Cathodic Protection of Steel from Corrosion in Reinforced Concrete Buildings using Sacrificial Surface Anodes of Zinc

Jaiprakash B. Sharma, Yogesh D. Patil, Gaurang R. Vesmawala

Abstract*: Corrosion of steel in reinforced cement concrete is one of the major factor for deterioration of RCC structures. The corrosion of steel leads to failure or needs demolition of structures. Cathodic protection technology is well proven for corrosion protection of steel and in 2020 this technology will complete its 200 years of existence. For RCC buildings cathodic protection technology is not common due to several reasons. The lack of awareness in public about the fact that maintenance is only cosmetic repair and it does not ensure the protection of steel from corrosion. The sacrificial anode CP system is well suited for buildings since the requirement of anode material will always be less in case of buildings. To make it popular a new system of SACP is developed and it is named as Sacrificial Surface Anode Cathodic Protection (SSACP) system. The device is designed as external, it is easy in installation, replacement and monitoring. It is reliable, economical and does not damage the aesthetic appearance of building. The present research is about onsite corrosion prevention of steel using Sacrificial Surface Anode. For evaluation of performance a number of SSA are installed in one of the multi-story buildings in Surat city about 18 km from sea shore. This includes the working of SSA which depends upon the resistivity and moisture content of concrete cover to reinforcement.

***Index Terms*: Cathodic Protection, Sacrificial Surface Anode, Resistivity of Concrete, and Conductivity of concrete.**

I. INTRODUCTION

The structures built before the innovation of modern cements used the lime as binding material and stone, bricks or timber were used for making structural elements. The raw materials used for production of cement are oxides of calcium carbonate and silica in majority so it is assumed that the concrete made by using today's modern cement will have a useful life more than 100 year. Similarly, it is assumed that the steel will have a useful life much more than concrete if protected and proper metallurgical composition is designed With the advancements in technology of cement and steel world became more confident that any structure made of reinforced cement concrete will have a life span of more than 100 years. In the race of development, we forgot the law of conservation of energy which is responsible for changing one form of material to another form. The cycle time may be few hours to thousand years.All materials natural, artificial or composite require proper storage or maintenance. The experience of last fifty years shows that the structures built with cement and steel available in seventies are still better compared to structures built in nineties. The reasons are lower grade of cement, low rise buildings, higher factor of safety lowering the actual stresses, and less number of structures to look after by the concerned agencies. Still many reasons are there we have put only few for attention of readers.

The present average life of RCC buildings in India in coastal areas is about 30 to 60 years depending upon a number of factors. The major cause is corrosion of reinforcement and further reduction of strength of structure. The various techniques in practice, to minimize or to stop the corrosion, are Metallurgical Methods, Corrosion Inhibitors, Coating to Reinforcements, Coating to Concrete, Design and Detailing and Cathodic Protection.

The metallurgical method, corrosion inhibitors, coating to reinforcement, design and detailing are the methods of corrosion protection which can be applied before or during construction. The coating to concrete is a method which delays the corrosion but for existing structure in which already corrosion has started or to stop initiation of corrosion the only method is cathodic protection.

II. HISTORY OF CATHODIC PROTECTION

The history of cathodic protection may be very old but the first cathodic protection was investigated in 1820 by Sir Humphrey Davy. He used small quantities of zinc and iron for protecting the copper sheeting. The terminology used by him was *cathodically protected*. In 1834 he discovered the relation between corrosion weight loss and electric current which laid the foundation for future application of cathodic protection.

After about 100 years of Davy's research cathodic protection was widely adopted as corrosion protection method. In US the cathodic protection was adopted for protection of thin walled pipe line used for transmission of oil and natural gas. Till 1945 this method was well established in United States.in 1959 Richard

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Stratfall of California Department of Transportation installed an experimental CP system on a bridge support beam.

In 1970 to address the corrosion problem of RCC structures efforts were made and numerous technologies were adopted to reduce the corrosion and CP was found to be most effective technology to stop corrosion of steel.

In UK after 1952 the CP was used for protection of fuel pipeline of about 1000 miles. In 1982 an FHWA policy statement reported that cathodic protection is the only technology which can effectively stop corrosion of reinforcement in RCC.

