Uluslararası İleri Doğa Bilimleri ve Mühendislik Araştırmaları Dergisi
Sayı 8, S. 76-84, 10, 2024
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Araştırma Makalesi

International Journal of Advanced Natural Sciences and Engineering Researches
Volume 8, pp. 76-84, 10, 2024
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Research Article

https://as-proceeding.com/index.php/ijanser
ISSN:2980-0811

Development of Sustainable Concrete to assure Resilience and Durability via Self-Sensing

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(Received: 11 November 2024, Accepted: 16 November 2024)

(3rd International Conference on Contemporary Academic Research ICCAR 2024, 10-11 November 2024)

ATIF/REFERENCE: Ahmed, H. A., Fahad, M. & Haroon, M. (2024). Development of Sustainable Concrete to assure Resilience and Durability via Self-Sensing, *International Journal of Advanced Natural Sciences and Engineering Researches*, 8(10), 76-84.

Abstract – Concrete is the most abundant construction material and requires sustainable practices for better performance. A main manifestation of deterioration in concrete structures is cracking due to the low tensile resistance of the material, thus affecting its durability, and resilience and also impacting sustainable practices. Crack detection and monitoring are essential for structural safety, especially when critical structures such as nuclear power plants and dams are concerned. The objective of the research presented here is to revisit the self-sensing potential of concrete including short carbon fibers. These carbon fibers are semiconductors and decrease the resistivity of concrete. The decrease in resistivity helps identify the generation of flaws, such as cracks. In this paper, electrical resistivity measurements were performed using the compressed electrode method, and a comparative study was conducted on four different concrete mixtures containing different amounts of short carbon fibers. The curing time of concrete is also considered a variable in the experimental program. So that the effect of curing on self-sensing behavior can be determined. Till now cement mortar was tested for this ability. In this study, concrete specimens were made and tested for self-sensing ability.

Keywords – Self-Sensing, Sustainable, Carbon Fibers, Resilience, Electrical Resistivity.

I. INTRODUCTION

Many techniques are used in monitoring the formation and growth of cracks in civil infrastructure. Such techniques include the use of sensors embedded and/or attached to concrete structures. The structures are thus made 'smart', where a smart structure is defined as one that can sense its strain and cracks formed in it. Sensors such as strain gauges, optical fibers, and piezoelectric sensors constitute an external mechanism for making a structure smart. The external mechanism only helps detect the cracks but does nothing to prevent the generation of cracks. These sensors are more expensive and quite often less durable, than the structural material. Furthermore, using an embedded sensor can cause degradation of mechanical properties. [1, 4-5, 8, 10-12]. In comparison, a desirable solution would increase concrete's resistance to crack generation and make the structure smart as well i.e., enabling timely detection of cracks. Self-sensing is the ability of a structure to sense its damage and strain [12-13]. Research has shown that concrete containing carbon fibers exhibits a self-sensing behavior under various types of loading [14]. Self-sensing behavior makes a concrete structure internally smart eliminating the need for embedded sensors.

II. RESEARCH SIGNIFICANCE

From the above-detailed literature, it can be easily concluded that to achieve both results simultaneously i.e. to prevent the concrete from cracking and to monitor the structures, the best solution is the use of carbon fiber reinforced concrete as a smart material that has much more resistance to cracking than normal concrete and also gives good results for using as monitoring material as compared to all other methods that are expensive and/or unreliable and also have compatibility issues with the concrete structures. However, by using carbon fiber reinforced concrete in structures there will be no issue of using two different materials. There will also be no threat of damaging any sensor inside the body of the structure.

Electrical resistivity measurement was determined for all concrete mixes containing different proportions of short carbon fibers. Depending on the number of short carbon fibers Four (4) types of concrete mixes were selected and marked as CC, Type A, Type B, and Type C having short carbon fibers of the amount 0%, 0.35%, 0.50%, and 0.65% by weight of cement respectively.

