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Research article

# Behavioral assessment of intrinsically formed smart concrete using steel fibre and carbon black composite

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ABSTRACT

In recent years, health monitoring consists of the periodic observation and analysis of existing systems to predict and avoid structural breakdown, thereby saving lives and significantly lowering the cost of structural maintenance and repair. Normally, non-destructive testing techniques and sensor technology are used to detect damage in concrete structures are expensive in nature. Self-diagnosing or smart concrete has emerged a new paradigm in concrete research for damage detection. Smart concrete was cast by blending functional fillers such as carbon black, and steel fibers with concrete to improve the performance. Under various load conditions, the mechanical properties of the proposed smart concrete were examined. The electrical resistance of smart concrete was measured using the Four Probe Method and the Arduino UNO software. SEM and XRD were used to investigate the microstructures of intrinsically smart concrete. Thermogravimetric analysis was employed as a Non-Destructive Testing method to observe the hydration process. Furthermore, the obtained data were linked with the electrical resistivity of the smart concrete to assess corrosion damage. The electrical resistivity method is also an economical method and effective method to monitor the rate of corrosion.

## 1. Introduction

The service life and functional performance are the most important parameters for ensuring the long-term durability of concrete materials and structures. Some of the most important structures in the world are nuclear power plants, dams, bridges, high-rise skyscrapers, and power utilities. These structures disintegrate over time due to inherent weaknesses in concrete. Age of the materials, severe weather, heavy utilization, overloading, insufficient inspection, and lack of maintenance are all reasons that cause concrete structures to deteriorate and fail. Many concrete structures are in poor condition, and need a considerable effort to restore them to a useable and safe state. In order to monitor and evaluate the structures to assure their safety and durability, structural health monitoring has become one of the most important things. The continuous or frequent monitoring the condition of a structure or system using non-destructive testing methods is known as health monitoring. Self-diagnosis of smart concrete has emerged as a new topic in

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**Table 1**
Properties of cement.

| S. No. | Properties | Obtained Values | Standard Values | Reference |
|---|---|---|---|---|
| 1 | Specific gravity | 3.14 | 3.10–3.20 | (IS 1727:1967 (Reaffirmed 2004) |
| 2 | Standard consistency | 33% | 25–35% | (IS 4031 (part 4):1988 (Reaffirmed 1995) |
| 3 | Initial setting time | 28 min | >30 min | (IS 4031 (part 5):1998 (Reaffirmed 2005) |
| 4 | Final setting time | 470 min | <600 min | (IS 4031 (part 5):1998 (Reaffirmed 2005) |

concrete research in recent years. These smart materials have the potential to contribute in the development of intelligent infrastructure by sensing and health monitoring capabilities, hence increasing the life of concrete structures [1–3].

Cracks are one of the first signs for identifying deterioration in concrete structures. Sometimes the continued extension of cracks causes greater damage to the structure as well as the inhabitant. To stop the cracks, preventative measures must be taken by manually monitoring and assessing the kind, nature, and width of cracks is a time-consuming operation, and this approach is entirely dependent on knowledge and experience, which leads to an incorrect assessment of the structures. To prevent these problems, the manual method was substituted by automatic image deduction. Even with the improved technology, photographs taken for crack analysis using image processing technologies will have certain challenges.

Electrical resistance measurements are useful for self-sensing damage in carbon fiber polymer-matrix composites. Flexure, tension (particularly tension-tension fatigue), and impact all cause irreversible damage to the resistance. Concrete structural deterioration can be identified as delamination (which increases through thickness resistance) and fibre breaking (which increases longitudinal resistance) [4–6]. It is also established to create a material sensing and health monitoring system that is designed to examine several material parameters that are essential for evaluating concrete's durability performance.

This sensing system consists of three electrical conductivity-based sensors and a temperature sensor. A concrete conductivity (t) sensor monitors the concrete hardening process and the material's transport properties. Electrical resistance increases up to crack propagation and gradually decreases after crack formation. The resistance shift is irreversible once it reaches the inelastic stage. A four-probe technique was employed to measure the change in elastic resistance, which was found to be reversible for elastic deformation. Replacing carbon fiber (50%) with carbon black reduces costs while increasing workability while retaining electrical conductivity and electromagnetic interference shielding capabilities [7–9].

Smart concrete is created by combining conventional concrete with smart elements. Carbon black blended concrete has excellent stiffness, good tensile strength, low weight, great chemical resistance, high temperature tolerance, and little thermal expansion. Steel fiber is best recognized for its use in reinforcing composite materials [7–10].

Corrosion of steel reinforcing bars embedded in concrete structural members is a major concern in bridge and parking garage construction. Moisture and chloride penetration through fissures are the primary causes of corrosion in such concrete buildings. Electrical conductivity of concrete is regulated by chloride and moisture levels. Electrical resistivity is an important parameter for determining a material's capacity to conduct electric current. Dry cementitious materials have exceptionally high electrical resistance due to their insulating characteristics [10–12].

Electrochemical techniques, including as conductivity and resistivity measurements, have been used to examine changes in the pore solution and microstructure of cement-based materials [13–16]. The electrical conductivity increases dramatically when 0.5 percent CNT is introduced, and it is three orders of magnitude greater when 2.5 percent CNT is applied. At 0.4 and 0.45 w/c ratios, hardened concrete was evaluated for electrical resistivity, ultrasonic pulse velocity (UPV), and carbonation [17–19].

Latest researches reveal an extensive behavioral investigation of intrinsically produced smart concrete with the combination of steel fiber and carbon black, including assessments of its resilience, toughness, and self-detection capabilities. Strength and conductivity are two essential parameters important for naturally formed smart concrete. These observations have the potential to open up new choice for the development of creative applications of smart concrete. Intrinsically produced smart concrete, for instance, may be used to create self-healing structures, track damage, and possibly even generate electricity.

The novelty of present study is to focus the different effects of carbon black and steel fibre on the mechanical and electrical performance of hybrid materials which provide useful information for future study about sensitivity of self-sensing property and to optimize design of self-sensing of smart concrete with low cost and to get sustainable solutions. According to the available literature, the majority of studies focus on mechanical properties, only a few studies on durability for concrete substituted with carbon black and steel fibre. As a result, the authors can attempt has taken to measure corrosion using the electrical resistivity approach.

The primary objective of this research is to get the desired mechanical and electrical resistivity of intrinsically smart concrete using the Four Probe Method and the Arduino UNO software. To investigate the microstructural and structural properties of intrinsically smart concrete using SEM and XRD, as well as to assess the hydration process using Thermogravimetric analysis. Finally, damage assessment carried out by correlating electrical resistivity in the form of corrosion within the material.

## 2. Materials

Cement, fine aggregate, coarse aggregate, and water are the main ingredients of plain cement concrete. Fine and coarse aggregates account for around 75% of total concrete components. Cement fine aggregate, coarse aggregate, steel fibre, carbon black, water, and a super plasticizer are the major constituents of Intrinsically Smart Concrete (ISC) [20,21].