In 1984 in UK there was increasing concern regarding the cost of repair and maintenance of buildings and highway structures arising from corrosion of reinforcement. The most significant research work in UK was TRL programmme to determine the efficacy of cathodic protection. As an estimate about 2 million square meter of concrete have been protected by cathodic protection throughout the world and about 200000 square meter of cathodic protection is applied in UK according to CPA data base [9].

The continuous research and application led the publication of European Standard EN 12696-2000.Norway and Denmark are leading supplier of cathodic protection system. CP system were installed in Australia and Hong Kong as early as 1996.

The CP technology is widely used now a days all over the world in cooling towers, bridges, car parks, jetties, wharfs, oil pipelines, oil storage tanks and buildings but it is not common for buildings in any region of the world.

III. CORROSION MECHANISM OF STEEL IN RCC

The present corrosion is deterioration of material due to its reaction with environment. Corrosion of steel can be considered as reverse metallurgy. Some metals like gold, silver and platinum occur in their natural form hence they are stable. Other metals like iron are found in the form of ores, natural oxides, sulphides and other reaction products. The iron is derived from its ores by metallurgical process and absorb and retain the energy needed to extract it from ore. This state of metal is unstable and it tends to recombine with the elements present in the environment to return to its natural form. The natural form is regained by losing extra energy absorbed during extraction process.

The corrosion of steel is an electrochemical reaction. The corrosion of reinforcing steel in concrete in the presence of oxygen but in the absence of chlorides occurs in few stages.

It involves the movement of electrons from one point of reinforcing steel (Anode) to the other point in reinforcing steel (Cathode).At the anode oxidation of reinforcing steel occurs and electrons are released .

$$Fe \rightarrow Fe^{2+} + 2e^-$$

The released electrons move to the area of reinforcing steel which behaves as cathode and these electrons combine with moisture and oxygen to produce hydroxyl ions.

$$2e^- + H_2O + ½ O_2 \rightarrow 2OH^-$$

The hydroxyl ions produced by this reaction combine with ferrous ions and form ferrous hydroxide as shown in figure 1.

$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$$

In the presence of oxygen and water the ferrous hydroxide is further oxidized and ferric hydroxide is formed.

$$4Fe(OH)_2 + O_2 + H_2O \rightarrow 4Fe(OH)_3$$

Subsequent oxidation produces iron oxide (rust)

$$2Fe(OH)_3 \rightarrow Fe_2O_3.2H_2O$$

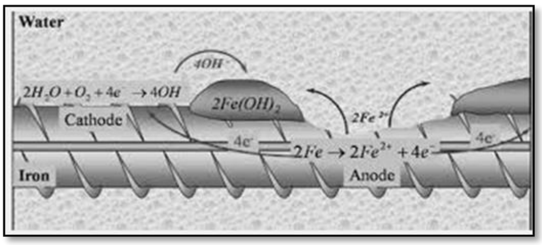

Figure 1: Electrochemical reaction in the presence of oxygen and water

When chloride ions attack the reinforcing steel it forms an intermediate soluble product iron chloride complex

$$Fe + 2Cl^- \rightarrow (Fe^{2+} + 2Cl^-) + 2e^-$$

This intermediate iron chloride complex diffuses at other location of reinforcing bar with more pH and higher oxygen concentrations. Its reaction with hydroxyl ions produce $Fe(OH)_2$.This product further reacts with water and produces ferrous hydroxide.

$$(Fe^{2+} + 2Cl^-) + 2H_2O + 2e^- \rightarrow Fe(OH)_2 + 2H^+ + 2Cl^-$$

Further these hydrogen ions and electrons combine and produce hydrogen gas

$$2H^+ + 2e^- \rightarrow H_2$$

Similar to the case of corrosion of reinforcing steel without chlorides, in the presence of oxygen and moisture ferrous hydroxide, is oxidized further to form iron oxide (rust)

$$4Fe(OH)_2 + O_2 + H_2O \rightarrow 4Fe(OH)_3$$

$$2Fe(OH)_3 \rightarrow Fe_2O_3.2H_2O$$

IV. CATHODIC PROTECTION TECHNIQUES FOR REINFORCED CONCRETE

The cathodic protection system can be classified as internal or external, Sacrificial Anode Cathodic Protection (SACP) system or Impressed Current Cathodic Protection (ICCP) system. After studying the comparison of SACP and ICCP it has been found that for buildings SACP is more suitable.

