porosity.	Moderate
Graphene based fillers	Graphene nano platelets	Enhances compressive strength, and piezo resistivity to detect strain.	High
	Graphene powder	Improves piezo resistive property and improves mechanical strength.	High
Metallic based fillers	Steel fiber	Boost mechanical strength, crack-bridging, lowers resistivity.	Moderate
	Metallic powders such as ferric, copper and nickel powder.	Enhances electrical conductivity to monitor strain.	High
	Steel slag	Improves compressive strength and lowers resistivity.	Low
Other fillers	Piezoelectric ceramics (e.g., lead zirconate titanate)	Enhances electrical conductivity to monitor strain.	Very high

Carbon based nano materials like single-walled carbon nanotubes and multi-walled carbon nanotubes gives a higher conductivity channel for electron transport within the concrete and also provides excellent mechanical strength [9][39]. Other key materials employed in concrete sensing include carbon nanofibers, which provide excellent mechanical strength and micro fracture bridging and simultaneously lower the concrete resistivity by conductive channel formation via tunneling conduction [7]. Even in hostile environments, the carbon-based functional filler offers a stable conducting network and enhanced mechanical properties, whereas steel slag and steel fiber are frequently prone to corrosion [35]. Research shows that fibrous fillers provide more stable conductive network when compared with particle fillers subsequently in terms of scale micro-scale fillers easily forms conductive network compared with nano- scale fillers but at the same time nano- scale fillers provide broader conductive network at lower concentration [36].

Hybrid filler combination shows optimized performance and cost reduction for example using 0.5% weight of carbon black with 0.1% weight of carbon nano tubes shows excellent strain sensitivity of 107 when compared with carbon nano tubes of 67 [37]. Industrial by products can be used as a functional fillers like steel slag, copper slag, carbon black etc., which reduces the cost for example fine steel slag with steel fibers shows excellent compressive strength of 184 MPa with gauge factor 246.59 using the recycled by products as a functional filler reduces the harmful impact on environment [38]. The selection of functional fillers based on its aspect ratio, conductivity of the filler, cost, etc., for example carbon fiber is more effective in crack bridging simultaneously enhances the conducting pathways with comparatively low cost when compared with carbon nano tubes. Steel fiber and steel slag offers sensing characteristics and also prone to corrosion in harsh environmental conditions [35]. The criteria for selection of fillers are also based on surrounding environments it considerably affects the durability of sensing composites.

5. Dispersing Methods of Nano Particles

Dispersing the particles is necessary to establish the right conductive network in the concrete. Dispersing nanomaterials are either done by chemical or mechanical method. Dispersion of nanomaterials such as carbon nanotubes and nanocarbon fibers became problematic due to their large specific area and development of fiber aggregation due to Van der Waals force which is weak intermolecular forces due to attraction between molecules. Mechanical techniques include mechanical stirring, ball milling, and the sonication process [39]. as shown in Fig. 2. Surfactants typically utilized in chemical techniques included methyl cellulose, polycarboxylates, and lignosulphonates [40,42]. Recent research shows that fly ash and silica fume [40] are also utilized for dispersing the nano materials like carbon nano fiber because the size of silica fume are much smaller than cement which allows nano materials to fill the void between them and reduces the gap where nano materials tend to agglomerate [7].

