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The influence of bending crack on rebar corrosion in fly ash concrete subjected to different exposure conditions under static loading

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HIGHLIGHTS

- Corrosion initiation period remained same for cracked fly ash concrete.
- Crack width was found to be the governing factor for crack sealing ability of concrete.
- The relation between corrosion depth and surface corroded area was introduced.

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ABSTRACT

In the present study an effort was made to clarify the performance of pre-cracked fly ash concrete against corrosion under different exposure conditions. A total of twenty specimens from two different concrete mixes were tested against three different exposure conditions for 106 days. It was observed that the crack filling ability of concrete is more sensitive to crack width than fly ash replacement and exposure conditions. Under submerged conditions the fly ash concrete showed greater pitting corrosion, while under wet and dry cycle conditions, the corrosion damage was found to be less penetrating as compared to normal Portland cement concrete.

1. Introduction

The durability aspect of reinforced concrete is typically related to the concrete matrix, i.e. a dense microstructure will most likely show lower permeability and reduce the transport of corrosive agents to reinforcement. However, in real reinforced concrete structures, it is certain to have cracks, either in the form of the micro cracks between aggregate and cement paste or macro cracks encountered during the service life due to loading or degradation process. In addition, the increasing demands for greater loads, for example long-span bridges, make the structures prone to more cracking. Cracking adversely affects the serviceability and durability of a structure, particularly when exposed to marine environments because of the corrosion of rebars. Cracking has become a critical feature of reinforced concrete structures and significant efforts have been done throughout the world to minimize the cracking problem in reinforced concrete structures. For the same reason, many codes and specifications have fixed the criteria of service life on the basis of allowable crack width [1,2].

Meanwhile, in last few years, the use of fly ash in concrete is becoming increasingly popular all over the world. The incorporation of fly ash in concrete can help to reduce the environmental impact of cement industry at a reduced or no additional cost [3]. Also, it is generally recognized that the inclusion of fly ash in concrete improves its resistance against chloride-induced corrosion of steel reinforcement by reducing its permeability, particularly to chloride ion transportation and increasing the resistivity of the concrete [4]. In addition, according to a recent study, provided enough curing, the fly ash concrete showed the same chloride threshold values as that of normal Portland cement concrete for corrosion initiation [5]. Moreover, it has also been shown that high volume of fly ash concrete has the ability to self-heal the cracks under moist conditions [6]. In addition, Na et al. [7] has shown that the self-healing performance in fly ash blended mixtures is dependent on the curing temperature, curing age and fly ash replacement ratio.

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In non-cracked concrete, the chloride induced corrosion initiates with a localized anodic reaction, limited to the area of steel where the chloride threshold value is exceeded. While in case of cracked concrete, the corrosion begins with the formation of a small anode at the crack and a large cathode consisting of passive steel in the non-cracked concrete around the crack [8]. It has also been reported that, for every active corrosion, the micro cell corrosion and macro cell corrosion normally co-exist [9]. The corrosion process of steel reinforcement embedded in cracked concrete is a complex phenomenon depending on exposure conditions, loading conditions, concrete composition, concrete resistance and crack width [10,11].

In the past, a lot of research has already been done to study the corrosion of steel reinforcement in cracked concrete. But most of the studies have focused on the effect of factors such as the crack width, crack depth, concrete composition, and loading conditions on the corrosion of reinforcement in cracked concrete, and relatively less research has been done on the corrosion of rebars with different exposure conditions, especially in fly ash concrete under cracked conditions. Furthermore, in most of the laboratory investigations, the cracked samples have been fully submerged in the salt solution in the unloaded state, which is quite different from the reality [12]. In addition, the mechanism of the corrosion reinforcement in cracked fly ash concrete with regard to its self-healing ability has not yet been made clear in the previous research studies.

This study was conducted to evaluate the effect of bending cracks on the corrosion of rebars in fly ash concrete under static loading while exposed to different exposure conditions. Specially designed apparatus was employed to sustain the flexural moment in the reinforced concrete specimen along with the application of salt solution within the limited region of crack. This configuration will bring a severe corrosive environment with co-existence of salt solution application. Overall, the current study will be helpful for understanding of reinforcement corrosion in cracked fly ash concrete under different environmental conditions along with self-healing abilities.