The various CP techniques have been developed for protection of steel from corrosion in reinforced concrete structures. EN 12696 elaborates various SACP methods like conductive coating anode system, activated titanium anode system, titanium ceramic anodes, conductive cementitious anodes, embedded galvanic anodes and surface mounted galvanic anodes. Cathodic protection technique is well proven and in use since 1820 but is not so common for RCC buildings in India. The reason may be the initial cost, lack of popularity and lack of awareness about preventive system of structural health. One of the reason may be the reliability of protection after installation in the minds of general public. All SACP methods do not facilitate the instrumental monitoring of the system, only surface appearance or removal of surface cover may show the effectiveness of system. Instrumental monitoring is possible only in ceramic anodes. For RCC buildings the SACP is most suitable but it will be only adopted widely if the SACP is external, easy to install, easy to replace, easy to monitor, reliable, economical and does not change the aesthetic appearance of building.

After studying all methods of sacrificial anode cathodic protection (SACP) it is felt that for RCC buildings there is a need of a cathodic protection device which is external, simple in installation and replacement, economical and facilitates monitoring for its reliable working. To fulfill these requirement the external Sacrificial Surface Anode Cathodic Protection (SSACP) device is designed in such a way that it justifies the above requirements i. e. simplicity in installation and replacement, economical and facilitates the monitoring of protection system.

The life of SSACP system will depend upon the life of wiring, polycarbonate box, but overall life of SSACP system can be expected between 10 to 15 years and with replacement anything between 10 to 120 years [9].

V. SACRIFICIAL SURFACE ANODE

The design details of **Sacrificial Surface Anode** is described below [18].

1. The anode is of zinc having size 75mm X48mm X12mm as shown in figure 2.
2. The zinc anode is provided with a 3mm hole to fix connecting wire of copper for connection. This facilitates the measurement of potential and current as shown in figure 2.
3. The zinc anode is packed in a synthetic woollen cloth bag with backfill and wire terminal is taken out from bag as shown in figure 3.
4. The backfill material has a composition of 75% bentonite and 25% gypsum which provides better surface contact with concrete and retains moisture for longer duration and improves electrical conductivity.
5. The bag containing backfill and anode is placed in polycarbonate box with 8 mm flexible PVC sheet packing as shown in figure 2. The flexible PVC sheet facilitates the accommodation of increase in volume of anode after oxidation.
6. The polycarbonate box of size 200mm X100mm X 50mm without cover is used to house the anode assembly. In this one side is open to have contact on concrete surface. The complete assembly is shown in figure 3. The material is durable for external use.

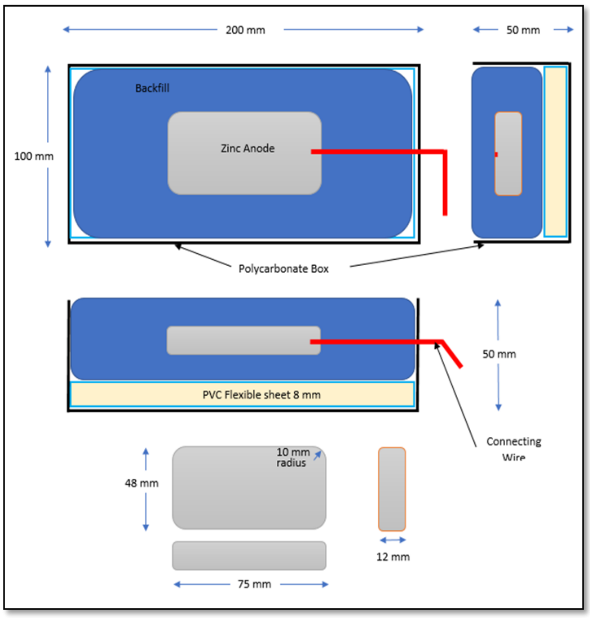

Figure 2: Sacrificial Surface Anode assembly

Figure 3: Sacrificial Surface Anode

VI. FUNCTIONING OF SACRIFICIAL SURFACE ANODE CATHODIC PROTECTION SYSTEM

The sacrificial surface anode is installed on the surface of concrete in the vicinity of reinforcement. This anode has a copper wire terminal. The other terminal is taken from reinforcement as shown in figure 4. The functioning of this Sacrificial Surface Anode can be ascertained by measurement of potential and current between reinforcement and anode.

