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Research Article

Corrosion Measurements in Reinforced Fly Ash Concrete Containing Steel Fibres Using Strain Gauge Technique

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Corrosion of steel bars in concrete is a serious problem leading to phenomenal volume expansion and thereby leading to cover concrete spalling. It is well known that the reinforced concrete structures subjected to chloride attack during its service life cause these detrimental effects. The early detection of this damage potential can extend the service life of concrete. This study reports the comprehensive experimental studies conducted on the identification of corrosion mechanism in different types of reinforced concrete containing class-F fly ash and hooked steel fibres. Fly ash replaced concrete mixes were prepared with 25% and 50% fly ash containing steel fibres at 0.5%, 1.0%, and 1.5% by volume fraction. Corrosion process was investigated in an embedded steel bar (8 mm diameter) reinforced in concrete by passing an impressed current in sodium chloride solution. Strain gauge attached to the rebars was monitored for electrical measurements using strain conditioner. Strain gauge readings observed during the corrosion process exhibited the volume changes of the reinforcement embedded inside the concrete. The corrosion potential of different steel fibre reinforced concrete mixes with fly ash addition showed higher resistance towards the corrosion initiation.

1. Introduction

Reinforced concrete corrosion studies have drawn significant attention owing to high potential for the deterioration of structures during its service life. The process of corrosion occurs in reinforced concrete due to depassivation of protective layer in steel. This can occur when the concrete quality is deteriorated over time as a result of improper material design. Permeability of concrete is the process by which the deterioration starts in cementitious systems. Also, the initiation of corrosion is primarily dependent on the alkalinity of concrete surrounding the steel bars. Depending upon the alkalinity, the process of depassivation occurs in concrete leading to formation of anodic sites on the steel bars. It was shown in many research studies that the incorporation of fine filler materials or the pozzolanic inclusions can form a refined microstructural formation in concrete. This also ensures a good quality of concrete which can serve better for long term durability. However, corrosion in reinforced concrete needs to be identified in the initial stages in order to protect and take remedial measures for protecting it. Several studies indicated that the addition of large volume fly ash in cement concrete provides adequate refinement of pore structure leading to impermeability. It was demonstrated that the ternary blends of fly ash, cement, and silica fume improved the resistance to chloride ion penetration and hence the corrosion rate was found to be significantly reduced [1]. Permeability of concrete dictates the durability performance of concrete and the deterioration is affected by the grade of concrete. Fibre reinforcements in concrete provide adequate tensile performance leading to reduction in cracking of concrete upon loading. In addition the type of aggregate used in concreting was found to affect the corrosion of rebar corrosion [2]. Corrosion resistance of reinforcing bars can be minimized with the addition of inorganic mineral admixture such as slag and fly ash. The improvements on the microstructural formation due to type of curing adopted provide early attainment of corrosion shielding and provide long term durability [3]. It is also suggested that the blended cements consisting of silica fume and metakaolin provide more resistance towards corrosion initiation. The effects of chloride content in curing water affect the early strength gain properties and hence

Table 1: Concrete mixture proportions adopted in the present study.

Mix ID	w/b ratio	F/c ratio	B/TA ratio	Steel fibres % (V_f)	Accelerator %	PCE %	Fly ash %	Cement	Fly ash	Fine aggregate (kg/m^3)	Coarse aggregate	Water
MC1	0.3	0.6	0.26	0	0	1	0	473	0	672	1113	142
MC2	0.3	0.6	0.26	0.5	0	1	0	473	0	672	1113	142
MC3	0.3	0.6	0.26	1	0	1	0	473	0	672	1113	142
MC4	0.3	0.6	0.26	1.5	0	1	0	473	0	672	1113	142
MFC1A	0.3	0.6	0.26	0	1	1	25	355	118	672	1113	142
MSF1	0.3	0.6	0.26	0.5	1	1	25	355	118	672	1113	142
MSF2	0.3	0.6	0.26	1	1	1	25	355	118	672	1113	142
MSF3	0.3	0.6	0.26	1.5	1	1	25	355	118	672	1113	142
MFC2A	0.3	0.6	0.26	0	1	1.5	50	237	236	672	1113	142
MSF7	0.3	0.6	0.26	0.5	1	1.5	50	237	236	672	1113	142
MSF8	0.3	0.6	0.26	1	1	1.5	50	237	236	672	1113	142
MSF9	0.3	0.6	0.26	1.5	1	1.5	50	237	236	672	1113	142

