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Influence of Material Properties of Reinforced Concrete Element on Acoustic Emission due to Corrosion

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Abstract

The material properties of reinforced concrete (RC) influence the corrosion process of steel rebar and subsequent cracking of concrete. This paper investigates the influence of material properties on acoustic emission (AE) due to corrosion of rebar in concrete. RC cylinders with various cover thickness to rebar diameter (C/D) ratios, cement types and steel types were studied to identify their influence on cumulative signal strength (CSS) of AE technique. The result of analysis of variance (ANOVA) indicated significant effect of steel type on CSS values due to corrosion followed by cement type, whereas C/D ratio has no significant effect.

Keywords: Reinforced concrete; Rebar corrosion; Accelerated corrosion; Acoustic emission; Analysis of variance.

1. Introduction

The corrosion of steel embedded in concrete and subsequent cracking of concrete are dependent upon the material properties of constituents of reinforced concrete (RC). Concrete provides chemical and physical protection to the embedded steel reinforcement. The chemical protection is through the formation of a passive layer (thin protective oxide film) over the steel surface due to high alkalinity of concrete pore solution while the physical protection is through the retarding access of oxygen, moisture, and various aggressive species to the steel/concrete interface [1]. Initiation of corrosion and progress of corrosion are both dependent upon the chemical composition of steel as well as protection provided by concrete cover [2].

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Corrosion of reinforcing bar in concrete is an electrochemical process that involves the transfer of electrically charged ions between two surface areas of a reinforcing bar with different potentials (anode and cathode) through the pore fluid of the concrete, which serves as an electrolyte. The corrosion rate of reinforcing bar in concrete depends on the ease of flow of the ions participating in the electrochemical process. Various factors such as electrical resistivity of the concrete, electrochemical potential of the reinforcing bar, availability of oxygen and moisture at the cathodic area, and ratio of cathodic to anodic area control the flow of electrically charged ions in concrete [3].

The corrosion process of rebar can be studied using Acoustic Emission (AE) technique. AE is not an electrochemical method, but by utilising the sensitivity of the technique to the growth and initiation of micro-cracks, AE is able to identify corrosion by detecting micro-cracking induced in concrete as a consequence of the corrosion reaction [2]. The major advantage of acoustic emission technique over other non-destructive techniques such as electrochemical technique or ultra-sonic pulse velocity measurements for corrosion monitoring is that, it does not require any electrical or physical contact with steel embedded in concrete.

Durability of RC element is influenced by corrosion which is largely dependent upon the material properties. However, very little evidence of research has been found that investigates the effect of material properties on corrosion and corresponding AE measurement.

The focus of this work was to examine the effects of type of cement, type of steel and ratio of cover to rebar diameter on the magnitude of cumulative signal strength (CSS) of AE due to corrosion. Statistical analysis was carried out to understand the significance of the properties affecting corrosion of steel embedded in concrete.

2. Methodology and experimental details

2.1. Outline

To examine the influence of material properties on AE measurements, the testing programme varied the cement type, steel type and cover to rebar diameter ratio keeping two variables constant. For example, two cement types were investigated, whilst keeping the steel type and cover to rebar diameter ratio constant. Corrosion was induced in the specimens using the impressed current technique. Acoustic emission technique was used to monitor corrosion continuously. The influence of the cement type, steel type and cover to rebar diameter ratio on the magnitude of AE were investigated.

2.2. Specimen details

Five series of singly reinforced concentric concrete cylinders were cast (Figure 1), with each series comprising of three cylinders. The design of the specimens was such that either the influence of the cement type, steel type or cover to rebar diameter ratio could be investigated, with all other factors remaining constant.