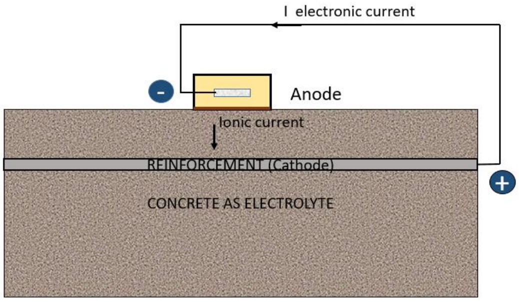

Figure 4: Schematic Diagram of Sacrificial Surface Anode Cathodic Protection System

To study the performance of sacrificial surface anode a building Sunstar Apartment of Adajan area of Surat city , Gujarat State, India as shown in figure 5 is selected and total 7 such anodes are installed in the building's first floor periphery in the manner as shown in figure 4. All such anodes are connected to the reinforcement. The copper wire were attached to the reinforcement at the time of repairing. The figure 5 shows the actual building which has undergone repairing 4 years back in which sacrificial surface anodes are installed. Figure 4 shows the anode installation and connectivity with reinforcement.

Figure 5: Sunstar Apartment in Surat City under SSACP study

VII. FACTORS INFLUENCING FUNCTIONING OF SSACP

The working of sacrificial surface anode is dependent upon electrical conductivity of concrete cover. The electrical conductivity means here Bulk Electrical Conductivity of concrete cover since the concrete is comprised of cement paste, fine aggregate and coarse aggregate. The ASTM standard C 1760-12 recommends a method for determination of bulk electrical conductivity of saturated specimens of hardened concrete [7]. This method cannot be employed here as the place at which the SSA is to be installed is in the proximity of reinforcement and reinforcement affects the results of conductivity. It can be used on cores taken from the structures. Also the deteriorated structures may have different conductivity at different location and a large no of core sections are required which may not be advisable for such structures. Also the conductivity of concrete cover is more important for the effective working of sacrificial surface anode. The conductivity is inverse of resistivity. In general resistivity is measured and the conductivity is determined as required.

A. Electrical conductivity

A number of factors affect the electrical conductivity of concrete they are elaborated here.

1. *Water cementitious material ratio*

The water cement ratio plays an important role in conductivity of concrete. Higher water cement ratio gives more pore space and facilitates movement of pore fluid and gives more conductivity [8],[1]. Such concrete are also less durable and more susceptible to corrosion of steel.

2. *Type of cementitious material*

Electrical conductivity decreases with the addition of silica fumes, pozzolana and other fine material. Such materials reduce the pore space and make the concrete dense and reduce the conductivity of concrete [1].

3. *Presence of salts in concrete making materials*

Presence of salt from mixing water or fine aggregates increases the conductivity of concrete [11].

4. *Age of concrete*

Age of concrete has dual effect on conductivity of concrete. The loss in pH of concrete increases conductivity and also, the loss of pore fluid decreases conductivity.

5. *Density of concrete*

The density of concrete has a major influence on conductivity of concrete. The dense concrete may not have more spaces for pore fluid and this causes decrease in conductivity. In other ways the concrete protects steel from environmental attack and makes the structure durable.

6. *Size and type of aggregates*

The size and type of aggregate affects the microstructure of concrete, pore size distribution, interconnectivity of pores and conductivity of pore fluid so it has a governing factor for conductivity of concrete [8].

7. *Air voids in concrete*

The conductivity of concrete is due to pore fluid and air voids in concrete facilitates the existence of pore fluid hence air voids increase the conductivity of concrete but too much air void in dry concrete may act as barrier and for saturated concrete may act as facilitator for conductivity.