Note: B/TA: binder to total aggregate ratio; F/c: fine to coarse aggregate ratio; w/b: water to binder ratio; PCE: polycarboxylate ether based superplasticizer; V_f: volume fraction.

causes durability degradation. Also the studies revealed that the longer curing of concrete showed good improvement on strength and durability index [4, 5]. It is also reported in another study that the corrosion of steel fibres occurs in concrete which causes the failure in bridging the microcracks and decreases the strength of concrete. The provision of adequate cover to reinforcement and incorporation of suitable corrosion inhibitors can avoid the corrosion process [6, 7]. The propagation of corrosion in reinforced concrete is affected due to environmental conditions such as humidity, moisture movement in cover concrete, grade of concrete, amount of cement, and mineral admixtures added. It is understood that structures exposed to wet environment with poor cover concrete draw significant corrosion initiation [8]. Microsteel fibre addition had shown significant improvements on the matrix densification and was found to be effective in mitigating the rebar corrosion. Test methods such as corrosion potential measurements and potentiodynamic polarization were best used for detecting the corrosion process. The corrosion of the fibres produces the spalling effects of concrete and could possibly reduce the sectional area of the fibres, posing threat to concrete durability for the design period [9, 10]. It was also observed that the structures subjected to different loading cycles can suffer serious stress corrosion due to bond slip with the substrate concrete. The well developed bond in corrugated steel showed lesser corrosion potential than plain steel due to effective bonding with concrete. It is also understood that the increase in corrosion thickness causes a reduction in the bond strength at the interface of concrete and steel [11–13]. Research studies in the past showed minimization of chloride transport and can lead to changes in the corrosion rate of steel in cement-based materials, such as concrete. It is well documented from the earlier studies that the addition of fine filler materials and discrete steel fibres in concrete can envisage the durability properties of reinforced concrete [14–17]. The above research studies clearly suggest the different mechanism of corrosion occurring in reinforced concrete. Corrosion is mainly caused in reinforced concrete due to permeability properties, poor cover concrete, and severe environmental conditions. It is also understood that suitable test methods are needed to examine the corrosion potential of embedded steel bar in different cementitious system. Also, a systematic evaluation is needed to identify the mechanism of corrosion in reinforced concrete with the effects of blended cementitious system. The rate of corrosion mechanism in accelerated corrosion environment and the effects of fibre reinforcements for controlling corrosion rate need to be evaluated systematically. The present study is motivated to identify the corrosion process occurring in embedded steel bar in plain cement concrete and compared with that of fly ash substituted reinforced concrete systems. The effects of steel fibre addition in different fly ash based concrete systems on the corrosion mechanism was given in this study. The corrosion potential was measured using strain gauge principle to monitor the volumetric expansion occurring in concrete and strain recordings were noted at different time intervals. The test results indicated that corrosion mechanism can be potentially monitored in concrete to assess the integrity of concrete to protect the rebar corrosion.

2. Experimental Methodology

Experimental investigations have been carried out using strain gauge sensors for the corrosion monitoring of reinforced cement concrete (RCC) element. The behavior of twelve different types of reinforced concrete specimens in an accelerated corrosive environment was studied. The details of various concrete mixture proportions taken for the study are given in Table 1. Concrete mixes were proportioned based on fine to coarse aggregate ratio (F/c) ratio of 0.6 with low water/binder (w/b) ratio of 0.3 containing an ordinary Portland cement (OPC) 53 grade. A low calcium class F fly

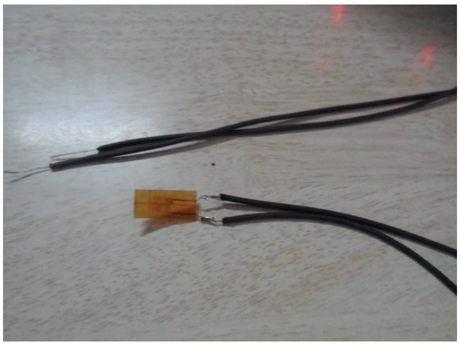

Figure 1: Strain gauge used for corrosion strain measurement.