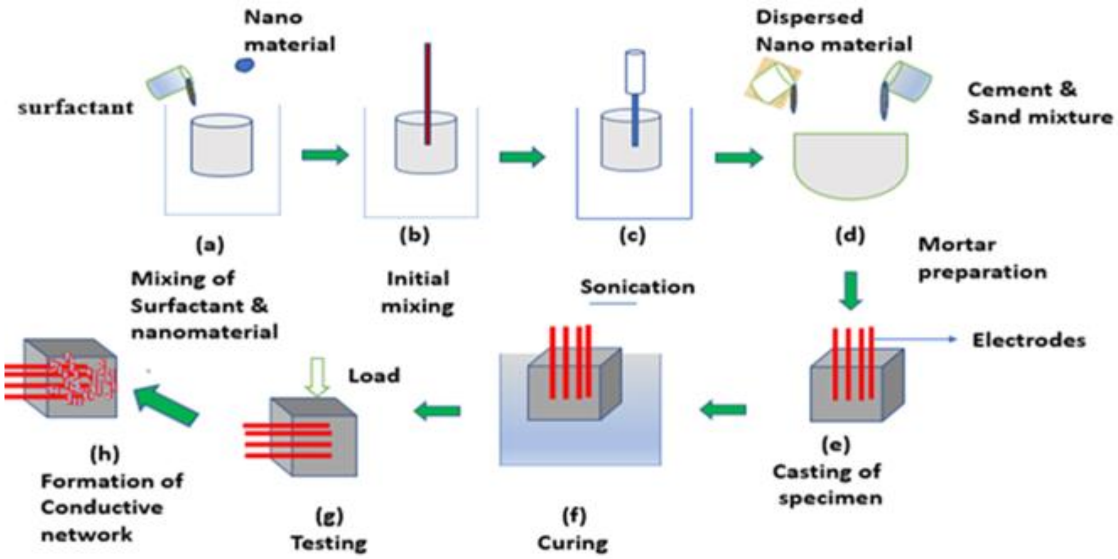

Fig. 2. Fabrication of sensing concrete

The dispersion of fiber is more effectively promoted via combined use of silica fume and methylcellulose than by using silica fume alone [3] [41]. To accomplish this dispersion, three major approaches have been developed; admixing, synchronous admixing, and later admixing [42] as shown in Fig. 3. The initial admixing technique is appropriate for fiber fillers, whereas the later admixing is appropriate for larger fillers. Hybrid mixtures of functional fillers are dispersed by synchronous admixing [12][30]. Research indicates that synchronous admixing is preferred to disperse carbon black and polyvinyl alcohol fiber to produce self-sensing concrete [42].

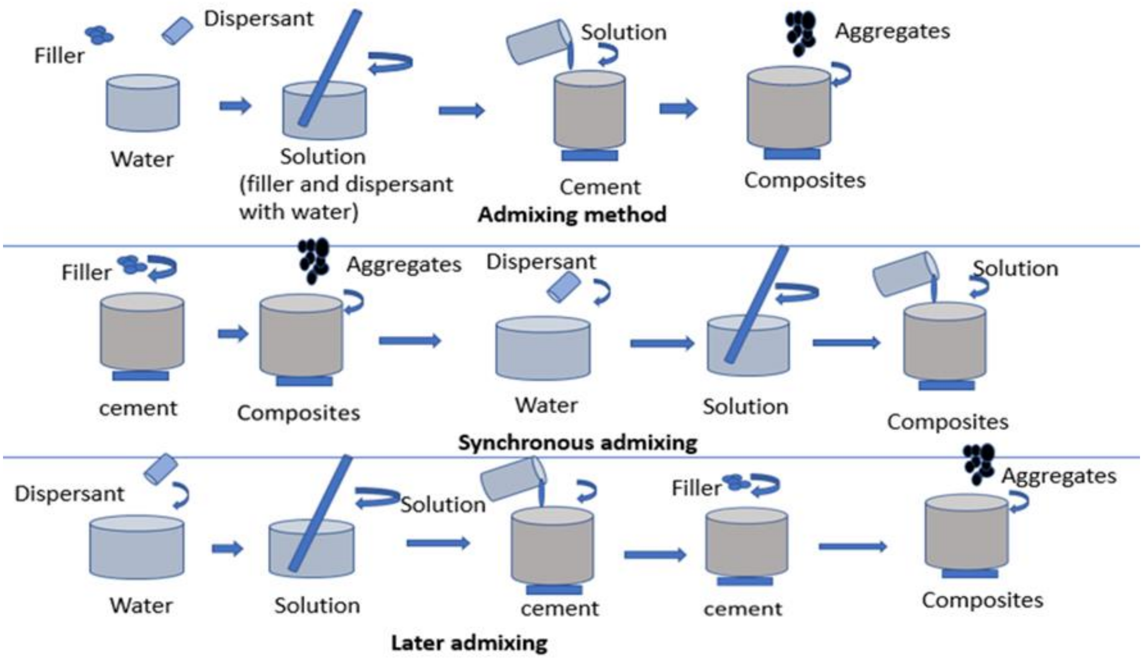

Fig. 3. Dispersion of nano materials

6. Principle

Electro mechanics is the theory that underlies the concrete's sensing mechanism, the study of electromechanics focuses on interaction between mechanical and electrical systems with one another which is based on the flow of electrons during mechanical loading [44]. According to Kousalya Ramachandran et al. (2022) the three elements of electromechanics are piezo-resistivity, piezo-permittivity, and piezo-electric functions [44]. In this case, piezo-resistivity is essential to the concrete sensing mechanism and is obtained by mixing conductive fillers into the concrete. The phrase "piezo-resistivity" refers to the variation in electrical resistivity; when the specimen is subjected to mechanical loading, stress or strain then it causes variation in resistivity here current and potential difference are important factors that influence the property. If the specimen is under the stress, then its geometry undergoes changes which leads to create the pathway between conductive fillers to allow the electron transfer allows the variation in resistivity then the strain is measured by change in resistivity which is given by