**Table 2**
Properties of fine aggregate.

| S.No. | Properties | Values |
|---|---|---|
| 1 | Specific gravity | 2.65 |
| 2 | Water absorption | 0.8% |
| 3 | Fineness modulus | 2.548 |
| 4 | Sieve analysis | Fine sand |

**Table 3**
Properties of coarse aggregate.

| S.No. | Properties | Values |
|---|---|---|
| 1 | Specific gravity | 2.66 |
| 2 | Impact value | 15.63% |
| 3 | Crushing value | 12.77% |
| 4 | Water absorption | 0.6% |
| 5 | Bulk density (Loose State) | 1450 kg/m$^3$ |
| 6 | Bulk density (Dense State) | 1620 kg/m$^3$ |

**Fig. 1.** Steel fibre.

**Table 4**
Properties of Steel fibre.

| S.No | Properties | Values |
|---|---|---|
| 1 | Diameter | 0.46 mm |
| 2 | Length | 35 mm |
| 3 | Aspect Ratio | 76.08 |
| 4 | Density | 7850 kg/m$^3$ |
| 5 | Tensile Strength | 400–1200 MPa |

**Table 5**
Properties of carbon black.

| S.No. | Properties | Values |
|---|---|---|
| 1 | Diameter | 120 nm |
| 2 | Bulk Density | 0.370 g/cm$^3$ |
| 3 | Density | 1.7–1.9 g/cm$^3$ |
| 4 | Specific Surface Area | 76 m$^2$/g |

**Table 6**
Properties of superplasticizer.

| Appearance | Yellowish green liquid |
|---|---|
| Specific gravity | @ 30 °C |
| Air entrainment | Typically less than 2% additional air is entrained at normal dosages. |
| Alkali content | Typically less than 72.0 g $Na_2O$ |

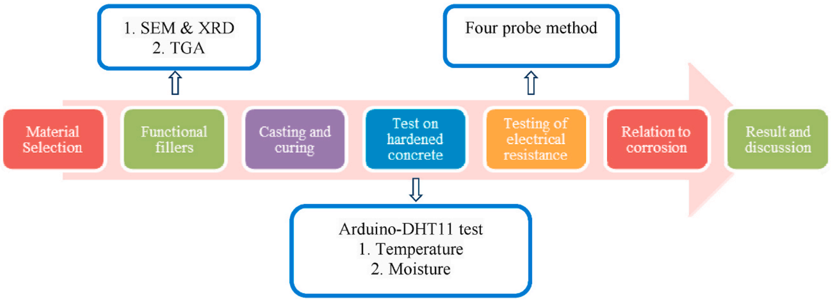


**Fig. 2.** Methodology.

**Table 7**
Mix proportion.

| Water/cement ratio | Water (lit) | Cement (kg/m$^3$) | Fine aggregate (kg/m$^3$) | Coarse aggregate (kg/m$^3$) |
|---|---|---|---|---|
| 0.35 | 155 | 442 | 725 | 1138 |
| Mix Ratio | | 1.0 | 1.64 | 2.57 |

**Table 8**
Details of test specimens (conventional concrete).

| S.No | Size of Specimen (mm) | Number of Specimen | | | Total |
|---|---|---|---|---|---|
| | | 3 days | 7 days | 28 days | |
| 1 | Cubes (100 × 100 × 100) | 3 | 3 | 3 | 9 |
| 2 | Cylinder (100 × 200) | 3 | 3 | 3 | 9 |

**Table 9**
Specimen details.

| S.No | Size of Specimen (mm) | Carbon Black (%) | Hybrid Material (CB + SF)in % | No. of Specimen | Total |
|---|---|---|---|---|---|
| 1 | Cube (100 × 100 x 100) | 0.5 | 0.5 + 0.4 | 6 | 36 |
| | | 1.0 | 1.0 + 0.4 | | |
| | | 1.5 | 1.5 + 0.4 | | |
| | | 2.0 | 2.0 + 0.4 | | |
| | | 2.5 | 2.5 + 0.4 | | |
| | | 3.0 | 3.0 + 0.4 | | |
| 2 | Cylinders (100 × 150) | 0.5 | 0.5 + 0.4 | 6 | 36 |
| | | 1.0 | 1.0 + 0.4 | | |
| | | 1.5 | 1.5 + 0.4 | | |
| | | 2.0 | 2.0 + 0.4 | | |
| | | 2.5 | 2.5 + 0.4 | | |
| | | 3.0 | 3.0 + 0.4 | | |

### *2.1. Cement*

Ordinary Portland cement (OPC) 53 grade is used in the study. The physical properties of cement were measured and listed in Table 1.