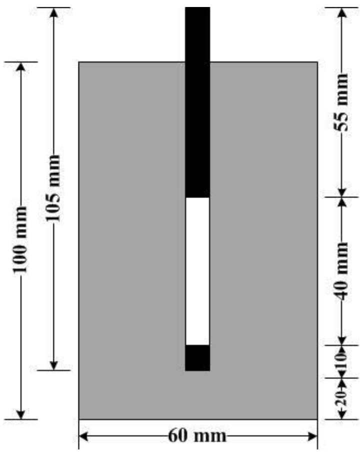

Figure 1. Cylindrical reinforced concrete specimen

Ordinary Portland Cement (OPC) and Portland Pozzolana Cement (PPC) were the types of cement used. The chemical compositions of cement are presented in Table 1. Tiscon thermo mechanically treated (TMT) steel and Tiscon corrosion resistant steel (CRS) were the types of steel used. The carbon content, phosphorus content and sulphur content of Tiscon TMT and Tiscon CRS steels used in the present investigation are 0.25%, 0.035% and 0.035% and 0.15%, 0.10% and 0.04%, respectively. The material properties of each series of singly reinforced concentric concrete cylinders are given in Table 2.

TABLE 1: CHEMICAL COMPOSITION OF CEMENT

Compound	OPC	PPC
CaO (%)	62.1	47.72
SiO_2 (%)	21.14	28.82
Al_2O_3 (%)	5.23	9.31
Fe_2O_3 (%)	4.42	4.6
MgO (%)	1.14	1.48
SO_3 (%)	2.3	2.1
LOI (%)	1.5	2.7

TABLE 2: SERIES DESCRIPTION

Series reference	Rebar diameter (mm)	Transverse cover (mm)	Cement type	Steel type
OPC-TMT-24/12	12	24	OPC	TMT
OPC-TMT-22/16	16	22	OPC	TMT
OPC-TMT-20/20	20	20	OPC	TMT
PPC-TMT-20/20	20	20	PPC	TMT
OPC-CRS-20/20	20	20	OPC	CRS

For all the specimens, M20 grade of concrete (concrete mix designed for 28 days compressive strength of 20 MPa) was prepared. Natural river sand confirming to zone I as per IS 383-1970 [4] was used as fine aggregates and crushed stone of nominal size 10 mm was used as coarse aggregates. The concrete mix was designed as per IS 10262:2009 [5] and the mix proportion obtained was 1: 2.78: 2.73 with water-cement ratio of 0.5. Average 7-days and 28-days compressive strength obtained for all specimens was 20 MPa and 32 MPa respectively.

A concentric reinforcing steel bar of 105 mm length was used in the cylindrical specimens. Before casting, the steel bar was drilled and threaded at one end to accommodate the threaded copper screw for electrical connections. Then the bar was wire brushed to remove any surface scale. Epoxy resin was then applied for the length of 55 mm from top and 10 mm from bottom in order to protect this portion from the corrosion activity. The remaining middle portion of 40 mm was subjected to accelerated corrosion. The epoxy resin was allowed to harden for 24 hours and then the weight of reinforcing bar was recorded to an accuracy of 0.01g.

A special moulding system was used for casting of specimens. The system was designed to accurately maintain the position and inclination of the bar with respect to that of the cylinder. With two types of cement, two types of steel and three cover to bar diameter ratio, total 5 concrete mixes were prepared with three replicates.

All the cylinders were cast in the special moulding system and were removed from the moulds after 24 hours of casting and kept for curing for the period of 7-days at a room temperature and relative humidity of 100%. On 8th day the specimens were immersed in 5% sodium chloride (NaCl) solution, approximately double the salinity of seawater, at a room temperature for 24 hours to ensure full saturation of the test specimen. From ninth day constant potential was applied to the specimen to accelerate the corrosion process using impressed current technique.

2.3. Accelerated corrosion set-up

In the present study, the specimens were subjected to accelerated corrosion using impressed current technique. The objective of inducing corrosion to the bar is to simulate the corrosion-damaged concrete. In impressed current technique, the specimen is immersed in NaCl solution and a direct current is passed through the reinforcing bar making it as an anode and another metal nobler than steel in electrochemical series as cathode [6].

In this investigation, a stainless steel (SS) mesh in the form of a strip was used as cathode. The cathode and the specimen were placed in 5% NaCl solution. The level of NaCl solution was kept 30 mm below the top surface of the specimen to alleviate corrosion at the steel-concrete interface and to accommodate the AE sensor. The DC regulated power supplier used in the present study could supply 200 mA DC at 30 V. The reinforcing steel bar was connected to the positive terminal of the external DC source and negative terminal was connected to the SS mesh. High salinity and the impressed current were both used to create aggressive environment by providing an abundance of chloride ions and by stimulating an increased flow of electrons, respectively. Anode to cathode current corresponding to constant applied voltage of 3V was monitored every day. The testing was stopped when the crack due to corrosion appeared and become distinct on the surface of concrete specimen.

