AN EFFICIENT EXPERIMENTAL SETUP FOR RAPID ASSESSMENT OF REBAR CORROSION IN REINFORCED CONCRETE STRUCTURES

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Abstract - Durability of concrete infrastructures is a major concern worldwide and subsequently been the dominant cause for structural service life issues in Bangladesh, where poor design and quality control is often prevalent. Deterioration of durability results in crack formation, leading to loss of structural strength and corrosion of embedded reinforcement, especially in coastal areas due to persistent high-saline conditions. This necessitates the assessment of the extent of damage of structures, to prevent any probable sudden failure. In this research, an experimental setup has been designed to investigate the accelerated corrosion phenomenon of reinforced concrete, using half-cell potentiometer. It is a simple, portable, low-cost, non-destructive test setup suitable for a developing country like Bangladesh. During the experiment, corrosion of the reinforced samples had been observed by varying aggregate type and reinforcement diameters. The outcome of the experiment has been promising, with corrosion occurring at a rapid rate, and potential readings that can be correlated with the level of corrosion, signifying potential damages.

Index Terms - Corrosion in RC, half-cell potentiometer, low-cost setup to assess corrosion

I. INTRODUCTION

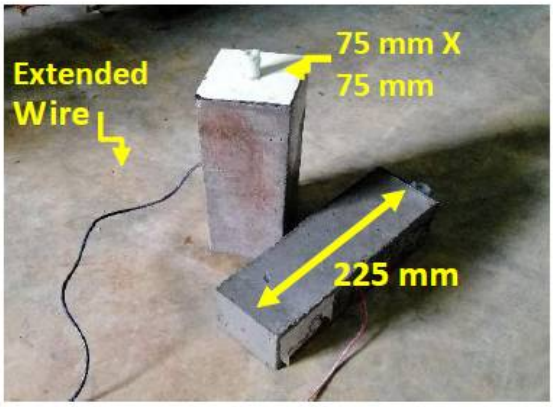
The concept of the conformity between strength and durability of reinforced concrete structures has often been deceptive in the construction practices of developing countries like Bangladesh. Being one of the vital aspects in the assurance of a proper construction, it is often assumed that durability of a structure is enhanced in accord to an increase in strength of the construction materials. However, this is not prevalent in most of the cases as durability of infrastructures lags behind. Accompanied by high saline conditions, corrosion of embedded reinforcements has been one of the dominant causes of deterioration and degradation of the reinforced concrete structures in Bangladesh [1]–[4]. The corrosion of the embedded steel bars is accountable to an ingress of chloride ions which depassivates the firmly adhering alkaline passive oxide film of γ-ferric hydroxide formed at a pH> 12.5 [5]. The corrosion products, having a greater volume, exert an expansive stress on the surrounding concrete that eventually results in cracking and spalling along with a reduction in bond strength at the steel-concrete interface [7]. A subsequent reduction in bar diameter due to corrosion leads to a decline in the load bearing capacity of the structure [8] which consequently shortens the service life. Rehabilitation of such concrete structures for an enhancement of serviceability requires a high maintenance cost [9], infeasible in the context of a developing country. With the advent of time, there have been increased efforts to overcome the challenges of infrastructural development in the harsh environments while substantializing the concern to boost the service life of reinforced concrete structures. Hence, the Southern belt of the country is about to undergo a major infrastructural outburst. The high saline conditions accompanied by highly permeable construction materials (brick aggregates) ubiquitously used in these regions aggravates the severity of durability issues due to corrosion. Moreover, lack of proper knowledge and poor quality control prevalent in construction practices adds to the tally of factors accountable to performance degradation and premature deterioration of RC structures by chloride induced corrosion of embedded rebars [6], [7]. There have been no quantitative studies regarding the corrosion performance of brick aggregates in a saline environment that can infer the serviceability. There is also a lack of awareness among practicing engineers regarding the underlying principles of non-destructive test methods due to limited experimental studies [10], especially in perspective of Bangladesh. Furthermore, there is an alarming paucity of adequate data to deduce the factors highly responsible for corrosion proneness of a structure and its effect on sustainability. Hence it substantializes the necessity for an explicit quantification of corrosion phenomenon of embedded reinforcement and its predictability towards determining the health of a reinforced concrete structure constructed with locally available aggregates. This study provides a vivid description of a simple, low-cost and non-destructive experimental setup and test procedures that can evaluate quantitatively the corrosion of a wide range of reinforced concrete samples emerged in a saline