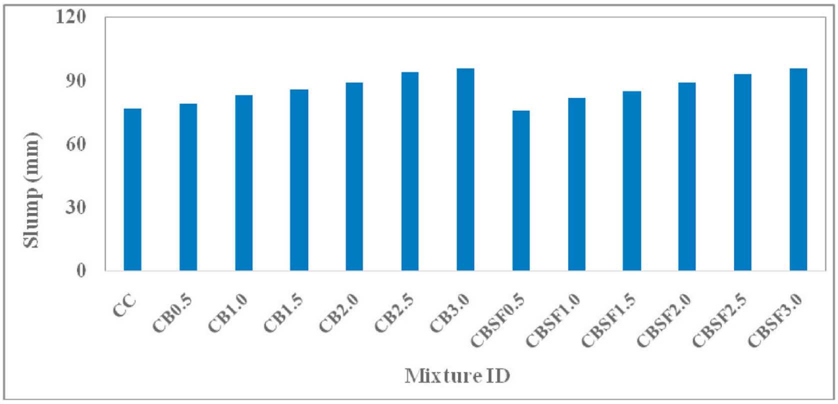


**Fig. 3.** Slump values.

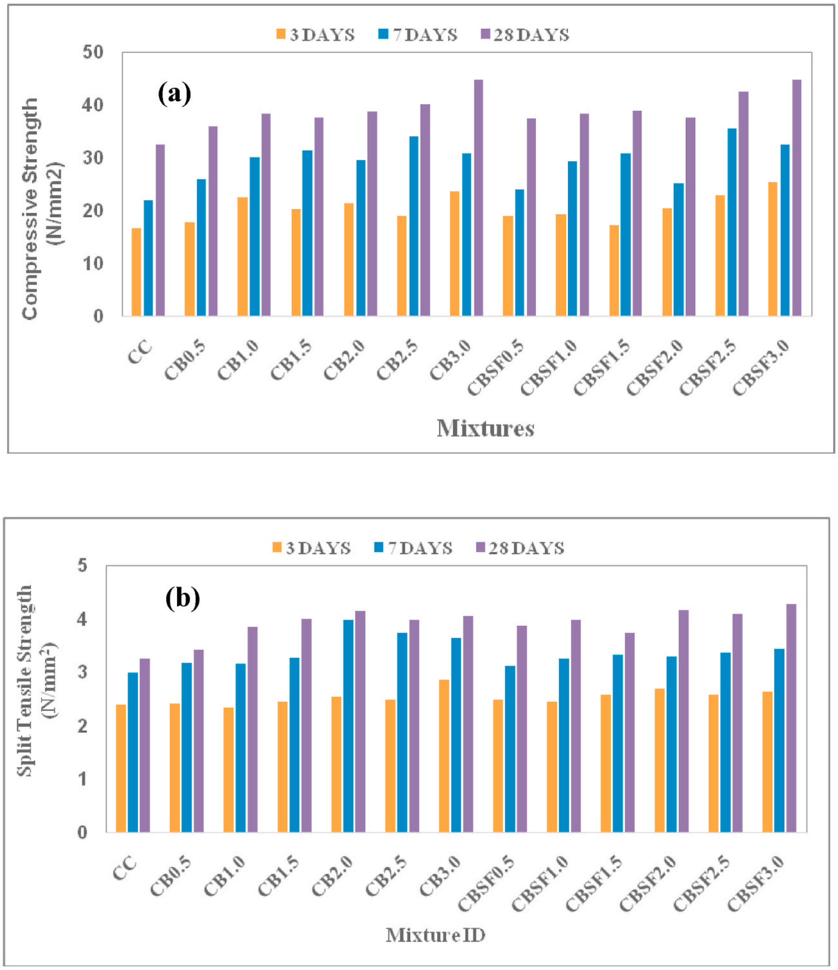


**Fig. 4.** (a) Compressive strength and (b) Split Tensile Strength of Concrete.

## *2.2. Fine aggregate*

Fine aggregates are materials that pass through an IS sieve with a mesh size of less than 4.75 mm. In this study, natural sand with 75 μm was kept on a filter was employed. The following tests are performed on fine aggregate in accordance with IS 2386 (PART 3)-1997 to determine its physical qualities, which are listed in Table 2.

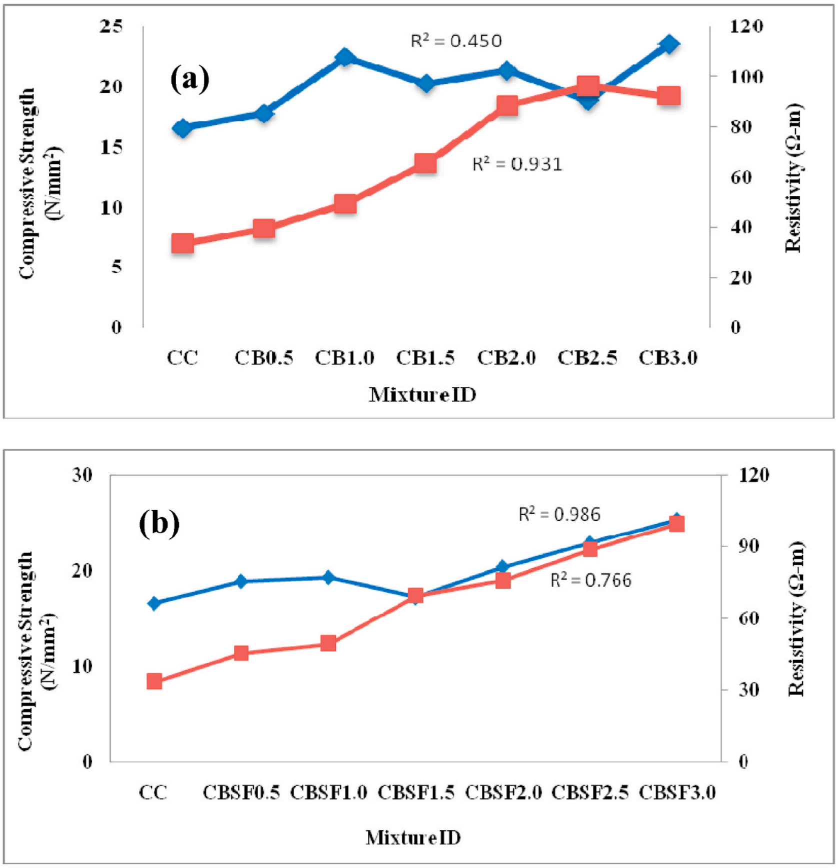


**Fig. 5.** Compressive Strength and Resistivity of concrete cube with (a) Carbon block and (b) Hybrid materials.

*2.3. Coarse aggregate*

Aggregates are chosen based on their size, texture, form, strength, moisture content grading, and other factors. In this study, natural aggregates that are passing through 12 mm sieve and were retained on a 4.75 mm sieve were employed. The following tests are performed on coarse aggregate in accordance with IS 2386 (PART 3):1997 to determine its physical qualities, which are listed in Table 3.

*2.4. Steel fibre*

A certain amount of steel fibre in concrete can create good changes in the physical properties of the concrete, considerably enhancing crushing resistance, impact, fatigue resistance and durability etc. Go Green Products in Chennai provided the crimped steel fibres. Steel fibres of the following specifications were used in this study, as indicated in Fig. 1. The physical properties are listed in Table 4.

*2.5. Carbon black*

Amorphous carbon in the form of carbon black has a high surface area to volume ratio. The average primary particle diameters of commercially manufactured carbon black range from 10 to 400 nm, while the average diameters of carbon black aggregates as a type of carbon material range from 100 to 800 nm. Light weight, chemical and thermal stability, permanent electrical conductivity, and low cost are all advantages of carbon black. The properties of Carbon black are included in Table 5.

*2.6. Superplasticizer*

Super plasticizer is a chemical admixture that allows 30% reduction in water content without sacrificing workability. Super plasticizer aids in the lowering of w/c ratio, increases concrete workability, and allows for the reduction of cement quantity consumption in the mix. In this experiment, FOSROC CONPLAST SP-430 superplasticizer was used and its properties are given in Table 6.

