Damage study in concrete subjected to various loading by monitoring the surface resistivity.

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Abstract. Detection of damages and cracks and their progress in concrete structure is a grave concern. Incipient damages are often not noticeable and hence visual inspections or using of low frequency response methods and other NDE techniques may not give a significant reflection on the same. Permitting the damages/cracks to progress until they are well noticeable and making an attempt to detect and restore the structure would be a serious threat to the reliability and service life of the structure at least in case of a strategically vital one. With the advantages of non-invasion, non-radiation, low-cost and high-speed, electrical resistance measurement is a promising technique in this regard. In this study an attempt is made to analyse the changes in electrical resistivity of concrete structural elements when subjected to different types of loading. Electrical resistivity measurements were carried out on specimens like cubes, beams and cylinders under the action of compressive, flexural and tensile load respectively. In addition, study was conducted on cubes under repeated cycles of compressive loading.

1. Introduction

Structural integrity and reliability is very essential for a safe and quality living of the society. Often these two parameters are at apprehension because of aging of the structure and exposure of the structure to various natural calamities due to a severe change in the earth realm as a whole and hence the atmospheric and climatic condition. Considering this scenario, having a sustainable and reliable method, which is economical and is non-invasive; for assessing the quality and reliability of a structure would be a boon to construction industry, and to the society as a whole. One such method is making use of electrical resistivity property as a tool to detect any kind of damage or defect in a structure \cite{1,2}. The area of application of electrical resistivity can also be extended to quality assessment, durability assurance and yet more. Observation of variation of electrical resistivity under various loading condition would enable to simulate structural performance of elements under corresponding loading. Monitoring of the electrical resistivity under live loading would be even beneficial, and the real time monitoring will give better idea on how the element would behave under loading \cite{4,1,3}. This would be a close match to the real life condition rather than behaviour under a constant static load.
1.1 Electrical Resistivity (ρ)

Electrical resistivity being a very geometry and pore structure dependent parameter, it is very sensitive to even microscopic cracking. The value of electrical resistivity varies between 1-10,000 kΩ-cm, depending on moisture content, type and quality of material used etc. [5]. When load is applied, it causes stretching of internal fibres (disturbing the homogeneity of concrete), and this causes changes in resistivity, which is owed to the deviation in ionic flow inside [2]. Surface resistivity is taken into account in the present study as it is more in compliance with the real conditions of the structure. There are a number of techniques to measure concrete resistivity. However, the four-probe Wenner Array technique is the most commonly used technique because of its speed, simplicity, and practicality [4,5]. It can be used to measure the surface resistivity of concrete from the surface in seconds without any intrusive process such as coring. Hence Four probe Wenner Array was used throughout the study.

The Wenner method consists of four equi-spaced copper electrodes (38mm) which are embedded into the concrete. Copper electrodes were used to ensure proper conductivity [6]. The electrodes were centred along the longitudinal axis of the specimens with a penetration depth of 50mm, to ensure a stable reading [7]. An alternating current of frequency 50 Hertz and voltage 230 Volts is induced into the outer electrodes and corresponding potential drop is measured between the inner electrodes [1,5]. Direct current (DC) is not recommended because it could polarize the electrodes and/or the underlaying reinforcement [3,6]. With a known value of current (I) and measured potential (V), resistivity (ρ) can be calculated by using equation:

\[ \rho = k \frac{V}{I} \]  

Where, \( \rho \) (Ω-mm) is the Electrical Resistivity, \( a \) (mm) is the distance between electrodes; \( V \) is the measured potential difference between the two potential measurement electrode, \( I \) (A) is the imposed electrical current and 'k' is the geometrical correction factor. For cubes and beams \( k = '2\pi a' \) [8,9]. In case of cylindrical specimens, \( k = \frac{2\pi a}{1.09 - \frac{0.527}{d} + \frac{7.34}{d^2}} \) [10].