environment. Since ingress of chloride ions, responsible for corrosion in coastal areas, is a slow process, an accelerated corrosion method is implemented to simulate and accelerate the corrosion process. This technique has been successfully used in several previous studies to effectively replicate the real scale corrosion process [11]–[16]. In the designed experimental setup, the corrosion potential is being measured using half-cell potential (HCP) method. HCP measures high impedance negative potential across the steel bar and reference calomel electrode [17], providing a reliable corrosion probability [9], [18]. The variation of corrosion potentials of reinforced concrete samples with time provides an in-depth insight into the corrosion phenomenon of embedded reinforcements. Moreover, the designed experimental setup provides a scope to assess the effects of different variables (types of aggregate, water-cement ratio, mix proportions, reinforcement bar diameter, concrete cover, etc.) on corrosion of reinforced concrete structures. The obtained corrosion potentials of reinforced concrete samples in a wide range of experimental environments can be conformed to the weight loss of embedded rebars, as a measure of the durability, which will establish a quantitative basis between the degree of corrosion (corrosion potential) and durability (rebar weight loss) of structures. This overcomes the necessity of destructive gravimetric weight loss (GWL) measurements to infer the corrosion state of underlying reinforcements. The infrastructural development in the country shall be complied with a proper knowledge of the durability performance of the locally available materials. Hence, this low cost, efficient experimental setup is capable of a rapid inference of the corrosion performance of locally available materials in the context of Bangladesh. The measured half-cell corrosion potentials of reinforced concrete structures under consideration can also act as an instant reliable interpretation of the remaining service life based on durability considerations.

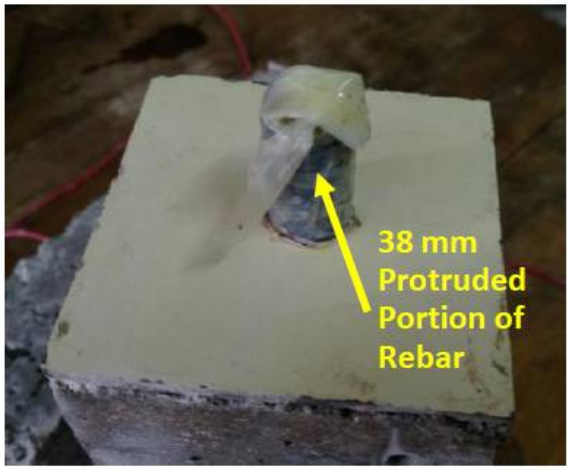
II. METHODOLOGY

A. Design of Test Specimens

A total of 6 concrete prisms (Fig. 1.a) was produced, as per the specification ASTM G1-90 [19], in the experiment to study the accelerated corrosion effect. In the experiment. Aggregate variation was used as a parameter to evaluate the corrosion behavior of locally available. Simultaneously, it was also used an indicator of the reliability of the setup in assessing the corrosion phenomenon quantitatively. In order to ensure a satisfactory and consistent result, 3 specimens for each aggregate type were prepared using a constant w/c ratio of 0.45 and a concrete mix proportion of 1:1.5:3. The RC prisms were prepared with dimensions of 75mm X 75mm X 225mm (Fig. 1.a). A constant cover of 37.5 mm from all the surrounding surfaces to eliminate the effect of concrete cover on corrosion potential. The specimens were uniquely designed to provide an efficient measure of corrosion. The unique features of the specimens were – a protruded portion of embedded rebar (Fig. 1.b) and a projected wire (Fig. 1.a). A 38 mm portion of the embedded reinforcement was left protruded and exposed outside the concrete to ensure a region with null corrosion potential against which potential drop in corroded portion of rebar can easily be measured (Fig. 4).



(a)



(b)

Fig. 1: RC Prisms with Protruded Rebar and Projected Wire [25]

To ensure an electrical connectivity between power source and embedded rebar, a wire projecting from the reinforcement embedded within concrete sample was used. This wire was connected to the rebar prior to the concrete casting and concrete was pored over it later. A secure connection was maintained between the conducting wire and the reinforcement to ensure a constant passage of electricity. The protruded portions of the reinforcements were properly rubbed to remove any existent corrosion on the exposed surface.