2.4. Acoustic emission

All the specimens were monitored continuously for AE activity due to corrosion. The AE sensor was attached to each specimen at the top periphery of concrete surface with the help of a highly viscous coupling agent and electric tape. An instrumentation of AE consists of a transducer, a preamplifier and an acquisition device (MISTRAS from Physical Acoustic Corp.). It consists of Single channel USB AE node, AE win-Light software including waveform option with license for USB based system. The sensors consists of R3A, 30 kHz resonant sensor having operating range – 25 KHz-530 KHz. During saturation of specimen in NaCl solution for 24 hours, the specimens were monitored using AE prior to the application of potential, to ensure that emission due to liquid absorption was not present and to obtain a typical background level of AE for a specimen to decide the threshold. Based on this, the threshold applied for all AE measurements was decided as 40 dB with the sample rate of 1 MSPS. The potential was then applied, and the specimens were continuously monitored for AE activity. The laboratory set up for AE measurement is shown in Figure 2.

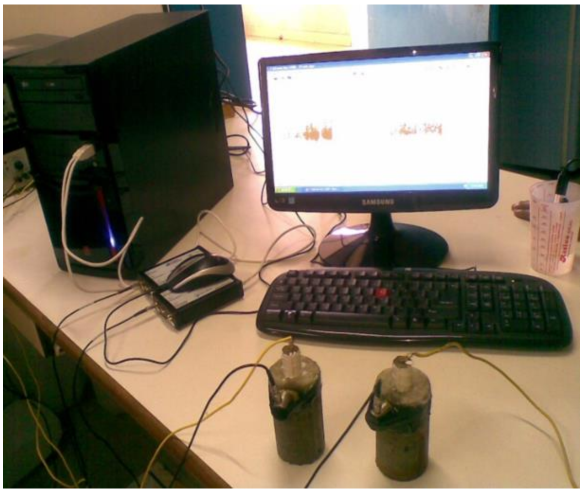

Figure 2. Laboratory set up for AE measurement

The major objective for these tests was to monitor the specimens continuously during active corrosion and to collect all the AE data for a set period, enabling an attempt at finding the influence of material properties on AE measurements.

3. Results and analysis

3.1. Acoustic emission due to corrosion

The study of data acquired using AE technique focuses the analysis on use of signal strength parameter of AE. It is defined as the measured area of the rectified AE signal, with units proportional to volt-seconds. The signal strength is often referred to as relative energy which is a measure of the amount of energy released by specimen [7]. The research shows that when CSS is plotted versus time, the CSS will generally increase sharply at a certain time which can be correlated to damage and corrosion [8]. In addition, it has been shown that AE can provide warnings of early stage of corrosion and that cumulative AE activity can be correlated with the severity of corrosion [9]. The researchers also identified that, CSS parameter of AE technique is a promising parameter for corrosion monitoring studies as it has a specific trend indicating active corrosion which is similar to the curve of typical corrosion loss of steel due to seawater immersion. They also compared CSS values with results of well-established electrochemical techniques viz. half-cell potential and Tafel-extrapolation technique and concluded that AE technique is effective for monitoring the progress of corrosion of rebar as well as damage to concrete [10]. Based on these findings, CSS parameter of AE is used to study the corrosion process in the present study.

3.2. Analysis of variance

The analysis of variance (ANOVA) is a very effective technique to evaluate the effect of independent variable on dependent variable. Sometimes it may be difficult to analyse the effect of different independent variables on variation of dependent variables. In such cases, ANOVA results help to find out the significance of different independent variables on dependent variable. In the present work, ANOVA calculations were carried out for CSS values of three replicates of each specimen with three values of cover to rebar diameter (C/D) ratio, two types of cement and two types of steel. As the range of CSS values observed varied from 6.9e6 to 1.3e10, log of CSS values were considered for analysis. These values were ranging from 6.8 to 10.1.