8. *Degree of saturation*

Degree of saturation is the most significant factor for conductivity of concrete. Since it provides electrolyte in the porous system of concrete. The conductivity increases with increase of degree of saturation. This phenomenon has been used for ideal location of Sacrificial Surface Anode.

9. *Temperature*

Change in temperature also affects the conductivity of concrete. Increase of temperature causes increase in conductivity .The effect of temperature on the conductivity is also significant since it reduces the moisture content also. The movement of ion is affected by temperature and the electrical conductivity of concrete increases with increase in temperature. It is also found that change in temperature by 1^0 Celsius affects the electrical conductivity by about 3%.

Figure 6,7 and 8 show the change in potential difference measured for three surface anodes which are installed on inner side of RCC sunshade and the outer side faces sunlight. The graph is for 24 hours midnight to midnight.

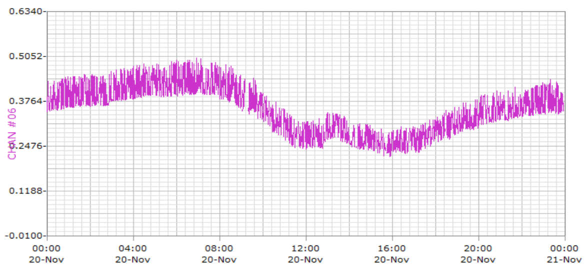

Figure 6 : Effect of sunlight on the conductivity of sacrificial surface anode at point 6A

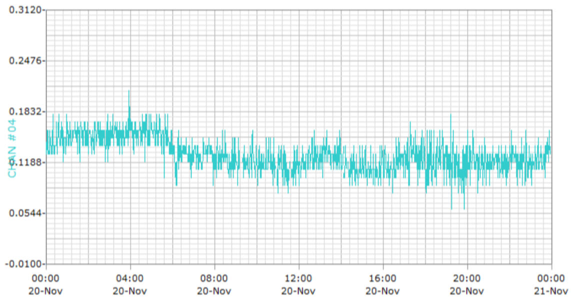

Figure 7 : Effect of sunlight on the conductivity of sacrificial surface anode at point 4A

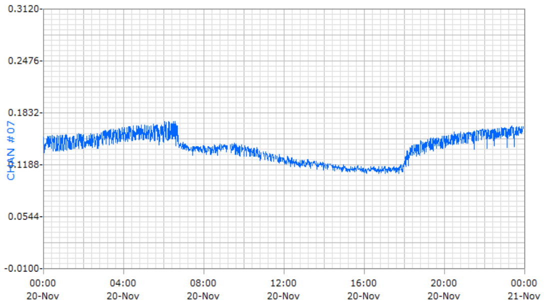

Figure 8 : Effect of sunlight on the conductivity of sacrificial surface anode at point 7A

10. Crack in concrete

When the interconnectivity of pore network in the concrete is broken the movement of ion is disrupted. The crack in the concrete acts as insulation barrier and the conductivity of concrete decreases. Therefore the conductivity of concrete can be used for detection of crack in concrete.

The concrete is porous composite material and variation in conductivity is dependent more on moisture content i.e. degree of saturation. It may exhibit conductive or insulating characteristic, it might show very high electrical resistance when it is dry.

B. *Measurement technique for measuring conductivity of concrete cover*

RILEM TC 154 EMC [16] specifies a method to determine the resistivity of concrete cover which is the governing factor for working of SSACP. In this method one electrode is placed on concrete surface and the other electrode is the reinforcement just beneath the cover as shown in figure 9. In this a circular disc of diameter a is placed on concrete surface in the vicinity of reinforcement. The resistance R between disc and reinforcement is measured with the help of multi meter.