ash based mineral admixture was used as cement replacement material and was substituted at 25% and 50% by weight of binder. The composition of fly ash consisted of 34.65% silica, 24.3% alumina, and carbon content of less than 5%. Hooked steel fibres of 35 mm long with 0.5 mm diameter were used as discrete reinforcing mechanism. The tensile strength of steel fibre was around 1210 N/mm^2 with an elastic modulus of 205 GPa. The fine aggregate passing through 2.36 mm sieve and crushed blue metal coarse aggregate passing through 12.5 mm were used as concrete fillers. Chemical admixtures such as accelerator (calcium nitrate) was used at 1% with addition of superplasticizer at 1% and 1.5% by weight of binder material for improving the strength gain and workability properties, respectively. Cylindrical specimens with a dimension of 100 mm × 200 mm [18] were cast and this specimen shape was preferred due to perfect geometry for the homogeneous intrusion of corrosive agents. A mild steel (MS) rebar of 8 mm diameter and 200 mm length was embedded into the fresh concrete specimen. Before embedding the rods in the concrete specimen, the portion on the rod at the strain gauge location was polished smoothly for attaching the strain gauge (snapshot shown in Figure 1). A gauge length of 150 mm of the reinforcement was embedded into the concrete specimen. The exposed length of the reinforcement is coated with an anticorrosive paint to prevent corrosion. Figure 2 shows the instrumentation details of the reinforcement. Strain conditioner was used for recording the strain signals obtained from the strain gauge and the snapshot is shown in Figure 3 and schematic picture of the test setup is shown in Figure 4. The specimen was left in this state for another 7 days till the specimen becomes fully saturated in the NaCl solution. After the specimen is fully saturated, the rod was connected to an electrical circuit which acts as the anode and a steel metal plate acting as the cathode. A constant supply of 60 V was applied and this setup was used to accelerate the corrosion process as shown in Figure 5. The corrosion process was monitored continuously using a data recorder and the strain gauge values obtained from the strain conditioner were recorded and analyzed. Any change in the strain is detected as the initiation of corrosion in the reinforcement bar due to the development of tensile stresses. At this level, cracks will appear on the surface of the concrete specimen due to the increase in diameter of the reinforcement. The strain

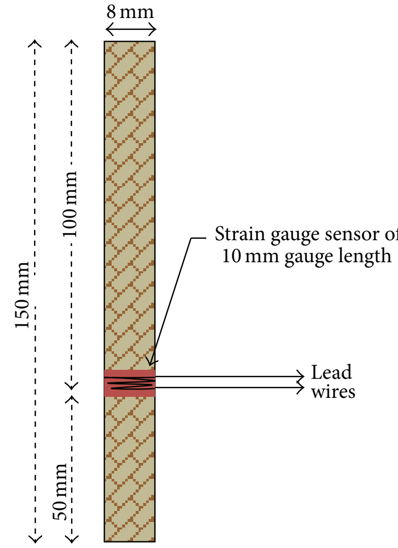

Figure 2: Instrumentation details of steel bar.

Figure 3: Snapshot for concrete specimens immersed in 3.5% sodium chloride solution.

developed in the concrete specimen, measured from the strain gauge sensor, was used to identify the corrosion process and snapshot of corroded rebar with rust stains on concrete surface as shown in Figure 6.

3. Experimental Test Results and Discussions

The strain gauge values obtained from the strain conditioner were recorded and the corresponding strain values were obtained for different time periods upto 90 days of testing. The feasibility of using this corrosion monitoring technique is evaluated for various concrete mixes containing different mix constituents containing fly ash and steel fibres. It can be noted from the test results given in Table 2 that corrosion initiation started after 7 days for all concrete specimens. In the case of rebar embedded in plain concrete, the corrosion started at 8th day with an indication in the strain gauge reading (as seen in Figure 7) with a maximum microstrain value of 1020 (MC1). The strain values obtained from the strain gauge conditioner were analyzed and it was seen that there was no considerable variation in the strain gauge reading till 7 days for all the specimens. After this, the strain value showed a considerable increase from 7th day to 15th day and thereafter