The log CSS values for all above were arranged in a tabular form. The total sum of squares was calculated, which is partitioned into sum of squares between factors and sum of squares (SS) within factors. After that the mean squares (MS) of the factors were calculated by dividing their corresponding SS by the associated degrees of freedom. Then the effect of individual factor was evaluated by testing the hypothesis of equality of variances, which is the significance test at a particular probability level. For this, the F-statistic is calculated as the ratio of MS between factors to MS within factors. This value was then compared to the tabulated F-values related to Fisher distribution. The F-values related to Fisher distribution depend upon the degrees of freedom (df) corresponding to between factors and within factor variance and the probability level, which are available in tabular form in relevant texts [11, 12]. The results of ANOVA for present study are discussed subsequently in detail.

3.3. Cover to rebar diameter ratio

From literature it is found that, damage to the cover resulting from the accumulation of corrosion products is characterised by cracking, delamination or spalling of the concrete, where the mode of failure is a function of C/D ratio [2]. This factor is considered the most influential in cracking initiation, where it has been shown that a linear trend exists between the C/D ratios versus attack penetration [13]. To study the effect of C/D ratio on AE measurements, the C/D ratio was varied by varying both cover thickness and rebar diameter. Table 3 shows the average value of CSS for various C/D ratios. From the Table it can be concluded that, with increase in C/D ratio, magnitude of CSS values decreased. By increasing C/D ratio, the time required to induce cracking was reduced. Hence, the specimens with a larger rebar diameter and lesser cover thickness were subjected to a greater extent of micro-cracking, resulting in higher magnitudes of CSS as shown in Table 3.

TABLE 3: MAGNITUDES OF CSS FOR DIFFERENT C/D RATIO

Series reference	**Rebar diameter (mm)**	**Transverse cover (mm)**	**C/D ratio**	**Average CSS values (pV-s)**	**Average log CSS values**
OPC-TMT-24/12	12	24	2	4.36×10^{7}	7.639
OPC-TMT-22/16	16	22	1.375	3.95×10^{9}	9.597
OPC-TMT-20/20	20	20	1	5.83×10^{9}	9.765

To validate these results, a one-way ANOVA test at a significance level $\alpha = 1\%$ was carried out under the null hypothesis that all the data are drawn from populations with the same mean that is, the average of the magnitudes of log CSS is the same for the three parameters considered. Tables 4 show the results of this analysis.

From this table it is observed that, the calculated F- value is lower than the corresponding tabulated F-values at 99% confidence level with P-value 0.07 (> 0.01) clearly indicates that there is not enough evidence to reject the null hypothesis. This suggests that, the variation in C/D ratio has no significant effect on CSS values, though with increase in C/D ratio, magnitude of CSS decreased.

TABLE 4: ANOVA RESULTS FOR C/D RATIO

Source of Variation	SS	df	MS	F-ratio	'F' from Fisher's distribution at 99% probability	P-value
Between factors	9.89	2	4.94	**4.28**	**10.92**	**0.07**
Within factors	9.89	6	1.16			
Total	16.82	8				

3.4. Cement type

In blended cements, the formation of additional C–S–H gel results in the formation of finer pore structure and thereby a denser microstructure in the hardened concrete. This increases the resistivity of concrete resulting in reduction of corrosion rate. Through experimental work, the researchers concluded that, the blended cements, like PPC and Portland slag cement (PSC) performed better as compared to OPC against chloride induced rebar corrosion in concrete [1].

In present work, to study the effect of cement type on AE measurements, cement type was varied by keeping steel type and C/D ratio constant. Table 5 presents the average magnitudes of CSS for OPC and PPC cements. As blended cements show reduced corrosion activity, for similar conditions specimens cast with PPC cement indicated more time for initiation and propagation of cracks in concrete as compared to that of OPC cement. This resulted in lesser extent of formation of micro-cracks in concrete with PPC cement indicating lesser magnitudes of CSS.

TABLE 5: MAGNITUDES OF CSS FOR DIFFERENT CEMENT TYPES

Series reference	Cement type	Average CSS value (pV-s)	Average log CSS value
OPC-TMT-20/20	OPC	5.83×10^9	9.765
PPC-TMT-20/20	PPC	5.59×10^7	7.747

Table 6 reports the result of ANOVA for two cement types. From this table it is observed that, the calculated F- value is higher than the corresponding tabulated F-values at 99% confidence level with P-value 0.0018 (< 0.01). This clearly indicates that there is enough evidence to reject the null hypothesis that all the data are drawn from populations with the same mean. This suggests that, the variation in cement type has significant effect on CSS values indicating better performance of PPC cement as compared to OPC cement under corrosive environment.