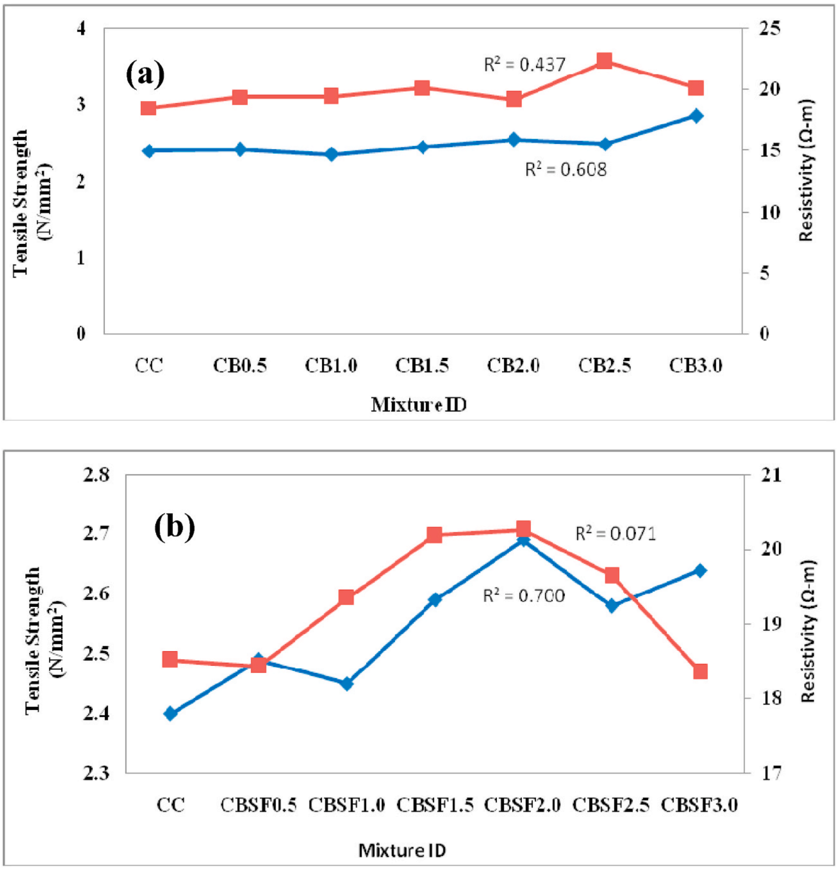


**Fig. 6.** Tensile Strength and Resistivity Vs of concrete cylinder with (a) carbon black and (b) hybrid material.

### *2.7. Water*

Water is an important component of concrete because it plays an active role in the chemical reactions that occur during hydration process. The strength of concrete achieved based on binding activity of hydrated cement paste. Because, water contributes to the strength of concrete, the quantity and quality of concrete should be constantly monitored. Excess water would generate cavities during hardening of concrete, so the amount of water delivered must satisfy the hydration process [22–25].

## 3. Methodology

The below mentioned methodology is followed in this present study as shown in Fig. 2.

### *3.1. Mix proportion and specimen details*

Six different M30 concrete mixes with varying concentrations of carbon black (0.5 percent to 3 percent at the interval of 0.5 percent) and steel Fibre (volume fractions of 0.4 percent) are used. Superplasticizer dosage is 1.2 percent is used. A Tables 7–9 shows the mix proportion and information about the specimens. The concrete specimen was prepared with right quantity of materials with water to cement ratio of 0.35 and cast specimens were allowed for 28 days normal water curing.

## 4. Result and discussion

### *4.1. Fresh concrete properties*

The workability of fresh concrete is determined by slump test, the result is shown Fig. 3.

From Fig. 3, it is observed that maximum slump value is obtained for CB3.0 and minimum for CBSF0.5. The workability increases with increase in carbon black addition up to its optimum percentage. The slump value recorded for the concrete mix shows the value between 50 and 90 mm which is typically used for reinforced concrete in practice. Carbon black added mix reveals high slump value

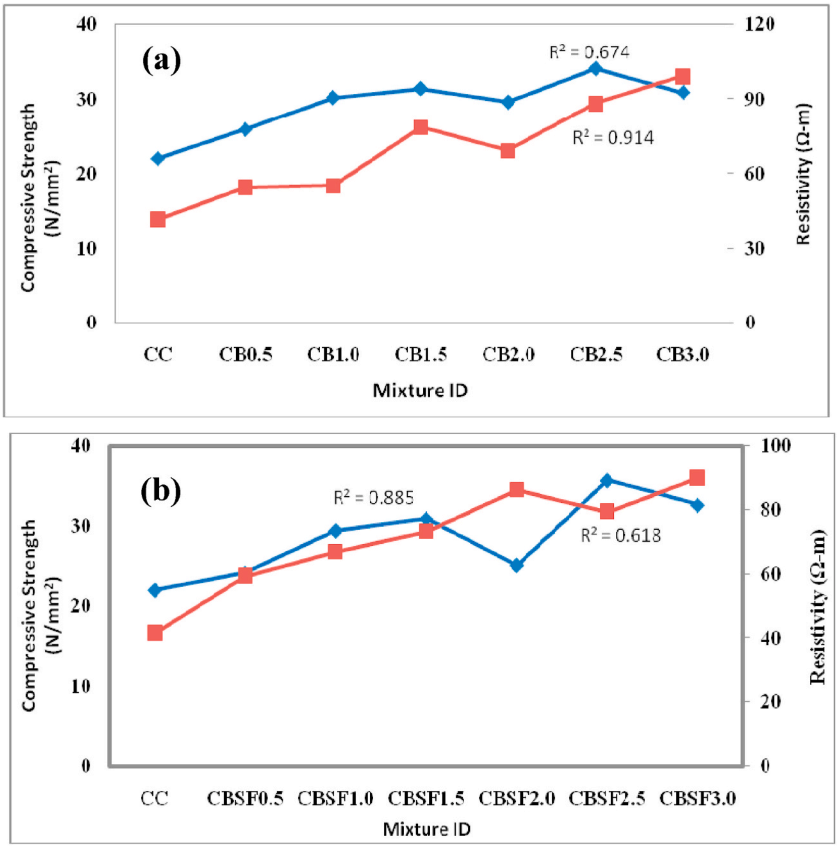


**Fig. 7.** Compressive Strength Vs Resistivity of concrete cube with (a) carbon black and (b) Hybrid materials.

since less friction among aggregate particles and reduction in total surface area. Thus more gel paste is available in the carbon black added mix increases the workability. The addition of steel fibre controls cracking due to plastic shrinkage and drying shrinkage and enhances additional energy absorption capability. Hence, the changes in the slump values are observed in this experimental work and compared with published data [26–29].

### *4.2. Hardened concrete properties*

The compressive strength was conducted as per IS 516–1959 and split tensile strength was conducted as per IS 5816–1999. Specimens are tested for 3, 7 and 28 days compressive strength in Compression Testing Machine (CTM). Compressive strength and Splitting tensile strength test are used to determine the strength of concrete as shown in Fig. 4a and b. From Fig. 4a, it is observed that the compressive strength of CBSF 3.0 mix is maximum in 3, 7 and 28 days whereas Controlled Concrete (CC) has the minimum strength compared to other mixes. While comparing CB and CBSF, CB has the maximum compressive strength with addition of carbon black. The addition of carbon black increases the corrosion rate of the concrete mix whereas; the addition of steel fibre has less influence on compressive strength gains at different time period. Carbon black is insoluble in water due to its fine grained structure; it has filling effect in concrete. It also reduces the requirements for binder in concrete due to the impact of changing with respect to percentage of addition [30,31].

From Fig. 4b, it is stated that the split tensile strength of CBSF3.0 is maximum in 3, 7 and 28 days whereas CC has the minimum strength compared to other mixes. While comparing CB and CBSF, CBSF mixes has the maximum tensile strength with addition of carbon black. The distribution and orientation of fibre influences the tensile strength, thus based on the orientation of the fibre variation in strength is obtained.