$$R = \rho \cdot L / A \tag{1}$$

R denotes the resistance of the specimen, ρ is the resistivity, L is the length and A is the cross-sectional area of the specimen [45]. "Piezo-permittivity" is the change in capacitance, is suitable for dielectric materials which is non conducting materials if is placed in electric field then polarization occurs it sense stress or strain in the materials due to change in properties of dielectric materials during loading it stores the electrical energy while unloading it releases the stored energy by measuring the capacitance the permittivity is calculated; frequency is a critical parameter that influences the property which is calculated by using this relation;

$$C = A\kappa\epsilon_0 / L \tag{2}$$

C denotes capacitance, ϵ_0 is free space permittivity 8.85 × 10^{-12} F/m, L is the length and A is the cross- sectional area of the specimen [46]. "Piezo-electricity" is the change in electric potential or charge when the material experiences an external stress causes internal atomic displacement; voltage is the main factor using this mechanism piezo electric sensors are used to measure integrity of structures [47].

7. Factors Influencing Sensing Mechanism

Siqi Ding et al. (2017) looked at the factors that influence the sensing process. The important parameter is pressure-sensitive qualities that include a range of metrics including signal-to-noise ratio, zero shifts, input and output range, and changes in electrical resistivity as a result of strain brought on by applying loads or deformation of the structures. One of the factors that influence the sensing mechanism was the optimization of functional fillers, its orientation and dispersion; if the right orientation and dispersion were not attained, the sensing mechanism would be affected [48,49]. The other crucial element is the concrete's ability to sense temperature as the concrete temperature rises, electrical resistance falls [31,42] because jumping of electrons across surfaces in the cement-based material causes resistivity to drop as temperature rises and also the movement of ions inside the matrix is high at high temperature this offers lower resistance and higher conductivity of the matrix [48]. Madhavi and Annamalai (2016) looked into concrete's electrical conductivity with saturated water content, fresh concrete functions as a semiconductor with an electrical resistance of 10^5 ohm, whereas hardened concrete functions as an insulator with an electrical resistance of 10^{12} ohm because well interconnected pores exhibit good ion mobility and water content act as a medium for movement of ions which is responsible for ionic conduction this increases the conductivity of concrete [50]. Tiny variations in the water content have a significant impact on the electrical conductivity or resistivity of the concrete because the passage of electrons is dependent on the mobility of ions in the water molecule [51,52]. The evaporable water in the concrete evaporates as it solidifies, causing a shift in the interconnectivity of the pores [30,42,44]. The curing phase is a crucial factor that influences conductivity. As the curing age increases, so does the hydration rate and product, resulting in a denser concrete member. The hydration product gets encased in the pores, restricting the creation of the conductive network [12,30]. The other important parameter to have an impact on the characteristics of concrete is the presence of corrosive substances in the environment causes ion permeation and lowers electrical resistivity, which in turn weakens concrete's sensing capabilities. The additional factors are voltage characteristics, frequency, and current between the electrodes influence the sensing mechanism [47]. Shape of the functional fillers like fibrous and flaky are more effective in forming conductive network when compared with particles like carbon black, activated charcoal. The filler structure has a considerable influence on percolation behavior as it influences a neighboring distance between them. It is possible to compute the spacing between neighboring spherical fillers d_s and fibrous filler d_f using [48];

$$d_s = a/2\,(4\Pi/3\Phi)^{1/3} \quad \text{and} \quad d_f = a/2\,(\Pi l/\Phi)^{1/3} \tag{3}$$

where a is diameter of filler and l is fiber length and Φ is filler concentration [48].

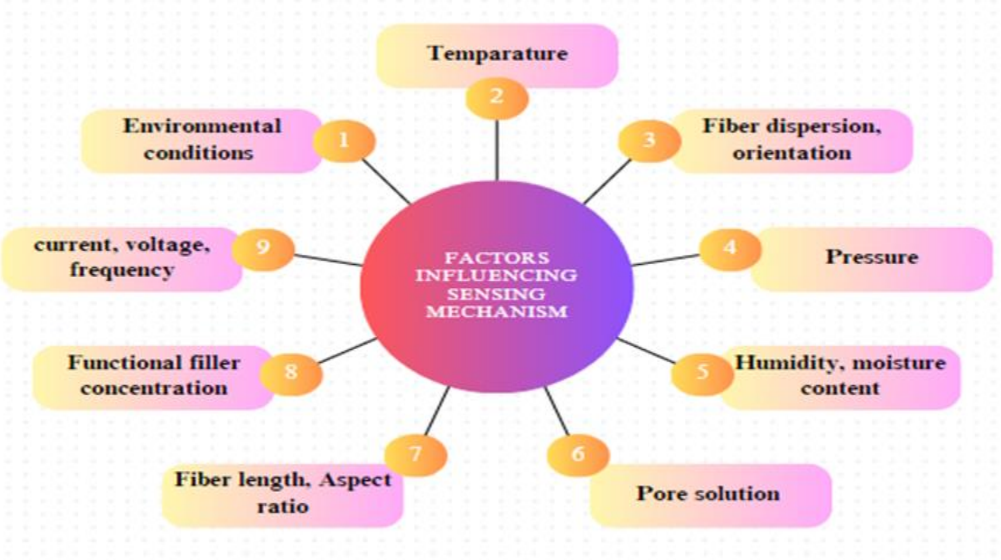

Fig. 4. Factors influencing sensing mechanism

8. Process of Conductive Mechanism

The technique by which concrete conducts electric impulses through them when the specimen or structure deforms is known as the conductive mechanism in concrete sensing. This allows the concrete specimen to sense signals during stress, strain, or any other deformation either by ionic conduction or tunneling conduction [53,54].