TABLE 6: ANOVA RESULTS FOR CEMENT TYPE

Source of Variation	**SS**	**df**	**MS**	**F-ratio**	**‘F’ from Fisher’s distribution at 99% probability**	**P-value**
Between factors	8.46	1	8.46	**53.09**	**21.19**	**0.0018**
Within factors	0.63	4	0.15			
Total	9.10	5				

3.5. Steel type

The corrosion performance of steel embedded in concrete exposed to chlorides is a function of both the concrete and steel characteristics. Corrosion propagation rates are influenced by surface characteristics, steel composition, and steel microstructure [14]. The corrosion resistance in RC structures is many times enhanced by using coating on rebars. Such coatings have ranged from cement slurries to epoxies and zinc [15]. However, these coatings suffer from the major disadvantage that they may be physically damaged or electrochemically penetrated so that the base steel is vulnerable to pitting corrosion. Debonding of rebar and concrete is another major problem in case of coated rebars. All these issues resulted into use of low-alloy steels or corrosion resistant steel (CRS) containing elements like phosphorus, copper, chromium and nickel which improve the corrosion resistance [15].

In present work, to study the effect of steel type on AE measurements, steel type was varied by keeping cement type and C/D ratio constant. Table 7 indicates the average CSS values for TMT and CRS steel. From table it is clear that CRS rebars performed better as compared to TMT rebars by showing lesser magnitudes of CSS which indicates that specimen cast with CRS rebars have shown better resistance to corrosion and hence lesser extent of micro-cracking.

TABLE 7: MAGNITUDES OF CSS FOR DIFFERENT STEEL TYPES

Series reference	**Steel type**	**Average CSS value (pV-s)**	**Average log(CSS) value**
OPC-TMT-20/20	TMT	5.83×10^9	9.765
OPC-CRS-20/20	CRS	2.25×10^7	7.352

Table 8 reports the result of ANOVA for two steel types. From this table it is observed that, the calculated F- value is higher than the corresponding tabulated F-values at 99% confidence level with P-value 0.00062 (< 0.01) which clearly indicates that there is enough evidence to reject the null hypothesis that all the data are drawn from populations with the same mean. This suggests that, the variation in steel type has significant effect on CSS values indicating better performance of CRS rebar as compared to TMT rebar.

TABLE 8: ANOVA RESULTS FOR STEEL TYPE

Source of Variation	**SS**	**df**	**MS**	**F-ratio**	**'F' from Fisher's Distribution at 99% probability**	**P-value**
Between factors	10.77	1	10.77	**94.77**	**21.19**	**0.00062**
Within factors	0.45	4	0.113			
Total	11.23	5				

4. Conclusions

This work demonstrates the potential of AE technique as a corrosion detection technique within the laboratory. The technique is successfully used to detect corrosion in a variety of singly reinforced concrete cylinders under accelerated corrosion. The influence of material properties is studied successfully using CSS parameter of AE technique. Though, the research is extensive in time and effort, it is believed that within the data presented, interesting results have been observed in an area where there is little published data. The following major conclusions can be drawn from the work investigated in this paper:

1. The research suggests that CSS value is a useful parameter to detect corrosion of reinforcement embedded in concrete and can be further used for study of effect of material properties on AE.
2. From the results of ANOVA, it is concluded that variation of C/D ratio has no significant effect on CSS values due to corrosion, though an increase in CSS values were observed for specimens with larger rebar diameter and lesser cover thickness.
3. The results of ANOVA indicate a significant effect of cement type and steel type on CSS values due to corrosion and steel type has the strongest effect on magnitudes of CSS followed by cement type.
4. Based on above study, it may be possible to carry out field investigation to assess extent of damage due to corrosion using CSS parameter of AE by considering the effect of variation in material properties.

It is recommended to extend the work further for obtaining larger data for confirmation of the results presented in this paper.

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