2. Experimental methodology

2.1. Material and specimen details

The coarse aggregate (G) was crushed stone with a maximum size of 13 mm and the fine aggregate used (S) was river sand. This size of coarse aggregate was selected because of the experimental limitations i.e. the size of specimen, cover depth and the time to achieve certain amount of corrosion. The specific gravity of coarse and fine aggregate were 2.64 g/cm^3 and 2.67 g/cm^3 respectively. Japanese Industrial Standard [13] Type II fly ash was used. Properties of fly ash are summarized in Table 1. Deformed steel bar, having a diameter of 19 mm, was used in all the specimen series.

Three different series of specimen, i.e. C, CB and CT, were prepared with constant water to binder ratio of 0.5. The notation C, CB and CT correspond to three different exposure conditions, i.e. wet and dry cycle, continuous application of salt solution from bottom side and continuous application of salt solution from top side of the specimen respectively. Wet and dry cycle correspond to the reinforced concrete structures exposed to dry and rainy seasons. The continuous application from the top represents the bridge slabs or RC structures in snowy areas like Hokkaido, Japan, that are exposed to snow for several months and to remove the snow salt is applied on the top surface. The continuous application from the bottom represents RC structures exposed to seawater like bridge piers. Fly ash concrete, for all three series, was made by replacing 30% ordinary Portland cement (C) with fly ash (FA). The target air content and slump was 5 ± 0.5% and 12 ± 2 cm respectively. All specimen series were cured for 91 days. The mix proportions for all three specimen series (C, CT and CB) of respective normal and fly ash concrete were same and can be found in Table 2.

Corrosive behaviour of rebar in concrete is normally involved in uncertainties resulting in a different manner even with duplicated specimens of the same batch being tested concurrently. Therefore, for the enhancement of the accuracy of the result, multiple duplicated specimens for each series were prepared and tested in this study. A total of twenty prisms (100 × 100 × 400) mm were prepared, and the detailed configuration of the reinforced concrete specimen is explained in Table 3. The cross section of the specimens is shown in Fig. 1(a). All specimens contain two reinforcing bars at a distance of 20 mm (UP) and 25 mm (DO) from the top surface. To avoid the bleeding water to accumulate underneath the rebars, fresh concrete was placed in the lengthwise direction. After the completion of curing period, all the surfaces of the specimens except top and bottom were sealed with butyl tape with outer alumina coating and top surface was gently cleaned with wire brush.

The cracks were generated by using a specifically designed apparatus as shown in Fig. 1(b). In sustained loading system, the load tends to decrease due to the creep effect of concrete, however in our specimens the load was regularly monitored but it was noticed that almost negligible adjustment of load was required, so this effect was not considered. The loads of approximately 20 kN for normal concrete while 17 kN for fly ash concrete was applied. The apparatus was uniquely shaped to keep the specimens under constant bending moment along with the application of salt solution only in the limited region. This was intended to cover the limited area near the crack opening exposed to saline solution, so that maximum transport of the saline solution occurs through the crack, which, as a result, will also limit the anodic area on the embedded rebars. The target anode to cathode ratio for the current methodology is quite small allowing the corroding zone to approach the pure anodic behaviour. In this regard, the present methodology will allow major contribution from macro cell activity to the overall corrosion rate.

A portable digital microscope was used to observe the crack width at the end of one complete cycle (wet and dry) for C series, while for CB series it was measured at regular interval of one month, and for CT it was measured twice, i.e. 60 days and after last cycle. The crack width in this study is defined as the distance between the two jaws of crack on the surface of concrete along its exposed side. The initial crack width, before the application of salt solution, for all the specimens was kept less than 0.1 mm. The crack width was not constant along the length of crack on the surface of concrete. It is common because concrete is not a homogenous material and response to same stress level can be different for different components of concrete. It was for the same reason that three points were selected along the length of crack and for each point the average of five measurement was taken. So the average crack width for each specimen refers to the average of fifteen points along the length of crack on the exposed surface of concrete as shown in Fig. 2. The average initial crack width for all the specimen series is shown in Table 4.

After the generation of cracks, all three specimen series C, CB and CT were exposed to 10% NaCl solution through wet and dry cycle, continuous application from top and bottom respectively. The duration of each wet and dry cycle was kept as 7 days for a period of 56 days and the duration of last wet and dry cycle was increased to 25 days each to increase the degree of corrosion damage. During the wet cycle, the cracked specimens were exposed to 10% NaCl solution, and, during the dry cycle, the specimens were