B. Materials

The materials used in this study reflect the range of construction materials used in the common

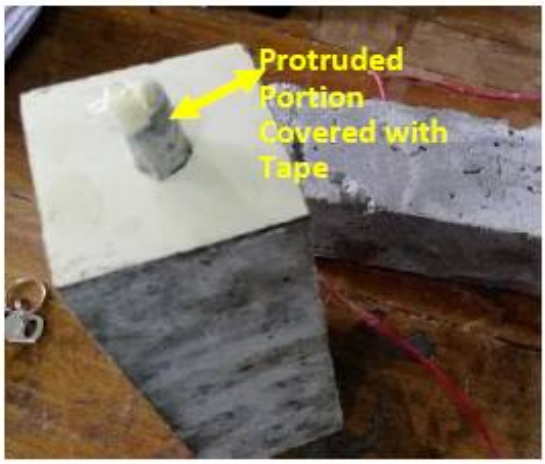
construction practices of Bangladesh. In the experiment, Ordinary Portland Cement (OPC), similar to ASTM Type I, was used as the binding agent. Both stone and brick aggregates with particle size of 19 mm downgraded were used as coarse aggregate and Sylhet Sand, with a Fineness Modulus of 2.5, was used as the fine aggregate in the sample preparation. Deformed reinforcement bars of 12 mm and 16 mm diameter with a yield strength of 420 kN/mm^2 were used as reinforcement.

C. Curing

All the test specimens were subjected to a constant curing condition (Fig. 2.a) prior testing to ensure a sufficient degree of hydration of the cement paste. This will ensure the attainment of adequate strength of the samples. During the curing period, the reinforced concrete prisms were fully



(a)



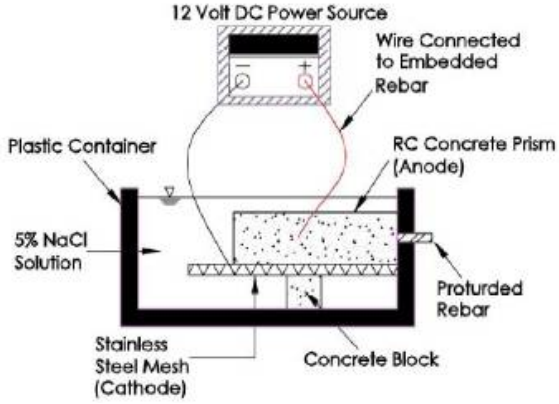
(b)

Fig. 2: Curing of RC Samples

submerged in normal water and were removed from the curing pond just before the start of the test. The protruded rebar portion was covered in 2 layers of insulating tape prior to submergence in order to prevent it from getting in contact with curing water and remain uncorroded (Fig. 2.b).

D. Experimental Set-up for Accelerated Corrosion Test

The accelerated corrosion test was performed as shown in Fig. 3.a. This test setup was designed with the purpose of simulating a real life corrosion scenario within controlled laboratory conditions. Fig. 3.a shows that the prisms are connected through an extended wire to a DC power supply (constant voltage source).



(a)



(b)

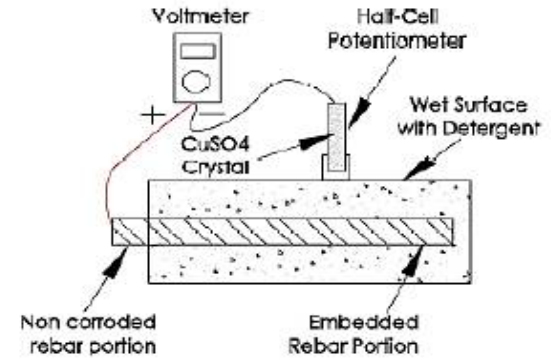
Fig. 3: a) Accelerated Corrosion Setup, b) Protection from corrosion of protruded portion [23]