### *4.3. Relationship between strength and electrical resistivity*

#### *4.3.1. For 3 days*

The resistivity of CB2.5 is higher than other mixes whereas compressive strength is higher for CB3.0. CB3.0 has possessed favorable values on both compressive strength and resistivity in 3 days as show in Fig. 5a. The rate of strength of gain and resistivity of carbon black blended mix are not significantly relevant each other at 3 days. The resistivity value increases up to 2.5% addition of carbon

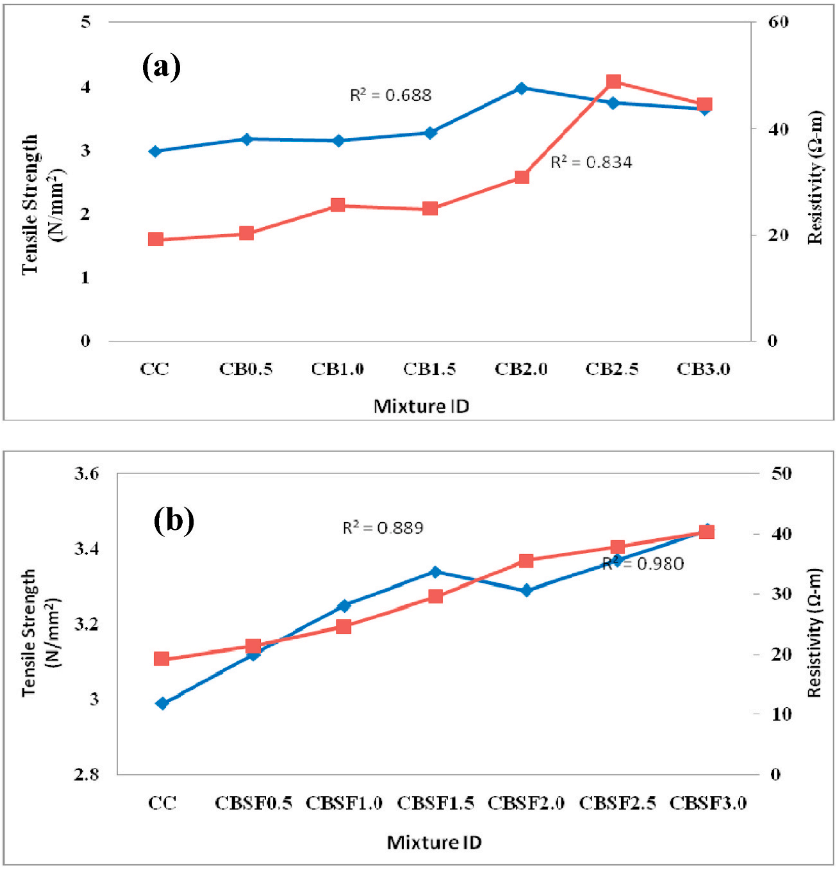


**Fig. 8.** Tensile Strength Vs Resistivity of concrete cylinder with (a) carbon black and (b) hybrid material.

black.

The resistivity of CBSF3.0 is higher than other mixes whereas compressive strength is higher for CBSF3.0. CBSF3.0 has possessed favorable values on both compressive strength and resistivity in 3 days as show in Fig. 5b. The electrical resistance capacity increases with increasing the addition of carbon black and steel fibre. The rate of resistivity value is low up to 1.5% of CBSF mix and then resistivity value increases at faster rate. The selection of mix is considered based on resistivity rather than strength value, since the functional performance of concrete is important criteria with moderate strength [32–34]. The orientation of fibre influences both strength and electrical resistivity and also the irregular distribution of fibres improve the resistivity values. The resistivity of CB2.5 is higher than other mixes whereas tensile strength is higher for CB3.0. CB3.0 has possessed favorable values on both tensile strength and resistivity in 3 days as show in Fig. 6a. The rate of tensile strength development and resistivity values mostly follow the same trend with addition of carbon black.

The resistivity of CBSF2.0 is higher than other mixes whereas tensile strength is higher for CBSF3.0. CBSF3.0 has possessed favorable values on both tensile strength and resistivity in 3 days as show in Fig. 6b. The rate of strength development and resistivity follow the same pattern from CBSF 0.5 mix to CBSF 2.5 mix.

### 4.3.2. *For 7 days*

The resistivity of CB 3.0% is higher than other mixes whereas compressive strength is higher for CB 2.5%. CB 2.5% has possessed favorable values on both compressive strength and resistivity in 7 days as show in Fig. 7a. The addition of carbon black gradually increases electrical resistivity value of concrete mix whereas the strength gain is increasing up to CB2.0 mix and then changes in different pattern.

The resistivity of CBSF3.0 is higher than other mixes whereas compressive strength is higher for CBSF2.5. CBSF3.0 has possessed favorable values on both compressive strength and resistivity in 7 days. From Fig. 7b, it is observed that there is no significant relevance between strength gain and resistivity value by addition of carbon black and steel fibre. The resistivity of CB2.5 is higher than other mixes whereas tensile strength is higher for CB 2.0. CB3.0 has possessed favorable values on both tensile strength and resistivity in 7 days as show in Fig. 8a. The tensile strength gain and resistivity value follow same trend up to CB2.0 mix.

The resistivity and tensile strength of CBSF3.0 is higher than other mixes which shows favorable values at 7 days as show in Fig. 8b. The consistent gradual variation in resistivity value is obtained in CBSF mixes, whereas tensile strength changing gradually up to CBSF