A. MIX PROPORTION

ACI 211.1 presents the methodology for determining the proportions of basic constituents of concrete, that is, cement, fine and coarse aggregates, and a ratio of water to cement to obtain concrete with a desired compressive strength. Accordingly, the mix proportion results that were obtained for a normal concrete with a compressive strength of 27.5 MPa, are presented in Table 1.

Table 1. Mix proportion values for normal concrete of 27.5 MPa target compressive strength

S. No.	**Material**	**Quantity (kg/m^3)**
1.	Cement	364
2.	Fine Aggregate	831
3.	Coarse Aggregate	906
4.	Water	208

Other materials that were used in the concrete include carbon fibers, silica fume (8% by weight of cement), methylcellulose (0.4% by weight of cement), and plasticizers (1.5% by weight of cement). Methylcellulose was used for dispersing the fibers in the concrete. (Chen, Chung, 1993) While silica fume was used to increase the bond strength of fibers with the cement paste. (Chen, Chung, 1993) Since the addition of silica fume renders the concrete mix quite thick and sticky plasticizers were added to achieve desired workability.

In this study, four different types of concrete mixes were prepared based on varying amounts of short carbon fibers. These mixes were named CC, Type A, Type B, and Type C, which contained 0%, 0.35%, 0.50%, and 0.65% carbon fibers by weight of cement, respectively (as detailed in Table 2). The mix CC was used as the control mix and its results were compared with those of the other three mixes. For all four mixes, various physical and mechanical properties were determined at 7, 14, and 28 days.

Table 2. Carbon fiber proportions in various mixes

Mix type	Carbon fibers (%)
CC	0
Type A	0.35
Type B	0.50
Type C	0.65

B. *MIXING PROCEDURE*

Mixing of concrete was carried out at 25±2 ºC temperature. Care was taken that during the mixing process; all the followed steps were by ASTM C1116. The concrete batches were prepared in a concrete mixer machine using the following sequence of operations:

a) Coarse aggregates were first placed in the mixer machine and some water was added to moist the aggregates. The coarse aggregates were mixed for 2 to 3 minutes.

b) 8% silica fume (as per ASTM C1240) by weight of cement was added to the mixer machine containing wetted aggregates.

c) Cement and fine aggregates were added to the rotating mixer.

d) Methylcellulose was dissolved in the water and stirred with hand for about 2 minutes and then carbon fibers were added to this solution. A black thick paste was formed as shown in Figure 1.

e) The methylcellulose and carbon fiber solution was added to the mixer containing coarse aggregates, fine aggregates, cement, and silica fume.

f) Plasticizers were added to the mix and all the materials were mixed for 3 minutes.

It should be noted that steps (d) and (e) do not apply to the preparation of the mix CC since it did not include any carbon fibers.

Figure 1. Carbon fibers in methylcellulose

C. *TEST PROCEDURE*

A comparative study was made to analyze the different properties of concrete containing short carbon fibers. Concrete that was used in this research was classified into four categories based on the number of carbon fibers by weight of cement.

1. Control concrete containing no carbon fibers.
2. Type A: 0.35% of carbon fibers by weight of cement.
3. Type B: 0.50% of carbon fibers by weight of cement.
4. Type C: 0.65% of carbon fibers by weight of cement.

The carbon fibers used in this study have a nominal length of 5±1mm.

III. PHYSICAL PROPERTIES

A. UNIT WEIGHT

The unit weight of concrete was determined by ASTM C642 on standard-size cylinders having a diameter of 152 mm and a length of 304 mm. The entire specimens were prepared and cured according to ASTM C192 [19]. Then the cylinders were kept in water for 7, 14, and 28 days to check the effect of curing age on unit weight.

B. WATER ABSORPTION

Water absorption was determined according to ASTM C642 on standard-size cylinders having a diameter of 152 mm and a length of 304 mm. The entire specimen was made and cured according to ASTM C192. Then the cylinders were kept in water for 7, 14, and 28 days to check the effect of curing age on water absorption.