8.1. Ionic Conduction

The pore solution and dissolved particles in the concrete are the primary determinants of the ionic conduction of the material as shown in Fig. 5. Because the concrete conducts ions in response to external stimuli or environmental cues, it may detect deformation such as stress and strain in the concrete specimen and structure via conducting electrical impulses through linked capillary spaces [30,53].

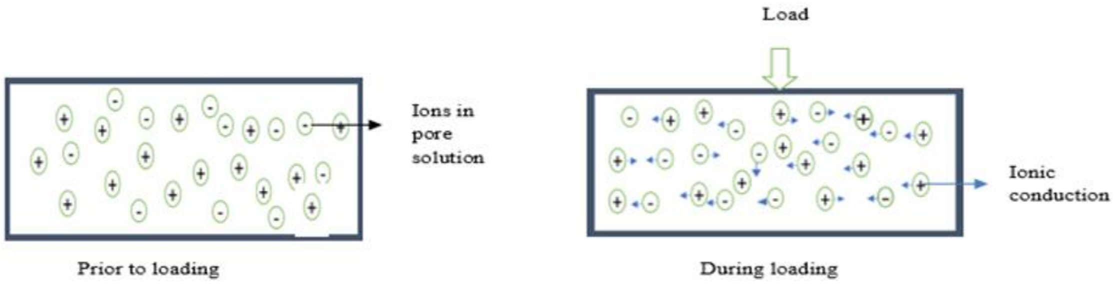

Fig. 5. Ionic conduction

8.2. Tunneling Conduction

This kind of conductive mechanism works by creating a strong electric field, which causes electrons to jump over barriers, conduct with nearby fibers, and create a conductive network as shown in Fig. 6. The electrons then conduct electricity and can detect deformation using an electromechanical method [33,54]. A key component of the concrete's capacity to recognize and react to environmental changes is tunneling conduction, which enables the tracking of stress and strain levels.

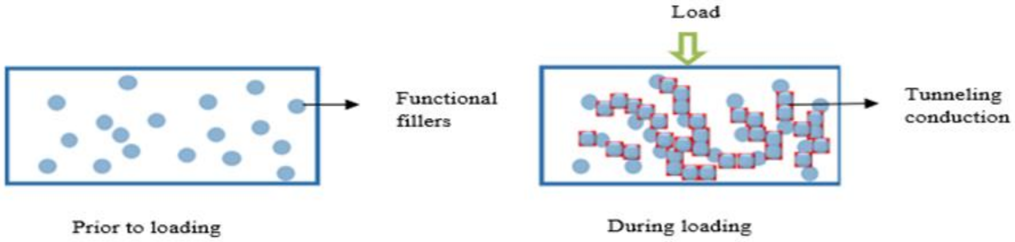

Fig. 6. Tunneling conduction

The smart concrete detect deformation through electrical impulses to its conductive network, which offers important information about the material's structural integrity [30,42]. Higher filler concentration form effective tunneling pathways for electron hoping across the barrier than lower filler concentration concurrently the uniform distribution of fillers should be ensured without agglomeration or cluster formation which affects the tunneling pathways and requires more energy for electrons to cross the barrier which leads to energy loss and limited the sensing mechanism [54]. The carbon fiber, CNT, steel fiber forms continuous network due to bridging up the gap between neighboring fillers and requires less energy for electron – hoping across the barrier [48].

Table 3. Comparison of ionic conduction and tunneling conduction

Characteristics	Ionic conduction	Tunneling conduction
Pore water	Pore water is essential, water act as medium for ions movement.	Pore water is not essential, electrons conduct the sensing mechanism
Filler concentration	Conduction is possible even at lower filler concentration	Conduction is not possible at lower concentration, because it forms weak conductive network between the neighboring fillers. At higher concentrations, the conductive network is strong, electrons cross the barriers to exhibit sensing properties.
Temperature	Temperature increases then the mobility of ions increases.	Energy of electrons is responsible for quantum tunneling, temperature is least effective in this mechanism