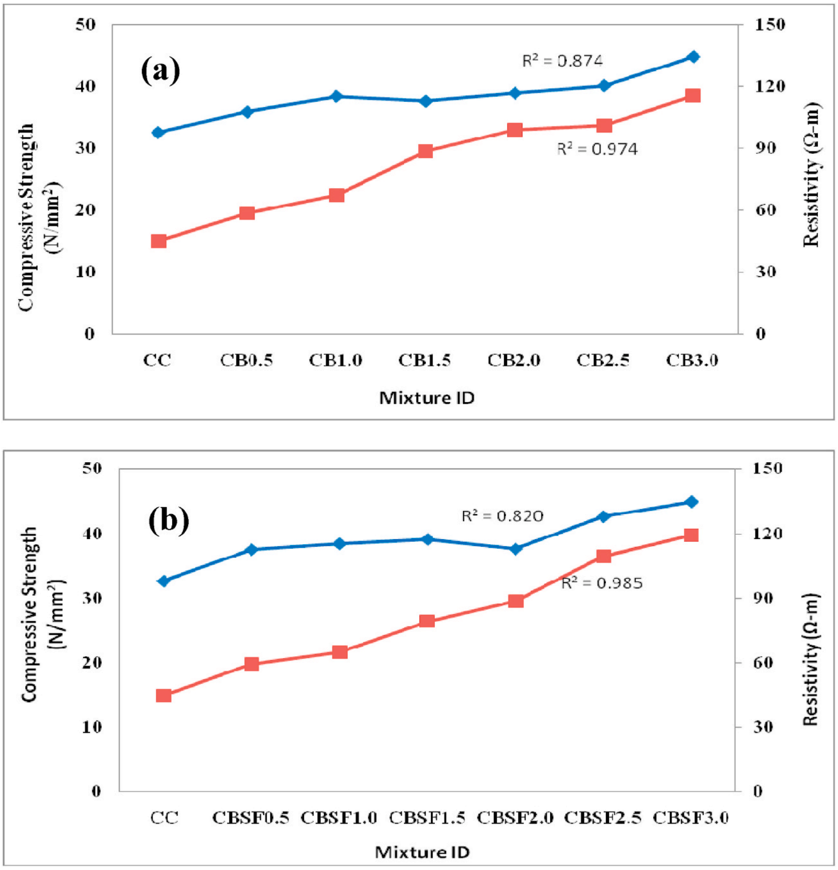


**Fig. 9.** Compressive Strength Vs Resistivity of concrete cube with (a) carbon black and (b) Hybrid materials.

1.5 mix and then a shift is taken in strength gain pattern [35–37]. The increase in addition of carbon black shows higher resistivity value at initial level between 3 days and 7 days and then reaches optimum level. The reason for this difference is mainly due to the special physical characteristics of carbon black, which possessed excellent water absorption ability.

#### *4.3.3. For 28 days*

The resistivity and compressive strength is higher for CB3.0 mix. CB 3.0 has possessed favorable values on both compressive strength and resistivity in 28 days as show in Fig. 9a. The resistivity and compressive strength of CBSF 3.0% is higher than other mixes. CBSF 3.0% has possessed favorable values on both compressive strength and resistivity in 28 days as show in Fig. 9b. Both strength gain and resistivity values follow same pattern for CB and CBSF mixes. The statistical significance value is 0.86 between compressive strength and resistivity for both CB and CBSF mixes.

The resistivity and tensile strength of CB3.0 is higher than other mixes. CB 3.0 has possessed favorable values on both tensile strength and resistivity in 28 days as show in Fig. 10a. Small changes occurred between tensile strength gain and resistivity value for CB mixes. The resistivity of CBSF 3.0 is higher than other mixes whereas tensile strength is higher for CBSF 3.0. CBSF 3.0 has possessed favorable values on both tensile strength and resistivity in 28 days as depicted in Fig. 10b. Tensile strength gain and resistivity values follow same pattern for CBSF mixes [37,38]. The strength and resistivity values of CB and SF blended mixes increasing with respect to curing age because the ions present in pore solution at earlier ages which influence the conductivity and at later stages hardened and dried conditions with pores delays conductivity hence improved resistivity value is obtained. The concrete matrix with carbon black acts as continuous for conductive path, whereas the carbon black and steel fibre combined mixture delays conductive paths, hence the resistivity is improved.

The addition of carbon black acts as effective functional filler, hence gradual increase in strength up to maximum level and then decreases due to negative filler effect. The strength variation by the addition of carbon black may be attributed to cohesion between cement matrix and carbon black agglomerations. In addition, cement particles encircled by high surface energy of carbon black might block hydration and generate gaps and cracks.

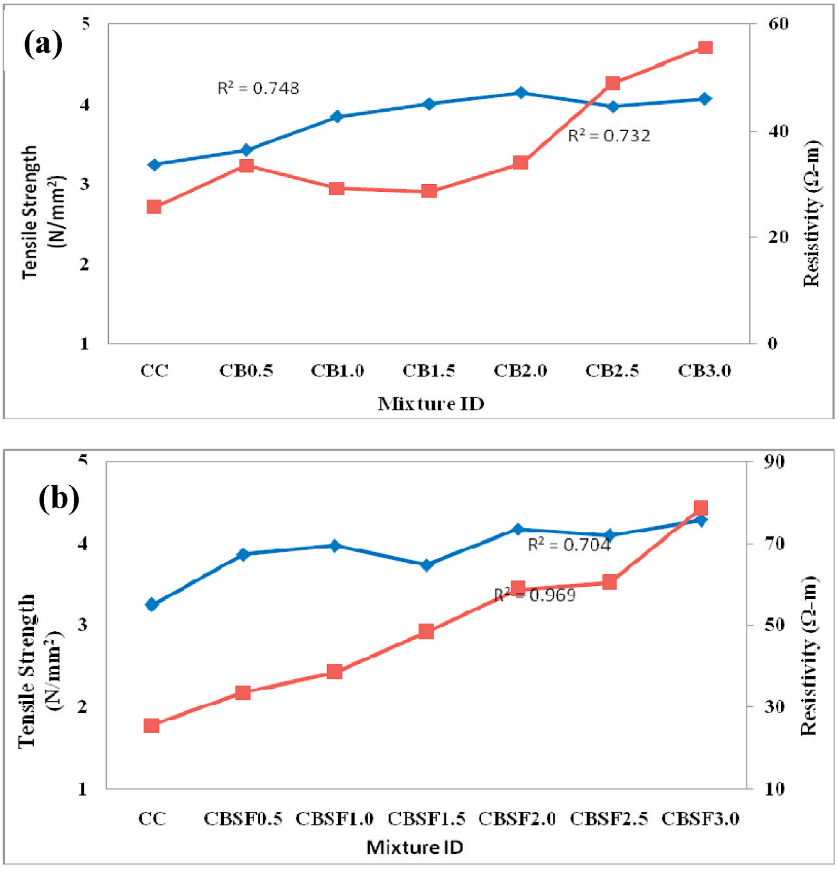


**Fig. 10.** Tensile Strength Vs Resistivity of concrete cylinder with (a) carbon black and (b) hybrid material.

### *4.4. Microstructure analysis*

Scanning Electron Microscopy (SEM) images of typical intrinsically smart concrete are shown in Fig. 11 a to c. The observed SEM images used to characterize the microscopic dispersion of carbon black, steel fibre and hybrid carbon black and steel fibre. Cluster of carbon black were identified with round particles of size more than 10 μm as shown in Fig. 11a. Cement concrete With steel fibre represents the discontinuity in between matrix as shown in Fig. 11c. The hybrid mixture shows the matrix bond of carbon black and steel fibre with cement matrix of size more than 100 μm.

The XRD results indicate very high baseline and peak intensity which confirms the existence of single graphite layers in carbon black sample. It is probable that carbon black is a homogenous mixture of particles which range from single graphite layers up to graphite crystals several layers thick as shown in Fig. 12. The intense small angle scattering is due to the difference between grain density and average density, caused by the loose packing of the extremely small grains. Based on the results, it's observed that carbon black influences changes in structural parameters.

Representative samples were examined by thermogravimetric analysis (TG/DTA). Carbon black powder was used as the reference material. The samples were dried at 105 °C in oven and cooled to room temperature before performing TG analysis. TG analysis results are shown in Fig. 13a and b [39,40].