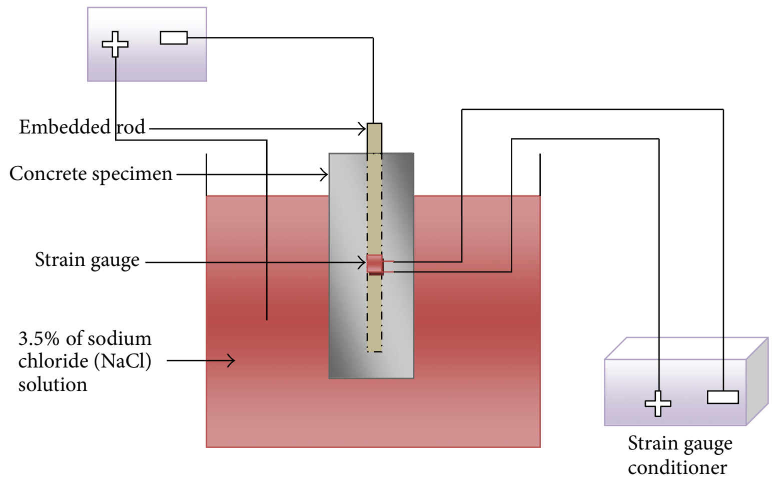

FIGURE 4: Schematic picture of the test setup.

TABLE 2: Microstrain values for various mixture proportions of concrete.

Mix ID	Fly ash %	Steel fibres % (V_f)	Microstrain (μm)							Total thickness of corroded bar at 90 days (mm)
			1 day	3 days	7 days	14 days	28 days	56 days	90 days	
MC1	0	0	0	0	0	601	731	842	1020	9.02
MC2	0	0.5	0	0	0	632	762	813	981	8.98
MC3	0	1	0	0	0	693	715	795	802	8.80
MC4	0	1.5	0	0	0	542	691	757	840	8.84
MFC1A	25	0	0	0	0	561	658	840	943	8.94
MSF1	25	0.5	0	0	0	494	582	701	750	8.75
MSF2	25	1	0	0	0	537	671	749	831	8.83
MSF3	25	1.5	0	0	0	571	642	810	933	8.93
MFC2A	50	0	0	0	0	415	580	642	758	8.76
MSF7	50	0.5	0	0	0	393	511	563	712	8.71
MSF8	50	1	0	0	0	372	434	519	696	8.69
MSF9	50	1.5	0	0	0	314	382	492	632	8.63

FIGURE 5: Accelerated corrosion test setup of concrete specimens connected to strain gauge conditioner.

FIGURE 6: Snapshot of corroded rebar with rust stains on concrete surface.

a steady increase in strain value was observed. Upon reaching the maximum strain value, visible signs of cracks appeared on the concrete surface due to the increase in diameter of the rebar during corrosion, whereas the steel fibre addition at 0.5% V_f showed that the initiation of corrosion occurred only after 11 days (as seen in Figure 7) with a microstrain value of 981. With an increase in steel fibre dosage to 1.5% V_f the corrosion process was found to be delayed and occurred after 15 days with a microstrain value of 840. This is significant due to the improvement in water tightness due to fibre bridging that the microcracks caused during the onset of cracking and subsequent expansion of steel rod. Steel fibres

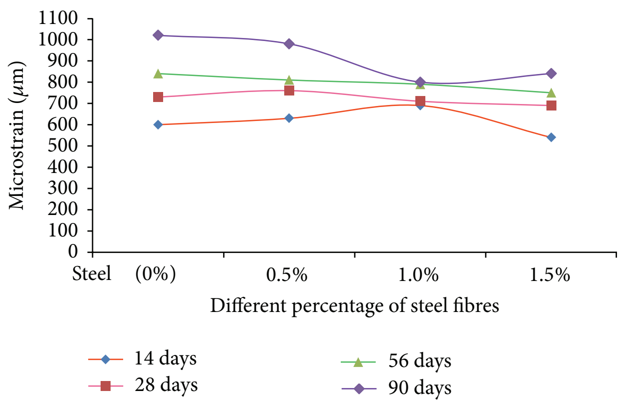

Figure 7: Microstrain measurements for plain reinforced concrete with steel fibres.