9. Percolation Threshold

The creation of conductive channels for physical characteristics of a heterogeneous composite is given by percolation theory [55]. A continuous network is expanded to the entire specimen as conductive particles come into touch with one another or the volume of the filler percentage exceeds a critical value or percolation threshold [11]. The conduction process follows three criteria based on the volume of functional fillers. Concrete's electrical resistance shifts from an insulating zone where functional filler concentration is lesser than the critical filler concentration significant electrical conduction is prevented in the absence of a well-connected network, while some electrons may tunnel through small gaps if particle's chance to be nearby. The point at which fillers starts to form a conductive network and provides pathway for electron movements by direct contact or tunneling conduction simultaneously there is sharp and sudden rise in electrical conductivity of the specimen when conductive filler concentration reaches the critical percolation threshold with the effective filler's dispersion without agglomeration [8,9,30,56]. After reaching the critical threshold the electrical conductivity of the specimen starts to gradual rise after that it starts to decline due to higher concentration of fillers paves a way for agglomeration [48].

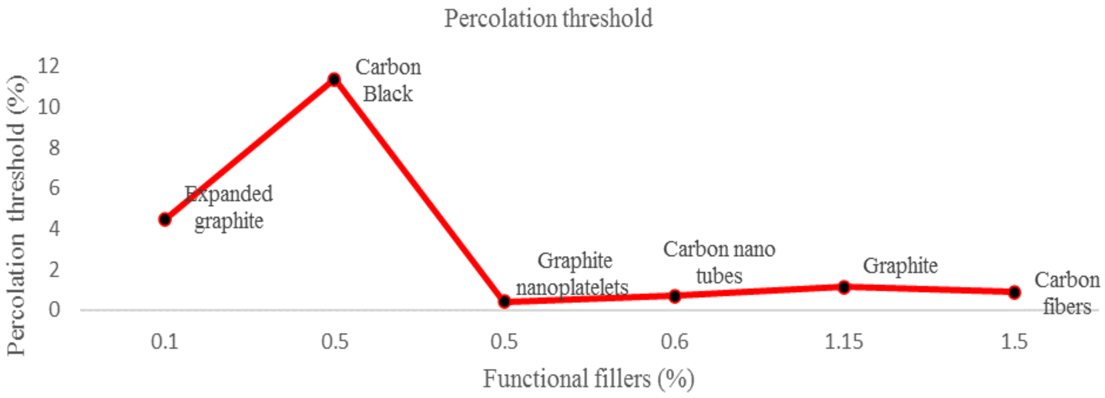

Fig. 7. Percolation threshold of various functional fillers [41]

The percolation value influenced by filler materials inter-particulate distance, large surface area and high aspect ratio particles [49,56]. The shape of fillers such as fibrous, flaky and tubes enhance electrical conductivity at lower percolation threshold as compared with spherical shape fillers. Micro and nano size filler particles like CNT have the potential to scatter more uniformly throughout the matrix and perhaps reduce the percolation threshold as compared to that of macro size fillers like steel slag, steel fiber. Dispersion of functional filler in the concrete matrix plays a critical role. If the fillers were evenly distributed, the sensing qualities produced by lower percolation threshold [41,48].

10. Methods of Measurement in Sensing Concrete

Electrical properties of the smart concrete are sensed either by two or four probe i.e., Wenner method as shown in Fig.8. This electrode configuration of the Wenner method produces a superior outcome as the contact resistance between the electrodes are minimized. The electrodes serve as a link between the composites and the assessing parameter [10,12,57]. Stable electrical conductivity and low electrical resistance are desirable qualities for an electrode. Electrodes made of metals like silver, aluminum, copper, and stainless steel could be formed into bars, metal foil, mesh, or any combination with the silver or copper conductive material [30,42]. Direct current (DC) and alternating current (AC) are the two current modes utilized to measure electrical behavior of the composite [7,8]. Although the direct current thought to be the easiest, the current has a limited range and may cause ions to migrate, which might cause electrical polarization in the composite. Electrical polarization makes it challenging to measure electrical resistance [58]. Initially it is subjected to DC voltage, which causes the polarization at the time of measurement [42]. Another work around for this problem is to use alternating current (AC); polarization occurs still, but it may be controlled by varying the range of frequency and voltage applied to the composite before loading to finish the polarization at the time of measurement by varying the AC voltage's frequency range and amplitude that gives the polarization process more control [10,58,59]. The AC can be transferred to the larger area as compared with DC with minimal loss of energy. DC current produces a constant, continuous flow of electrons in same direction hereby reduces fluctuations in resistivity whereas AC current does not produce the constant flow of electrons and it mainly depends on frequency by using AC current capacitance and inductance also measured unlike DC current where resistance only measured [57]. Polarization is high in DC current and used for static measurements while low in AC current and used for dynamic measurements [58,59].