IV. MECHANICAL PROPERTIES

A. COMPRESSIVE STRENGTH

Compressive strength test was carried out on standard-size cylinders of 304 mm length and 152 mm diameter according to ASTM C39. For making and curing of test specimens ASTM C192 practice was followed. ASTM C617 was followed for the capping of concrete cylinders. Besides capping, a steel plate was placed on the specimen to ensure uniform distribution of the applied load. The machine that was used for this test was a properly calibrated machine having a capacity of 200 tons. The rate of load application was continuous and without shock.

B. FLEXURE STRENGTH

Beam samples having 450 mm x 100 mm x 100 mm size were made to determine the modulus of rupture as per ASTM C78 standards. All the beam specimens were cast and cured by ASTM C192 specifications. Beam specimens, tested using a Universal Testing Machine (UTM), were supported on both sides. 75 mm length of beam from each face of the support was supported on thick steel plates. The remaining 300 mm length was divided into three equal portions to accomplish the ASTM C78 requirements that the distance between load points should be equal to the depth of the beam. Circular rods, with an overlying thick steel plate, were used to equally transfer the point load applied through UTM.

C. SPLITTING TENSILE STRENGTH

Standard cylinders were made of the size 152 mm diameter and 304 mm height for split tensile strength test according to ASTM C496. The specimens were prepared and cured in a laboratory following ASTM C 192. The specimens were tested using a UTM of 200 tons capacity. Cylinders were placed in a direction such that the load application was perpendicular to the longitudinal axis of the cylinder. The rate of load application was continuous and without shock.

D. STRESS-STRAIN BEHAVIOUR UNDER COMPRESSION

Tests were performed on the standard cylinder of size 152 mm diameter and 304 mm length by ASTM C39. All specimens were prepared and cured by ASTM C192. The cylinders were capped using locally available plaster of Paris. Besides the capping, a steel plate was also placed over the specimen to ensure that the load was distributed uniformly. The displacement control method of testing was used to determine the behavior after the ultimate strength. A strain gauge was attached to the cylinder to measure the amount of displacement during the test. Displacement was controlled through the load cell apparatus and the data logger arrangement. During the test, a constant rate of displacement was applied for which the amount of load was determined. In this manner, a series of load values were obtained even after the cracking of concrete, for a specified value of strain.

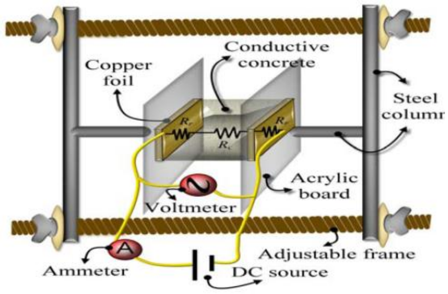

Figure 2. Proposed circuit arrangement

V. ELECTRICAL RESISTIVITY MEASUREMENT

For determining the electrical resistivity of concrete, cubes of the size 152 mm x 152 mm x 152 mm were made. All the cubes were cast and cured per ASTM C192. The specimens were tested at the age of 7 days, 14 days, and 28 days to check the effect of curing age on the resistivity property of concrete. For finding the electrical resistivity of the desired specimen, the compressed electrode method was used. The proposed circuit of the compressed electrode method for measuring the electrical resistance of concrete is shown in Figure 2. The apparatus consists of an assembly that contains an exterior frame containing rods arranged in a manner as shown in Figure 3.

The frame was tightened to compress the copper plates that were in direct contact with the specimen. The copper plates were attached through wires that were then connected to an AC source. An ammeter was connected in series and a voltmeter was connected in parallel in the same circuit. In the circuit thus made, the concrete specimen acted as a resistor whose resistance value had to be determined. Ohm's law was used to find the resistance of the concrete.