The wire is eventually in contact with the embedded rebar of the RC prisms as it was connected to the reinforcement before casting ensuring a continuity in connection. The other end of the connecting wire of the power source was connected to a perforated steel mesh which also provided as a supporting base to the concrete specimens. The concrete cover acted as a transit interfacial medium between the conducting reinforcement and steel mesh. In the electrochemical setup, the RC prism was acting as the anode (+), whereas the conducting steel mesh positioned under the samples was the cathode (−). To ensure an accelerated ingress of chloride ions to initiate the corrosion process, all the RC prisms were totally submerged in a 5% NaCl [2], [20] solution, as seen in Fig. 3, and a constant power supply of 12 volts [20]

was maintained throughout the whole experimental period. The corrosion activity was monitored at each hour interval for a total 12 hours for all prism samples based on the electrical current passed. The probability of corrosion was observed using the half-cell potential test by measuring the potential difference between the embedded steel bar and a reference electrode. Half-Cell Potentiometer actually measures the potential difference between a corroded portion of embedded rebar and the non-corroded protruded portion (Fig. 4). The difference in corrosion between the uncorroded region and the corroded portion was used as a reliable measure of the degree of corrosion. To prevent any contact between the protruded portion and the saline water in order to eliminate any corrosion initiation in this zone, the protruded portion was shielded at the junction using layers of an insulating material (Fig. 3.b).

E. Half-Cell Potential Measurements

In this study, the Half-cell corrosion potential measurement technique was adopted to detect any corrosion activity within reinforcements embedded in the reinforced concrete samples. The test was performed as per the specifications of ASTM C 876 [18]. A half-cell potentiometer was used to measure the potential difference, when the readings on the multimeter became stable, at 3 uniformly spaced surface points at each hour interval from the start as being illustrated in Fig. 4.



(a)



(b)

Fig. 4: Half-Cell Potential Measurement

A Copper-Sulphate reference electrode was used inside the potentiometer to measure the potential drop of corroded portion of rebar against the non-corroded portion of the reinforcement. The positive and negative ends of the voltmeter were connected to the non-corroded part of the reinforcement and the reference electrode, respectively, as shown in Fig. 4. The surface between the half-cell potentiometer and the concrete surface had been pre-wetted using detergent soaked sponge in order to ensure a conducting channel for the free electrons. The averages of the 3 aforementioned readings were taken as a reliable measure of corrosion of the entire sample.

III. RESULTS & DISCUSSION

The half-cell corrosion potential readings were taken at 3 equally spaced points on the surface of the specimens after they had been subjected to an accelerated corrosion. The variation of the average corrosion potential readings with time is illustrated in Fig. 5 and Fig. 6 for embedded reinforcement bar diameters of 12mm and 16mm respectively for both brick and stone aggregate concrete. The conformation of the degree of corrosion was validated by comparison with ASTM standards. As per the specifications of ASTM C 876 [18], all the obtained corrosion potentials for all the samples conforms to a range that corresponds to a corrosion probability of 95% with visible evidence to infer the phenomenon (Table I) [21], [23].

Potential Difference (mV)	Chance of rebar being corroded
Less than -500	Visible evidence
-350 to -500	95%
-200 to -350	50%
More than -200	5%

Table I: Potential risks of corrosion based on potential difference [21], [22]

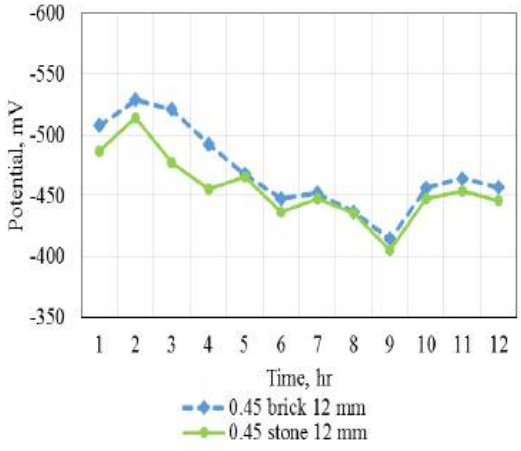


Fig. 5: Effect of different aggregate on variation of Half-Cell Corrosion Potential with Time (12 mm bar)