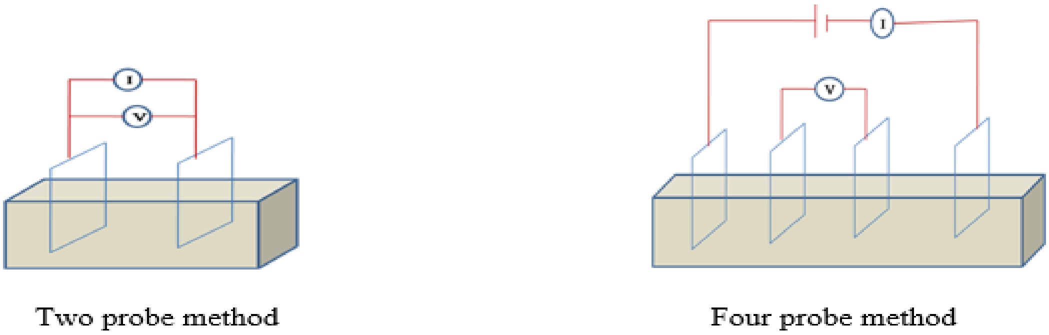

Fig. 8. Measurement of electrical parameter in smart concrete

11. Sensing Mechanism Under Various Loading

11.1. Loading Under Compression

During loading new cracks erupt due to stress and cracks expand under uniaxial compression. Functional fillers approach one another as a result of pressure compaction, strengthening the conductive network inside the sensing concrete this cycle repeats continuously. During loading the resistivity of sensing concrete decreases because spacing between the functional fillers is reduced which makes the flow of electrons to the nearby neighboring fillers became quite easy with well - established conductive network through various number of conducting pathways [60] while unloading it increases subsequently the conductive network is destroyed and then rebuilt as a result of new cracks sprouting. The conductive network breaks down when the fracture widens [12,42,61]. The initial resistivity and resistivity variation are recoverable within elastic region when the stress amplitude is below 30% [30].

11.2. Loading Under Tension

Tensile tension causes the concrete's electrical resistance to rise because it pulls apart the functional fillers within the concrete and thus increases the electrical resistance during loading and decreases while unloading [62,63] because tensile force pulls the fiber out from the matrix which disrupt the formation of conductive pathways [60]. The initial resistivity and resistivity variation are recoverable within elastic region if the amplitude of stress increases then the initial resistivity and resistivity variation are irrecoverable [42,63].

11.3. Loading Under Flexure

When a concrete beam bends, the top surface compresses and the bottom surface tenses. Flexural loading introduces compressive and tensile strains into the concrete; the compression side of the concrete beam electrical resistance is less, while the tension side electrical resistance is high [30, 61].

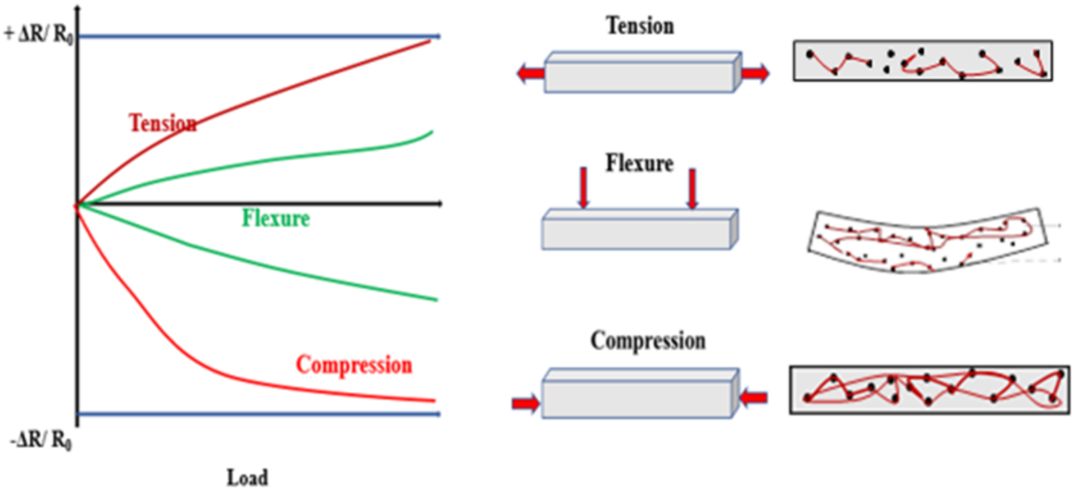

Fig. 9. Sensing mechanism under various loading

12. Piezo Resistive Sensing Mechanism

The resistivity change is influenced by the functional filler content inside the concrete matrix. The percolation phenomena are seen from the Fig. 10., and its existence is explained by varying functional filler concentrations [44]. Insulating zone, where resistivity is high, percolating zone, where resistivity drops suddenly, and conducting zone, where resistivity is low, make up the three sections of the curve [42]. Insulating zone is characterized by a filler concentration in the concrete matrix that is significantly less than the percolation threshold, large spacing between fillers, and sparse filler gathering [59].