The thermogravimetric analysis indicates the well dispersed curve which indicates the degree of reaction hydration process and the content of hydration products; hence the strength and resistivity properties were enhanced. The first lower peak addresses about the presence of free water, in between first and second peak reports dehydration phase and the remaining phase represents decarbonization phase.

### *4.5. Four probe method*

Four probe method is one of the standard and widely used method for the measurement of resistivity in structural health monitoring. A current is fed through the sample via the two outer electrodes embedded in concrete. It generates a voltage drop across the two electrodes, which is measured by a high impedance voltmeter. The maximum resistivity values of carbon block blended cubic and cylinder specimen with and without steel fibre measured with respect to different and addressed in Table 10. The maximum resistivity

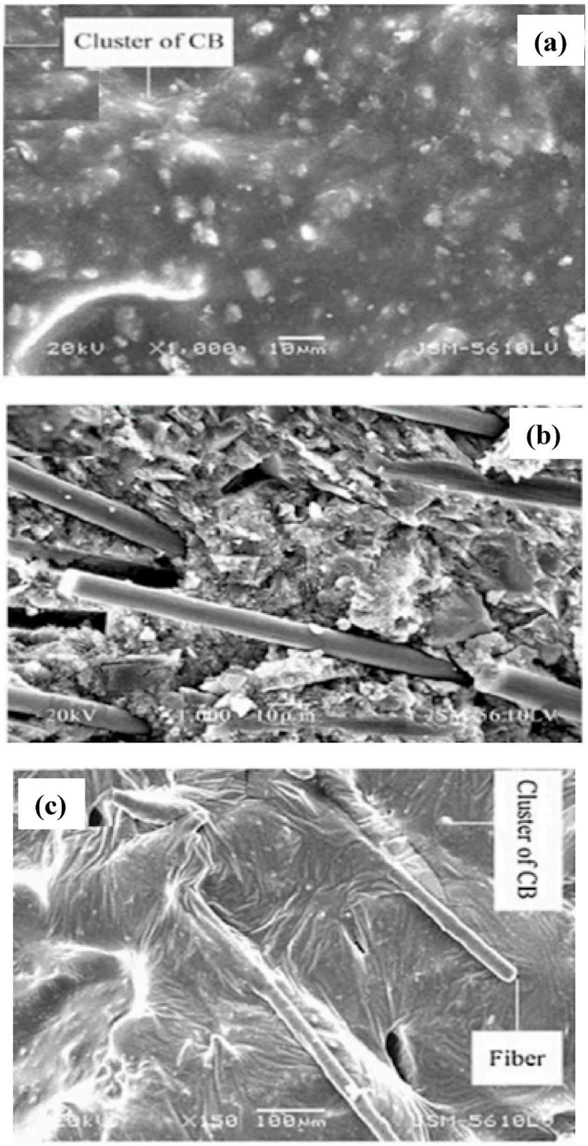


**Fig. 11.** Sem image of cement concrete with (a) carbon Black, (b) steel fibre and (c) hybrid carbon Black and steel fibre.

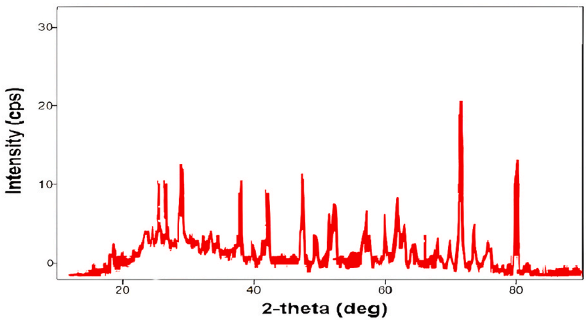


**Fig .12.** XRD spectra for Carbon Black Sample.

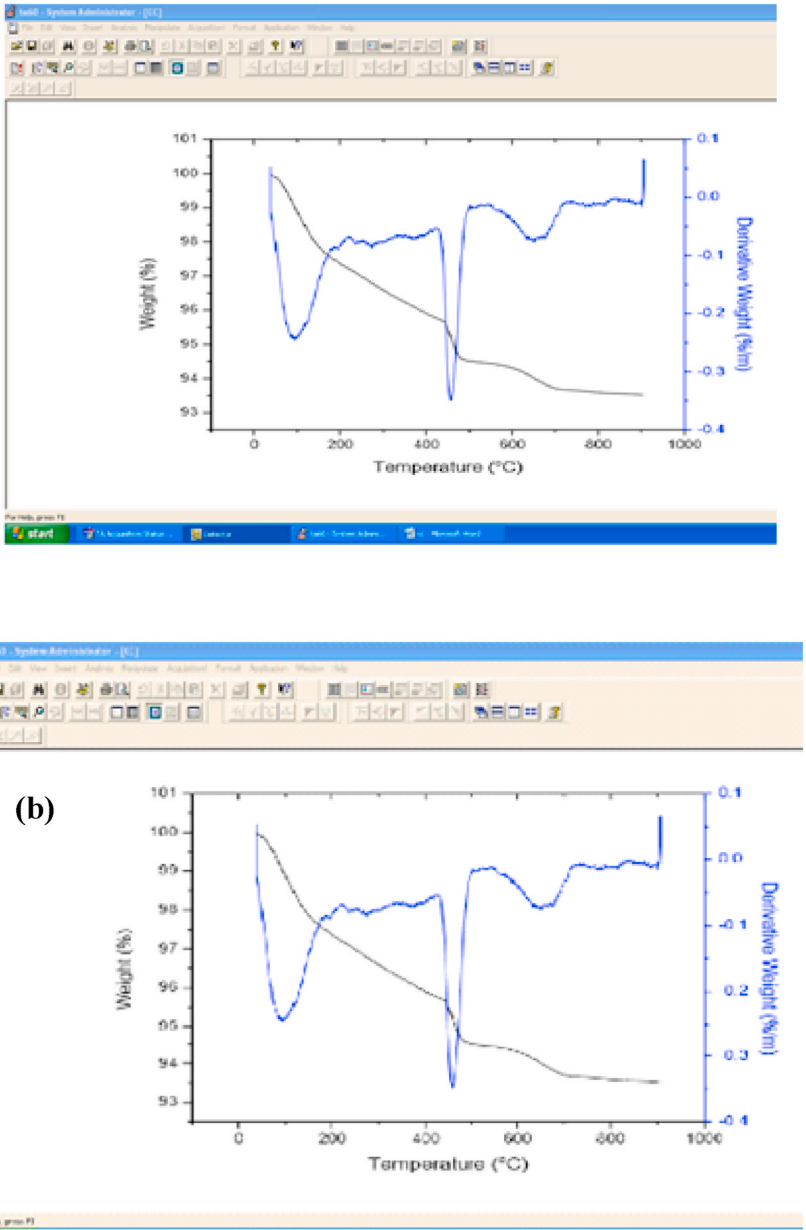


**Fig. 13.** TG analysis for (a) 7 and (b) 28 Days samples.

value of 99.65, 99.15 and 119.4 Ω-m are obtained for CBSF2.5, CB3.0 and CBSF3.0 mixes at 3, 7 and 28 days respectively.