![Figure1. Experimental set up for resistivity measurement](image)

2. Experimental Study

The study was carried out with three different grades of concrete on three types of specimens, Cubes (150x150x150mm), Beams (500x100x100mm), Cylinder (300x150mm). A set of three specimens were cast and tested under each proportion for each cases of loading. Mix design was carried out for M20, M30, M40 grades as per IS 10262:2009 and is detailed in the successive section.
2.1 Materials
Cement: PPC of grade 53 was used for casting the specimens. The cement used has been tested for various properties as per IS: 4031-1998 and was found to be conforming to various specifications of IS: 12269-1987.

Aggregates: M-sand of proper gradation (particles ranging from 150 microns to 4.75mm in suitable proportion) was used for casting the concrete specimens. Coarse aggregate of size 20mm and 12.5mm in a ratio 70:30 was used for casting the specimens. The aggregates used were conforming to IS 383:1970.

Water: Potable water was used for the preparation of concrete.

Admixture: Conplast SP 430 was used for the study to maintain adequate workability.

2.2 Mix proportion
As per IS 10262:2009, M20, M30 and M40 grade mix are designed to prepare the test specimens. Different trials were carried out to determine the design mix. Table 1 shows the mix proportion for each grade of concrete.

| Grade of concrete | Cement (Kg/m³) | FA (Kg/m³) | C.A (Kg/m³) | W/C Ratio | Admixture (L) | Slump (mm) |
|-------------------|----------------|------------|-------------|-----------|---------------|-----------|
| M20               | 329.00         | 827.2      | 1138.0      | 0.45      | 3.026         | 110       |
| M30               | 394.32         | 724.04     | 1236.2      | 0.40      | 3.272         | 110       |
| M40               | 415.88         | 809.45     | 1094.6      | 0.36      | 2.911         | 105       |

3. Test on Hardened Concrete
After curing period, the specimens were subjected to loads. Three types of loading condition on unreinforced specimens have been studied- Compressive loading, tensile loading and flexural loading on cubes, cylinders (placed horizontally) and beams respectively. Loading was applied on a face were electrodes were not embedded. The resistivity was measured at various stages of loading and has been plotted. An input alternating current of 230 Volts and 50 Hertz frequency was induced to the outer electrodes and potential drop was measured at the inner electrodes. Surface Resistivity was further calculated using the equation \(1\). Voltage and current readings were observed at different ranges of loading to study the changes in the resistivity values under progressive loading.

4. Results and Discussion
The variation in resistivity while loading each specimen has been discussed in this section. Resistivity Vs load graphs have been plotted for each case.

4.1 Resistivity of Cubes subjected to loading
Concrete cubes were subjected to loading until failure and simultaneously current and voltage readings were observed at different stages of loading. It is observed that as the loading increases, resistivity was found to be decreasing. This can be allied to the fact that, as the specimen is loaded it disturbs the pore structure due to stretching and cracking, which in turn will increases the ionic flow leading to higher conductivity and thus low resistivity [2]. The resistivity variation under compressive
loading was in line with the study in [3]. Similar trend of variation in resistivity was observed for all the three grades of concrete. The load Vs resistivity plot is given below (See Figure.2).

![Resistivity of Cubes under Compressive Loading](image)

**Figure 2.** Variation in measured resistivity of Cubes

4.2 Resistivity of Beams subjected to loading

Concrete beams were subjected to loading until failure and simultaneously current and voltage readings were observed at different stages of loading. From the graph, it is observed that, as loading progresses a fractional decrease in resistivity was observed initially and then a drastic peaking, until failure. This can be allied with the theory that, at the initial stages of loading, ionic flow increased due to the cracks developed in the inner core of concrete, contributing to reduced resistivity. There after a sudden cresting in resistivity was observed at failure of the specimen. This is due to the breakage of the current circuit due to the transverse fracture of beam into two halves leading to poor conductivity and thus higher resistivity. As in case of beam a drastic peaking