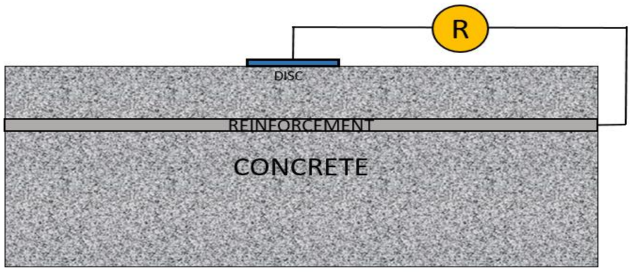

Figure 9: Measurement of resistance of concrete cover

This measured resistance of concrete is converted to resistivity of concrete by the following equation given by RILEM TC 154-EMC [16].

$$\text{Resistivity} \quad \rho = k * R\ (\text{disc-bar})$$

The constant k depends upon disc diameter, thickness of concrete cover, reinforcement diameter and spacing. It can be assumed as 2a where a is the diameter of the disc in meter. Therefore

$$\text{Resistivity} \quad \rho = 2 * a * R\ (\text{disc-bar})$$

$$\text{Conductivity}\ \sigma = 1/\rho$$

This equation is valid when the resistance of reinforcement is very-very less than the total resistance of disc [16]. The electrode shall be of any conductive material but it shall be in circular shape which has already been established by Newman's work [14]

C. *On site measurement of electrical conductivity of concrete cover*

The conductivity of concrete is influenced by a number of factors as discussed earlier so it becomes important for onsite measurement of conductivity for working of sacrificial surface anode.

To measure the conductivity the probe as shown in figure 10 is made with different disc sizes. The steel discs of size 50 mm, 56 mm and 75 mm are used to make probe as shown in figures11 and 12. A rectangular probe of size 105mm x 75 mm is also made to understand the effect of probe shape in conductivity measurement as shown in figure13.

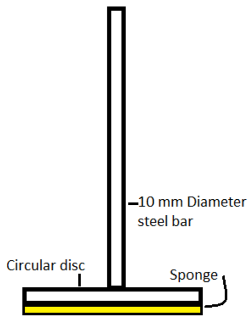

Figure 10: Steel probe design for measurement of electrical conductivity

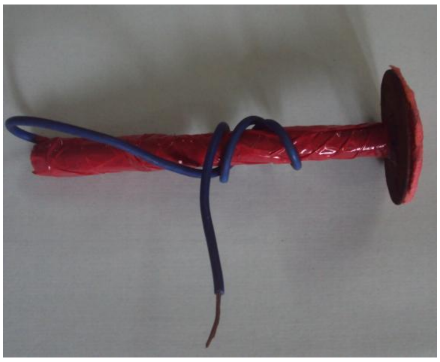

Figure 11: Circular disc probe of diameter 50mm

Figure 12: Circular disc probe of diameter 75mm

Figure 13: Rectangular probe of size 105mm x 75mm

The resistance of concrete cover R and moisture content of the concrete cover for consecutive three days were measured with different probes at two places 2A and 6A in the building Sunstar as shown in figure 14 and 15. The terminals from reinforcements were taken at the time of repairing. To have proper contact with concrete surface a 5 mm thick sponge is attached to all probes.

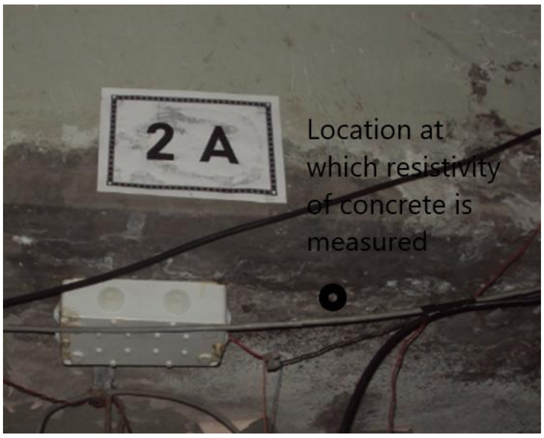

Figure 14: The location where resistance of concrete cover is measured near S S Anode