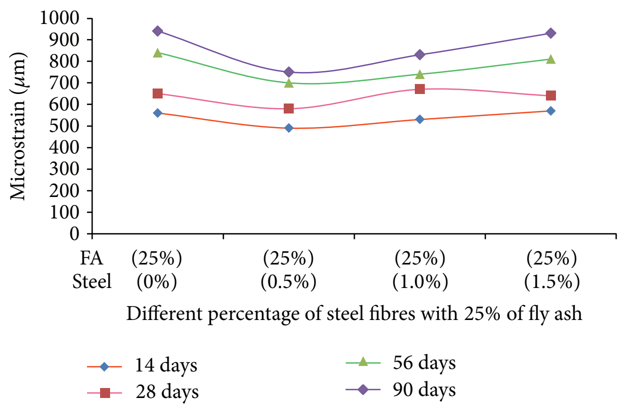

Figure 8: Microstrain measurements for reinforced fly ash (25%) based concrete containing steel fibres.

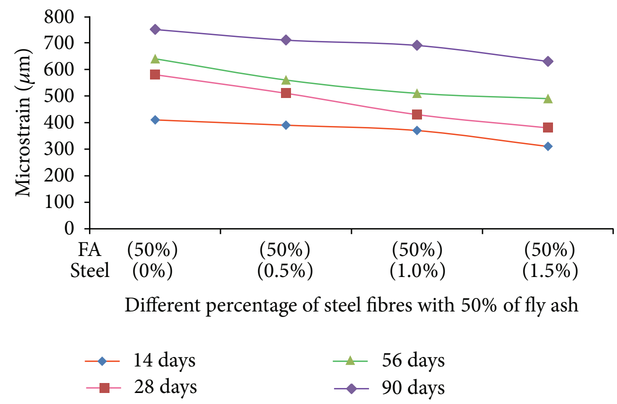

Figure 9: Microstrain measurements for reinforced fly ash (50%) based concrete containing steel fibres.

Figure 10: Snapshot of plain concrete specimens with corroded rebar.

are known to play a vital role in preventing or delaying crack formation. The additional discontinuous reinforcements such as steel fibres are known to cause significant crack inhibition during any chance of rebar corrosion and further expansion. However a significant improvement was noted in the case of fly ash concrete specimens where the corrosion potential was found to be considerably reduced than the plain steel fibre concretes. The addition of steel fibres along with 25% fly ash addition has delayed significantly the corrosion potential due to synergistic interaction in pore refinement and crack arresting during volume expansion (as seen in Figure 8). Also, the increase in fly ash addition upto 50% exhibited a higher value owing to higher water tightness and well defined microstructural formation (as seen in Figure 9). The intensity of corrosion that occurred in plain reinforced concrete specimen is shown in Figure 10. The thickness of corroded bar in all the specimens was analysed using a microscope and the resolution of image was calibrated using a graduated scale kept on the specimen while capturing the image. The microscopic images of selected concrete specimens of plain and fly ash concrete are provided in Figures 11, 12, and 13. It is noted from Table 2 that the thickness of corrosion product for plain concrete was around 9.02 mm and the microscopic image of plain concrete is shown in Figure 11. It can be also seen that the steel fibre addition reduced the thickness of corrosion (8.84 mm). The addition of fly ash and steel fibres in plain reinforced concrete was found to reduce the corrosion intensity. The corroded rebar in the case of 25% fly ash is shown in Figure 12 and the maximum corrosion thickness was around 8.93 mm. It can be seen from the microscopic analysis that the fly ash addition upto 50% showed significant improvements on the microstructural alterations owing to additional hydration reaction at later ages. This leads to the reduction in corrosion intensity with the formation of thickness of the corrosion product around 8.63 mm. The microscopic image of corroded bar in 50% fly ash substitution in concrete is shown in Figure 13. This subsequently led to the water tightness and closed pore structure formation protecting the embedded metal inside the concrete. The higher fly ash (50% by weight of cement) substitution had a remarkable effect on the pore refinement since the calcium hydroxide crystals are consumed during complete hydration process. It is well understood from the test results that the corrosion mechanism is primarily dependent on the pore structure interaction with the external intrusion of chloride ions. The necessary barrier in the form of pore closure is primarily developed inside the concrete system with suitable pore fillers such as fly ash based mineral admixtures. In the case of vulnerable environmental condition wherein the breakup of barrier occurs, the presence of steel fibres envisages the crack

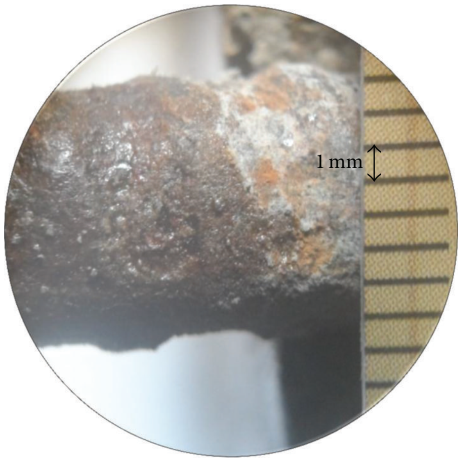

Figure 11: Microscopic image of corroded rebar in plain concrete.