CBSF2.5 mix possesses higher resistivity at 3 days and CB3 mix possesses higher resistivity at 7 days when compared to other mix compositions. High corrosion rate is possible for CBSF2.5 and CB3 mixes due to its resistivity value lies between 50 and 100 Ω-m according to ACI 222 guidelines. CBSF3 possess higher resistivity at 28 days when compared to other mix compositions. Low to moderate corrosion is possible for CBSF3 mix due to its resistivity value lie in between 100 and 200 Ω-m according to the guidelines of ACI 222 as presented in the same Table 10.

### 4.6. Arduino UNO interface DHT11

The Arduino UNO consists of analog input pins which can read the signal from an analog sensor like the humidity sensor or temperature sensor and convert it into a digital value that can be read by the microprocessor. It is a low-cost, flexible, and easy-to-use programmable open-source microcontroller board that can be interfaced with other Arduino boards. CBSF1.0 and CB1.5 mixes possess higher resistivity value of 27.458 Ω-m at low temperature for 3 days and 7 days respectively than other mix compositions. CBSF0.5 has

**Table 10**
Resistivity relation to corrosion for cubes and cylinders by Four Probe Method.

| Cubes | | | | |
|---|---|---|---|---|
| Days | Higher Resistivity (ρ) | | Corrosion rate | ACI 222 Guidelines |
| | Mix ID | Values (Ω-m) | | |
| 3 | CBSF2.5 | 99.65 | High | 50–100 Ω-m |
| 7 | CB3.0 | 99.15 | | |
| 28 | CBSF3.0 | 119.4 | Low to Moderate | 100–200 Ω-m |
| Cylinders | | | | |
| 3 | CB2.5 | 22.35 | Very high | <50 Ω-m |
| 7 | | 48.96 | | |
| 28 | CBSF3.0 | 78.63 | High | 50–100 Ω-m |

CB2.5 possesses higher resistivity at 3 days and 7 days than other mix compositions. Corrosion rate is very high for CB2.5 mix due to its resistivity value of 22.35 Ω-m is < 50 Ω-m ACI 222 guidelines. CBSF3 possesses higher resistivity at 28 days than other mix compositions. Corrosion rate is high for CBSF3 mix due to its resistivity value of 78.63 Ω-m is lie in between 50 and 100 Ω-m according to the ACI 222 guidelines [39,40]. There is no significant variation in resistivity value between the different curing ages of concrete cube specimens, whereas the significant variation is obtained between cube and cylinder specimens. The percentage of variation in resistivity value of cylinder specimen between 3 days and 7 days is 54% and between 7 days and 28 days is 38%. In this method of measurement of resistivity, surface area is directly correlated and contact distance between electrodes is indirectly correlated. Hence, the cube specimens showed higher resistivity values than cylindrical specimens.

**Table 11**
Resistivity relation to corrosion for cubes and cylinders by Arduino UNO.

| Cubes | | | | | |
|---|---|---|---|---|---|
| Days | Resistivity (ρ) | | Temperature °C | Corrosion rate | ACI 222 Guidelines |
| | Mix ID | Values Ω-m | | | |
| 3 | CBSF1.0 | 27.458 | 25 | High | <50 Ω-m |
| 7 | CB1.5 | 26.064 | 26 | | |
| 28 | CBSF0.5 | | | | |
| Cylinders | | | | | |
| 3 | CB 1.5 | 26.064 | 26 | High | <50 Ω-m |
| 7 | CB 2.0 | 24.805 | 27 | | |
| 28 | CBSF 0.5 | 26.064 | 26 | | |

higher resistivity value of 26.064 Ω-m at 28 days at than other mix compositions. Corrosion rate is very high for CBSF1.0, CB1.5 and CBSF0.5 mixes due to its resistivity values are less than 50 Ω-m according to ACI 222 guidelines and the data were presented in Table 11 [40–42].

CB1.5 and CBSF0.5 mixes showed higher resistivity value 26.064 Ω-m at 3 days and 28 days respectively than other mix compositions. CB2.0 possess higher resistivity value of 24.805 Ω-m at 7 days than other mix compositions. Corrosion rate is very high for CBSF1.0, CB1.5 and CBSF0.5 mixes due to its resistivity values are less than 50 Ω-m according to ACI 222 guidelines [43–47]. The resistivity values obtained from Arduino UNO are lesser than four probe method. And it is evident that there is no significant variation between resistivity values of different mixes. In this method, resistivity values are influenced by temperature and moisture content.

## 5. Conclusion

In this study, M30 grade smart concrete with carbon black and steel fibre was cast and tested under static loading conditions to determine the mechanical and resistivity properties. The following conclusions were obtained from this experimental study with the addition of carbon black and steel fibre: Conventional concrete with 3% addition of carbon black CB3 mix and CBSF(3% CB& 0.4% of SF) showed effective results in mechanical properties and electrical resistivity properties at 3, 7, and 28 days than compared with other mixes which represents sensitiveness of carbon black and steel fibre on strength and resistivity properties. In the microstructural analysis, SEM images showed the proper filler dispersion of carbon black to enhance the electrical resistivity property of smart concrete with the hybrid cement matrix. The XRD analysis indicates the presence of a single layer of graphite crystal at different diffraction angles at the peak intensities of carbon black. The thermogravimetric analysis confirms the different phases of hydration process of the smart concrete hybrid mixture.

In the four-probe method, the carbon black blended cube specimens have a higher resistivity compared to the Carbon Black blended cylinder specimens. The rates of corrosion of carbon black blended and hybrid (CBSF) mixes based on resistivity were recorded from Low to Moderate and High. In the Arduino UNO method, carbon black blended concrete mixes and hybrid (CBSF) mixes of both cube and cylinder specimens indicated consistent resistivity vales. Based on the resistivity value high rate of corrosion was observed in both cube and cylinder specimens. This study enables monitoring the damage in the hybrid concrete by correlating the durability parameter of corrosion with their electrical resistivity property to determine the possibilities of corrosion in concrete with low cost and high sensitivity.

## Data availability statement

The data can be available proper request from the editor.

## CRediT authorship contribution statement

**M. Rama:** Writing – original draft, Methodology, Data curation. **J.S. Sudarsan:** Writing – original draft, Investigation, Conceptualization. **N. Sunmathi:** Writing – review & editing, Supervision, Methodology. **S. Nithiyanantham:** Writing – original draft, Supervision, Formal analysis.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:S. Nithiyanantham reports was provided by Thiru Vi Ka Government Arts College Department of Physics. S. Nithiyanantham reports a relationship with Thiru Vi Ka Government Arts College Department of Physics that includes: non-financial support. S. Nithiyanantham has patent no pending to no. not to declare anything related to this work If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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