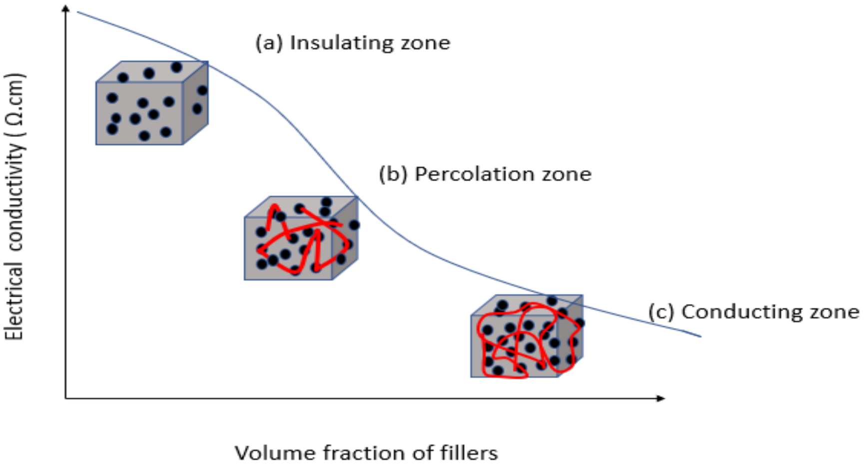

Fig. 10. Variation in Electrical conductivity

As a result, it is difficult for a conductive path to form and for electrons to move between fillers, and the composite exhibits nearly the same high resistivity as the matrix [10,12,30]. The percolation zone is distinguished by the filler content is around the percolation threshold then those fillers begin to build a conductive channel due to tunneling and ionic conduction subsequently reduces the distance between the fillers and thus sharply rises the conductivity of the composites [53,54]. The conducting zone is characterized by the filler content is above the percolation threshold and forms a well- established conductive network results in small increment in conductivity [30,42,44]. At the same time composites with a larger filler concentration did not exhibit the same sensing effect as the composites with comparatively lower filler concentration [73]. This might have happened because there was more tunneling barrier to alter during cyclic loading, but a high filler concentration could result in more conductive pathways, which would have prevented the network from growing further [9,10,55,57]. Therefore, a filler content that is either excess or insufficient could not result in piezoresistive performance.

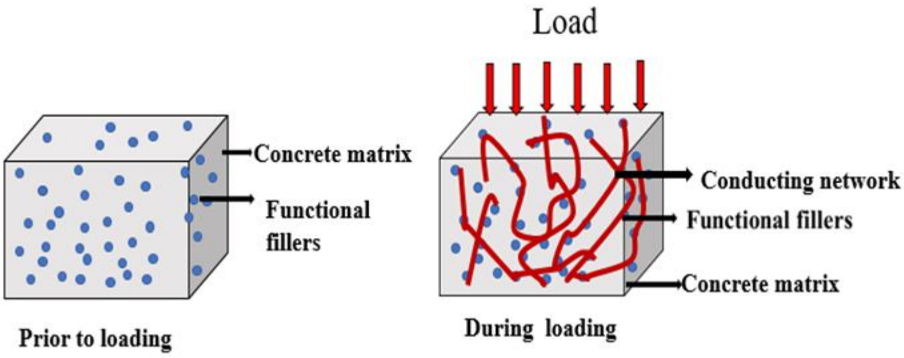

Fig. 11. Piezo resistive mechanism

12.1. Sensitivity Measurements

Sensing behavior is defined by sensitivity characteristics such as a fractional change in electrical resistivity ($\Delta R/R_0$), force sensitivity coefficient ($\Delta R/R_0$) / F, stress sensitivity coefficient ($\Delta R/R_0$) / σ [35]. By monitoring the passage of electrons between the electrodes at a constant voltage, the stress and strain under both dynamic and gradually changing loads were assessed with the electromechanical tests. The functional relation between axial strain (∈) and electrical resistance (ΔR) may be expressed as follows [52];

$$\Delta R/R_0 = k\epsilon \tag{4}$$

where ∈ is the axial strain, k is the gauge factor, and R_0 is the initial resistance. Polarization effects were responsible for the temporal drifts. The material's electrical properties are also crucial for determining sensing characteristics. Ohm's law determines electrical resistance [44];

$$V = IR \tag{5}$$

V is potential difference measured in volts (V), I is the current flow in the circuit measured in terms of ampere (A), whereas R is the electrical resistance measured in terms of ohms (Ω). The signal reception of sensing concrete has also been done recently using innovative methods as electrical capacitance tomography (ECT) [74], electrical impedance tomography (EIS) [75] and Electrical resistance tomography (ERT) [15]. More detailed information may be obtained using these new methods than with the conventional measurement techniques. For instance, the EIS approach may be applied to collect data concerning the microstructural features of the concrete and electrode-concrete interfacial zone [75], in addition to being employed as the sense the signal in concrete, EIT or ECT or ERT methods can picture the distribution of capacitance or impedance or resistance in two or three dimensions, defining the location, form, and degree of structural change of self-sensing concrete [15,74,75].