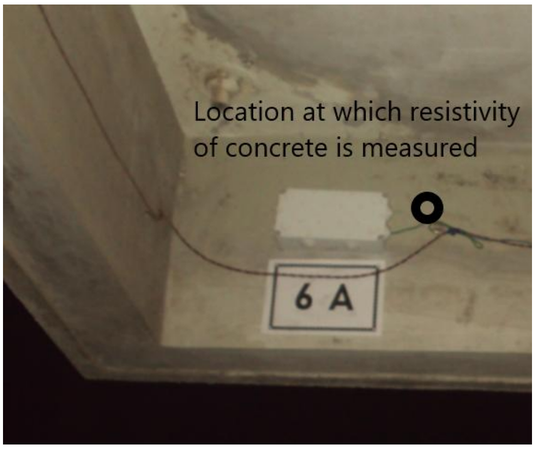

Figure 15: The location where resistance of concrete cover is measured near S S Anode

The observations are tabulated in table 1. The observations are average of three days measurement at 7 pm when atmospheric temperature was about 31 degree Celsius.

Table 1: Moisture content and resistance of concrete cover

S.N.	Location	Average Moisture Content	Disc size Dia. in m/ Rectangular in m	Average Resistance in k ohm	Resistivity in ohm-m	Conductivity Siemens/m
1	2A- Bottom of slab of first floor below wash room(parking area)	17%	0.050	250	25×10^{3}	4×10^{-5}
2	-Do-	17%	0.056	260	29×10^{3}	3.45×10^{-5}
3	-Do-	17%	0.075	270	40.5×10^{3}	2.47×10^{-5}
4	-Do-	17%	0.105x.075 equivalent dia = 0.100m	260	52×10^{-3}	2.56×10^{-5}
5	6A- Beam of first floor (parking area)	6%	0.050	550	55×10^{3}	1.8×10^{-5}
6	-Do-	6%	0.056	580	65×10^{3}	1.5×10^{-5}
7	-Do-	6%	0.075	610	91.5×10^{3}	1.1×10^{-5}
8	-DO-	6%	0.105x.075 equivalent dia = 0.100m	550	110×10^{3}	0.9×10^{-5}

The results show that the conductivity of concrete cover is favorable to install the sacrificial surface anode on the surface of concrete. The observations in table shows that when moisture content is high the conductivity of concrete is high. The conductivity is a governing factor for working of Sacrificial Surface Anode. The anodes attached at these two places for SSACP are shown in figure 14 and figure 15.

The arrangement of anode is similar to as shown in figure 4. Measurement of potential and current is recorded by a 16 channel data logger. The half-cell potential by copper-copper sulphate half-cell potentiometer, approximate distance between anode and terminal taken from reinforcement is tabulated in table no 2.

Table2: Location of sacrificial surface anode, half -cell potential and distance between anode and reinforcement terminal

Installation Point	Sacrificial Surface Anodes Points at	Electrically Connected to reinforcement at (Half-cell potential)	Locations	Approxim-ate shortest distance	External Condition (Visual)
2	2 A	2 B -0.530 V	Below first floor washroom (Flat no 1)	5m	Visible seepage along with water drops
6	6 A	6 B -0.460 V	First floor bottom beam (Flat No 6)	6m	

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The potential difference between sacrificial surface anode and cathode (reinforcement) is shown in figure 16 and the flow of current in the circuit is shown in figure 17 for anode 2A and in figure 18 & 19 for anode 6A.

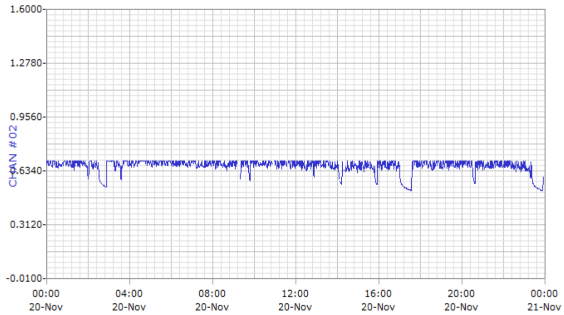

Figure 16: Channel 2-Potential difference (mV) between point 2A (Sacrificial Surface Anode) and point 2B (Reinforcement)