4.3 Resistivity of Cylinders subjected to tensile loading

Concrete cylinders were subjected to tensile loading until failure and simultaneously current and voltage reading were noted at different stages of loading. From the graph, it is observed that, as loading progresses, a fractional decrease in resistivity was observed initially followed by an increase in value until failure. This can be allied with the theory that, at the initial stages of loading, ionic flow increased due to the cracks developed in the inner core of concrete, contributing to reduced resistivity. There after a slight increase in resistivity was observed at failure of the specimen. This is due to the breakage of the current circuit caused due to the longitudinal splitting of the cylinder into two halves, leading to poor conductivity and higher resistivity. As in case of beam a drastic peaking
of resistivity was not seen in cylinders even though cylinder specimens were also split into two halves at failure. This is because of the static current present in the circuit, as the specimen was split longitudinally and not in transverse direction and thus leaving the four electrodes on one half even after splitting. Similar trend of variation in resistivity was observed for all the three grades of concrete studied. Similar trend of variation in resistivity was observed for all the three grades of concrete studied. The load Vs resistivity plot is shown in Figure 4.

![Figure 3. Variation in measured resistivity of Beams](image1)

![Figure 4. Variation in measured resistivity of cylinders](image2)
4.4 Resistivity of Cubes subjected to repeated cycles of compressive loading

The cubes were given four repeated cycles of compressive loading. Resistivity values of first cycle of loading are on the extreme right of the graph followed by subsequent cycles and corresponding readings on to the left. During the loading and unloading cycle, the resistivity was gradually decreasing at the beginning and then a sudden fall in the value was observed due to unloading in the first cycle. In subsequent cycles, the resistivity values had a gradual rise during first set of loading and then a gradual decrease and finally a sudden fall in the value due to unloading. Behaviour under repeated cycles of compression was in line with the studies in [3]. This can be explained with the help of defect damage mechanics [4,1,3]. In the first cycle, as loading increased the ionic flow increased due to damage caused and stretching of inner pore structure and thus resistivity was decreased. This falls under the crack generation stage. On further loading the specimen, the resistivity was increased, which indicates a diminution of cracks formed, which caused the ionic flow to lessen. This is the crack propagation stage. After first cycle every succeeding cycles of loading and unloading witnessed the same trend of variation in resistivity i.e. Initial increase and then gradual decrease and finally a sudden drop during unloading. From the second loading cycle onwards, the resistivity values were decreasing swiftly when compared to the baseline resistivity which indicates the crack extension stage causing the specimen to undergo irreversible plastic deformation. Figure 5 shows the load Vs resistivity.

Figure 5. Variation in measured resistivity under repeated cycles of compressive loading
5. Conclusions
Electrical resistivity measurement provides a means of sensing damage in concrete. The damage is indicated by a decrease in resistivity, which is due to the increase in the pore ionic flow and corresponding increase in conductivity. From the experimental studies, it was observed that, for cubes under compressive loading resistivity decreased under progressive loading until failure. In case of beams under flexural loading and cylinders under tensile loading, resistivity values showed a decrease as the loading was increased and a sudden summiting of resistivity was observed at the failure load. This is due to the poor tension bearing capacity of the unreinforced specimens unlike in case of compression which had only a gradual decrease in resistivity.

Defect dynamics and minor damage in concrete was monitored under repeated cycles of compression. Resistivity was gradually decreasing under progressive loading and unloading of specimen instigated a sudden drop in the resistivity value. Three phases of cracking were analyzed with respect to the changes in resistivity. During crack generation stage resistivity was decreased i.e. during the first cycle of loading. And in further loading and unloading cycles, an initial increase in resistivity and then decrease was observed. This is the crack propagation stage. It is proven that while further loading a brittle damaged specimen like concrete, it can cause closure of minor cracks, leading to low conductive ionic flow and a high resistivity. This should be the reason for increase in resistivity in the beginning of second cycle. Crack extension stage was characterized by a huge decrease in baseline resistivity values when compared to the resistivity values of first cycle, indicating an irreversible plastic deformation of the specimen. Thus it is likely to relate changes in resistivity values and damages in concrete elements and even a prediction on the extend and stages of cracking is possible.

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