Table 4. Mechanical, Durable and FCR of various functional fillers

Fillers	Compressive strength (MPa)	Split tensile strength (MPa)	Flexural strength (MPa)	Durability (Water absorption)	FCR	Reference
Steel fiber	29.18	3.82	4.13	3.98%	0.194%	[65]
Steel slag	55.4	4.2	4-5	11.1%	0.198	[33,66]
Carbon fiber	48	5.8	12.1	3.9%	3.0%	[42,67]
CNT	72.1	7.21	10.5	1.565%	2.0%	[42,68]
Graphene	70-80	4-5	5-6	1.5-2%	2.2%	[42,69]
GNP	50-60	2.8	8-9	3-3.5%	2.5-3%	[42,70,71]

13. Applications

The smart sensing concrete provides various applications in various fields like traffic monitoring, smart bricks, anti- icing in pavements etc., as indicated in Table 3.

Table 5. Research area in sensing concrete

Research area	Materials	Characteristics	References
Anti -icing in pavements	Asphalt concrete with carbon fibers	Enhances electrical conductivity and improves self-heating in pavements.	[16,77]
Smart bricks	Clay with stainless steel fibers	Identify and localize earthquake-induced damage in masonry structures.	[78]
Traffic monitoring	Carbon nano tubes	The actual moments of vehicle flow monitoring with a low false-alarm rate and a high detection rate in concrete pavement technology.	[15,79]
Structural health monitoring	Graphene nanoplate (GNP) and Silicone hydrophobic powder (SHP)	Continuous monitoring of cracking, temperature fluctuations, load distribution, and moisture intrusion.	[80]
Corrosion monitoring	Carbon nanofibers (CNFs) and recycled Milled carbon fibers (rMCFs)	It detects changes in electrical conductivity, pH levels, or moisture content, which are indicators of corrosion activity.	[81]
Nuclear fuel storage	Carbon and polymeric fibers	To measure flow rate, temperature gradients, pressure levels.	[82]
Electromagnetic shielding	Carbon fibers	It reflects electromagnetic radiation, minimizing their penetration into concrete.	[83]

14. Conclusion

Self-sensing concrete has developed from a theoretical notion to a workable technology with promising applications. Concrete's sensing capabilities have been greatly improved by the use of nanoparticles, especially carbon-based additions. The technique shows variety of applications, including structural health monitoring for buildings and bridges, smart pavements, and nuclear power plant constructions. This adaptability highlights its potential to transform infrastructure management. Even yet, there are still a number of obstacles to overcome. These concerns include the necessity for standardized testing and assessment procedures, the integration of self-sensing systems into current infrastructures, and the long-term dependability and longevity of self-sensing materials. The creation of these standards is crucial for ensuring the dependability and longevity of smart concrete buildings and gives criteria to implement sensing concrete for widespread applications. Fabrication of sensing concrete is a time-consuming process due its prior dispersion of functional fillers in to the concrete. The dispersion of nano materials is problematic and tedious process it might be difficult to evenly distribute nanoparticles into concrete subsequently applications on a massive scale, standard methods like ultrasonication or the use of surfactants might not always be practicable or successful. Factors such as voltage, frequency, current flow, type of electrode and material of electrode, curing process, temperature influence the sensing characteristics it may results in data inaccuracy and it is challenging to record data under various environment conditions. The embedment of sensing concrete in the existing structures for monitoring damage detections became quite difficult. Cost of the functional fillers is high and cause economic barrier in cost effective projects yet the use of hybrid combinations of functional fillers enhances serviceability of the structures, concurrently replace and eliminates periodical maintenance of sensors minimizes the economic barrier as compared to that of conventional concrete. The integration of sensing concrete with robotic and Iot application could pave the way to avoid catastrophic failure and potential risk of the structures by improving efficiency and reducing human error paves the way for reducing the wastage of resources by increasing the life span of structures. The incorporation of sensing composites in concrete can be used to build more safer, more durable and more sustainable structures. Integrating data from different structures into larger urban management systems can enhance the resilience in earthquake-resistant structures, self-monitoring bridges, energy-efficient buildings or smart city infrastructures and general planning of cities. Future studies should concentrate on resolving these issues, enhancing the materials' sensitivity and accuracy, and investigating novel applications.

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