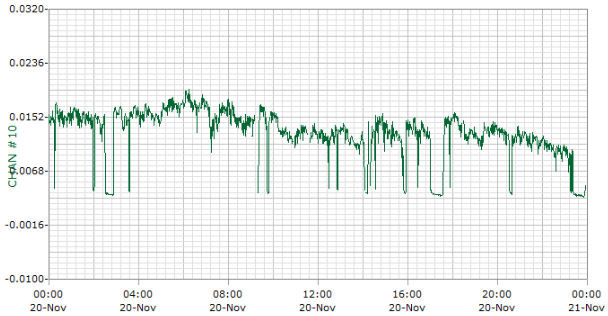

Figure 17: Channel 10-Current flow (mA) between point 2A (Sacrificial Surface Anode) and point 2B (Reinforcement)

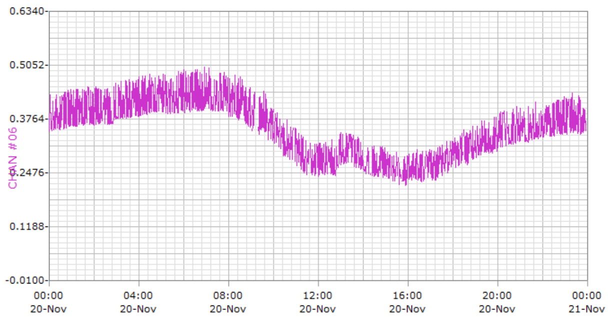

Figure 18: Channel 6-Potential difference (mV) between point 6A (Sacrificial Surface Anode) and point 6B (Reinforcement)

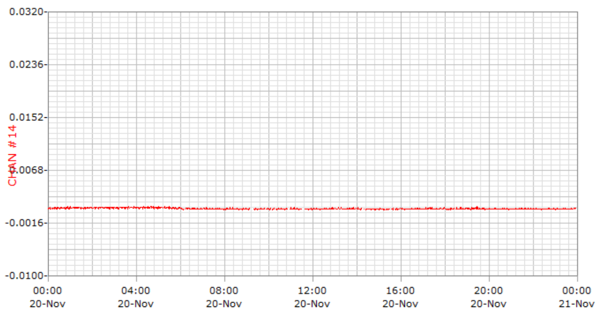

Figure 19: Channel 14-Current flow (mA) between point 6A (Sacrificial Surface Anode) and point 6B (Reinforcement)

VIII. RESULTS AND DISCUSSION

The average resistivity of concrete by different probes at point 2A is ranging from 25 x 10^3 to 52 x 10^3 ohm-meter and it is less than 1000 x 10^3 ohm-meter so the concrete is in the stage of conductive range.

The measurement by steel probe indicates that the moisture content of concrete is governing factor for conductivity of concrete. Higher moisture values show higher conductivity.

The value of resistivity by different probe size at the same location is different this is a matter of further investigation in laboratory since on one side reinforcement as liner element is there and on other side circular element is there. The application of fundamental equation of resistance in which area of cross section of conductive material is required is not fulfilled here and some empirical relation is to be developed. In this study this part of study is not conducted.

Similarly at anode point 6A the resistivity of concrete cover is less than 1000 x 10^3 ohm-m the sacrificial surface anode works well. The potential difference between anode and reinforcement at 2A-2B and 6A-6B is recorded and is shown in figures 16 and 18.The potential difference is more at point 2A since the conductivity is high due to more moisture in concrete compared to point 6A. Also the sag in potential difference in the figure 18 is due to day time temperature since anode is installed on inside surface and outside faces sunlight. This may be due to loss in moisture.

The corrosion current at anode point and reinforcement 2A-2B and 6A-6B is recorded and is shown in figure 17 and 19. The magnitude of current shows the intensity of corrosion process. Thus this surface anode facilitates monitoring of this cathodic protection system which other SACP system do not have. The corrosion current is high at point 2A and at this place seepage in the slab at some places is found.

IX. CONCLUSIONS

From above experiments it can be concluded that if concrete cover conductivity is available the sacrificial surface anode can be used as corrosion protection device. Also the monitoring by measurement of potential and current ensure the protection of steel from corrosion. At any time if the system does not work it is displayed in the data logger as discontinuity of potential and current. The sacrificial surface anode being external gives advantage of ease in installation and replacement. The total cost is much less than the existing system of SACP in the market. The cost analysis is not provided in this paper for some reason.

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