Figure 3. Resistivity measurement

VI. RESULTS AND DISCUSSIONS

A. PHYSICAL AND MECHANICAL PROPERTIES

From the results tabulated below in Table 3, it can be found that the fiber addition does not have a very great influence on the unit weight of concrete. If taking the controlled concrete (containing 0% fibers) as a reference, then the unit weight of the other specimen is very close to the reference concrete. From Table 4 it can be seen that water absorption at 28 days is very much similar for all 4 types of concrete. However, the 7-day absorption is very much higher for concrete containing short carbon fibers as compared to controlled concrete. Also, the 14-day results for all types of concrete are very similar. For 28 days, if taking the controlled concrete as a reference, the other specimen has absorption values by percent of 109, 102, and 102.5 for Type A, Type B, and Type C concrete respectively.

Table 3. Unit weight of concrete

Age (Days)	**Unit Weight (kg/m^3)**			
	CC	**Type A**	**Type B**	**Type C**
7	2267.57	2280.23	2239.70	2262.45
14	2291.92	2299.13	2277.66	2287.12
28	2309.54	2321.07	2296.41	2300.57

It can be evident from Table 5 that the inclusion of short carbon fibers has very little effect on the compressive strength of concrete. And do not increase or decrease the compressive strength up to any considerable range.

Table 4. Water Absorption test

Age (Days)	**Water Absorption (%)**			
	CC	**Type A**	**Type B**	**Type C**
7	2.34	8.14	8.76	9.97
14	1.95	4.20	3.95	4.06
28	1.82	2.00	1.86	1.87

The concrete that gave the most appropriate results in the electrical resistivity test was Type C concrete; it behaves very well and gives a big change in resistivity before its failure which was the main objective of this research. So it can be stated that Type C concrete with 0.65% of carbon fibers is best to use for the measurement of change in electrical resistivity and therefore can be used as a smart material that can sense its damage and strain.

Table 5. Compressive strength (MPa)

Type of Concrete	7days				14 days				28 days			
	C1	C2	C3	Mean	C1	C2	C3	Mean	C1	C2	C3	Mean
CC	15.30	14.54	13.77	14.54	15.45	18.85	19.83	18.46	22.69	25.54	24.52	24.25
Type A	14.67	14.03	12.65	13.78	17.68	16.87	17.20	17.25	21.60	23.71	23.20	22.82
Type B	14.66	13.14	14.38	14.06	18.92	13.20	17.66	18.89	22.75	24.20	22.20	23.04
Type C	15.16	16.13	15.58	15.63	19.78	18.82	20.90	19.84	23.65	24.25	25.72	24.54

B. ELECTRICAL RESISTIVITY VALUES

Taking into account the following four graphs, i.e., Figure 4, the following conclusions can be made.

At 7 days of curing age, the overall resistivity of all the three concretes i.e., Type A, Type B, and Type C is very much less than that of resistivity at other ages taken into account in this research. For normal concrete the resistivity value was very much greater than that of the concretes with carbon fibers. In the case of normal concrete, the change in resistivity was after its failure and that change was also noted to be of very small amount. On the other hand, the change in resistivity for all the other three types of concrete started as the load was applied to the concrete.

Table 6. Flexural Strength (MPa)

Type of Concrete	Beam 1	Beam 2	Beam 3	Mean
CC	5.057	4.843	5.106	5.002
Type A	5.382	5.209	5.513	5.368
Type B	5.347	5.547	5.602	5.499
Type C	5.547	5.602	5.761	5.637

At 14 days of curing age, the overall resistivity of all three concretes i.e., Type A, Type B, and Type C increases by a considerable amount as compared to that of resistivity at 7 days. For normal concrete, the resistivity value was not much increased than that of its resistivity at 7 days of curing age. At 14 days the same behavior was observed in normal concrete, the change in resistivity was after its failure and that change was also noted to be of very small amount. On the other hand, the change in resistivity for the other three types of concrete was started as displacement was produced in the concrete.

The graphical representation of electrical resistivity values for all four types of concrete at a curing age of 28 days is shown in Figure 7. The following conclusions can be made. At 28 days of curing age, the overall resistivity of the three types of concretes i.e., Type A, Type B, and Type C increases by a considerable amount as compared to that of resistivity at 7 & 14 days.