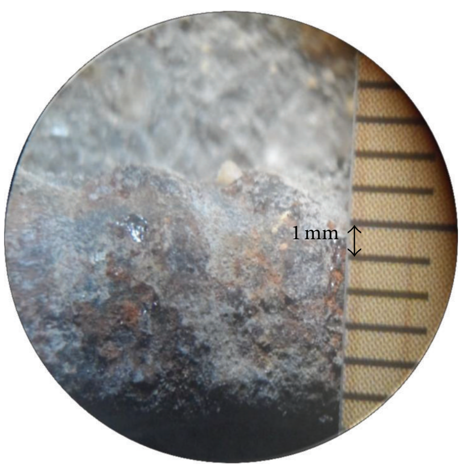

Figure 12: Microscopic image of corroded rebar containing 25% of fly ash concrete.

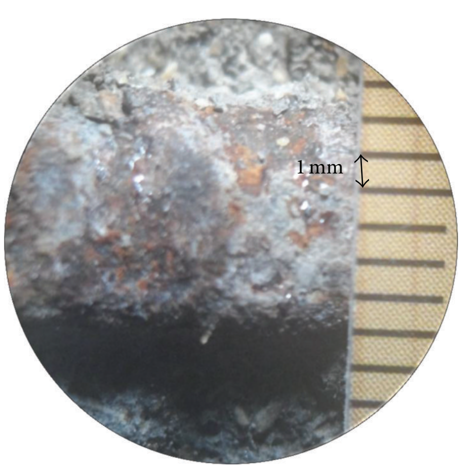

Figure 13: Microscopic image of corroded rebar containing 50% of fly ash concrete.

bridging during volume expansion. It is also understood that volume expansion occurring in concrete due to shrinkage can be also an instrumental factor for cracking in concrete apart from corrosion cracking.

4. Conclusions

The following salient conclusions are drawn within the limitation of the present study.

(i) The present technique developed for monitoring the corrosion of reinforced concrete using strain gauge sensors was found to provide a reliable estimate on the intensity of corrosion. Experimental studies showed the sensitivity of strain gauge sensors to identify corrosion activity in reinforcement (RCC) structural elements.

(ii) Corrosion monitoring has been successfully conducted on the various concrete specimens containing fly ash and steel fibres at different dosage levels.

(iii) In the case of steel bars embedded in plain concrete, the initiation of corrosion started immediately after the 7th day and a maximum corrosion strain (1020 microstrains) was observed compared to all other reinforced concrete specimens. However, the addition of steel fibres at increased fibre dosage showed that the corrosion intensity was minimized gradually.

(iv) The effect of adding fly ash was significant in terms of reduction in the corrosion process as the fineness of fly ash improved the pore refinement and further access to deteriorating agents was minimized even at accelerated corrosion process. This effect was more appreciable with higher substitution of fly ash.

(v) The intensity and thickness of corrosion were found to be minimal for fly ash based concrete systems in the accelerated corrosion environment.

(vi) Microscopic image analysis for different corroded rebars in concrete was found to provide a reliable estimate on the severity of corrosion.

(vii) The strain gauge technique for corrosion monitoring was found to be an effective method to identify the point of initiation and propagation of corrosion in a reinforced concrete structure. This detection methodology can suggest protective measures for rebar corrosion protection and can be helpful for a protective material design.

(viii) It was also noted that the point of initiation and propagation of corrosion in all reinforced concrete specimens suggest the time of occurrence and the start of depletion of alkalinity in the system.

(ix) Corrosion propagation varies depending upon the various conditions to which the concrete specimen is subjected to deterioration and this is a feasible technique suitable for identifying the initiation of corrosion in the initial stages.

(x) Monitoring of corrosion is an essential part of structural health monitoring and necessitates the proper instrumented facilities for detecting early occurrence of corrosion in RCC structures.

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