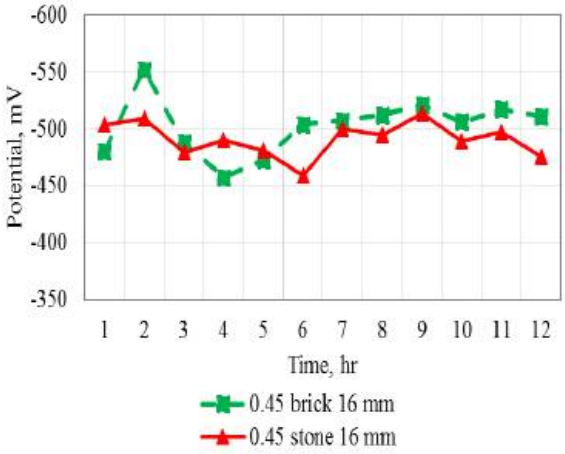


Fig. 6: Effect of different aggregate on variation of Half-Cell Corrosion Potential with Time (16 mm bar)

The obtained results validate that the experimental setup adopted for an accelerated corrosion phenomenon is successful in imitating and quantifying a high degree of corrosion to draw reliable conclusions. It also signifies that the experimental design is adequate to replicate the long real life corrosion process in a short span of time. The variation trend of corrosion potentials with time provides a valuable insight into the corrosion phenomenon of embedded reinforcements in concrete structures. It can be deduced from the graphs that the process of corrosion is a dynamic equilibrium reaction which do not proceed at a constant rate but has the highest rate at the initial intervals. This is exemplified by the highest values of corrosion potential at around the 2nd hour for all the samples. The observed pattern relates to the fact that the ionization process of iron occurs at a significant rate following the initiation of corrosion which also represents the most critical time for corrosion proneness. This initial period is being followed by a stable period with more or less constant values of corrosion potential. The stabilized values of corrosion potentials in all cases signify the attainment of dynamic equilibrium condition with an equal rate of dissolution and deposition of iron on the reinforcements.

It can be inferred from Fig. 5 that the corrosion potential for concrete samples with brick aggregates is substantially higher as compared to those with stone aggregates at all the time intervals. This has also been numerically justified by a higher negative peak corrosion potential for brick aggregate concrete (-529 mV at 2nd hour) than stone aggregate (-514mV at 2nd hour). A similar case has also been evident in Fig. 6 for an embedded bar diameter of 16mm with a more prominent difference in peak corrosion potential for the samples (-573mV and -482mV for brick and stone aggregate concrete respectively).The observed pattern signifies that concrete with brick aggregates has a greater proneness to a higher chloride ingress and a subsequent high degree of corrosion of embedded reinforcement. This can be accounted to the higher permeability of the concrete mixes imposed by the higher porosity of the brick aggregates in comparison to stone aggregates [24]. Hence, the results obtained by the use of the designed experimental setup corresponds towards a poor durability performance of reinforced concrete structures with brick aggregates in terms of corrosion.

CONCLUSION

The concern for durability and prolonged service life of reinforced concrete structures using indigenous concrete mixes is rapidly gaining its significance in the corrosion prone areas of Bangladesh prior to the prevalent infrastructural bloom. However, paucity of sufficient quantitative data on the effect of corrosion on durability vitalizes a research study on the corrosion of RC structures. The objective of this study was to design a suitable low-cost and efficient experimental setup to assess the corrosion behavior of embedded reinforcement in a lab simulated corrosion environment. The results obtained are quite promising where the designed setup was able to simulate the real scale corrosion scenario in a span of hours while obtaining significant convenient measures of corrosion potential. The obtained results depicted a general varying pattern of the corrosion phenomenon and the poor durability performance of RC structures when brick aggregates are used in the concrete mix. The designed experimental setup provides the scope to decipher the effects of several factors (w/c ratio, concrete cover, mix proportions, etc.) on the corrosion behavior of RC structures by incorporating a large sample size. The corrosion potentials, as a measure of degree of corrosion, can be correlated to the weight loss of the embedded reinforcements as a measure of sustainability. The correlation can be used as a reliable quantitative basis for determining the health of the structure based on half-cell surface corrosion potential which eliminates the need of any destructive test. Hence, this technique will play a vital role in detecting any early damages of structures and safeguarding the (sustainability/health) of infrastructures.

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