Table 7. Splitting Tensile Strength (MPa)

Type of Concrete	7 days				14 days				28 days			
	C1	C2	C3	Mean	C1	C2	C3	Mean	C1	C2	C3	Mean
CC	2.159	2.311	2.132	2.201	2.573	2.339	2.435	2.449	2.773	2.671	2.628	2.691
Type A	2.208	2.228	2.021	2.152	2.366	2.532	2.635	2.511	2.822	2.904	2.781	2.863
Type B	2.194	2.263	2.063	2.173	2.421	2.477	2.677	2.525	2.939	2.794	2.981	2.904
Type C	2.352	2.311	2.166	2.277	2.671	2.491	2.497	2.553	3.029	2.863	2.987	2.961

It can be easily seen from the graphs that when deformation is produced in the concrete, its resistivity changes. And it increases by an increase in deformation. However, after the failure, the resistivity drops down rapidly showing the fact that the increase in resistivity was due to the crack production, and when the crack size increases the resistivity also increases. When concrete fails, it does not resist any load, and further application of any load causes cracks to get close. So, after the failure, the increase in deformation causes the resistivity to decrease.

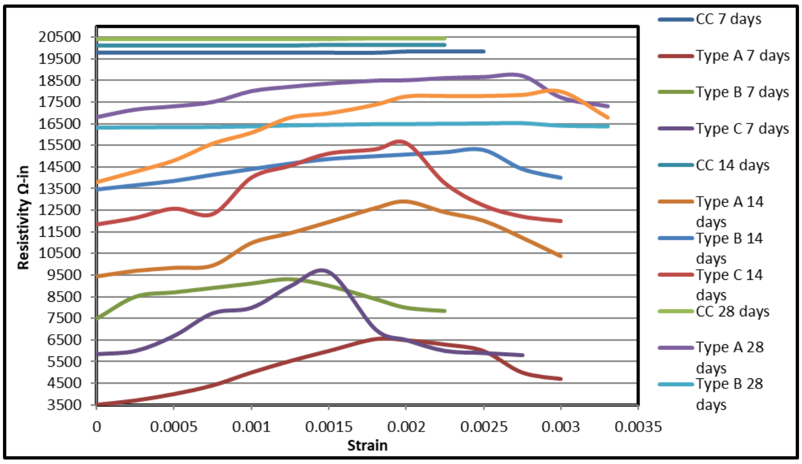

Figure 4. Electrical resistivity curves for all concrete types at curing ages of 7, 14, and 28 days

VII. CONCLUSIONS

Up till now work done on self-sensing was limited to cement mortar cubes and/or very small samples. It was the first time when concrete was tested and cubes of size 152 mm3, beams of size 100 mm x 100 mm x 400 mm, and cylinders of size 152 mm x 304 mm were made and tested. The mechanical properties of concrete generally improve by the inclusion of fiber addition. All four types of concrete described above were tested against each property at curing ages of 7, 14, and 28 days. The mechanical properties that were evaluated include compressive strength, flexural strength, split tensile strength, and stress-strain behavior under compression. Hence by performing the mechanical properties evaluation, it can be clearly said that by increasing the fibers in concrete its mechanical properties improve. Of all the four types of concrete, Type C concrete (containing 0.65% carbon fibers) gives the best results and acts very efficiently in this evaluation.

The electrical resistivity test was also done on all types of concrete for different curing ages. It was concluded that the performance of Type C concrete (0.65% of carbon fibers) is best in all regards. It gives excellent results in all aspects i.e., mechanical properties, physical properties, and resistivity properties.

So, from all the above discussions, it can be stated that Type C concrete gives excellent results in all respects and hence can be used for monitoring without the use of any embedded sensor. It will give surely the following advantages to the common methods of monitoring:

1. Ensuring sustainability, durability, and resilience.
2. Ability to provide qualitative signals with high sensitivity and resolution.
3. Fast response for real-time monitoring.
4. Not weakening the structure.
5. Not requiring peripheral equipment.

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