

Study on reinforcement corrosion in high performance concrete under pre-loading condition

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Abstract: The mutual effects between subjection of pre-loading and corrosion of reinforcing steel were investigated. Three concrete beams of 1170 mm long x 100 mm wide x 150 mm high were used as test specimens. Two of them were made of high performance concrete incorporating fly ash and slag, while the other was control specimens of 100% OPC as binder. The beams were reinforced with a single Ø16-mm 60-grade bar and subjected to four-point loading at a constant load level of 80% of the average ultimate flexural strength. The corrosion process was accelerated by employing 5% NaCl solution. Galvanized current measurements were taken to monitor the corrosion initiation. After corrosion had initiated, an external current was applied to expedite the corrosion propagation, and responsive voltages were measured. Performance of the high performance concrete was evaluated in terms of corrosion resistance. The results suggested that influence of material propositions should be considered in combination with environmental aspects and service-load conditions.

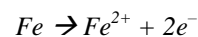
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1. Introduction:

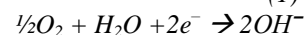
Corrosion of reinforcement is one of the most common harmful damage that occurs in reinforced concrete. This damage reduces the service life of structural member and can create a safety hazard as the member is crushed. Steel in concrete is usually protected against corrosion by passivation of the steel arising from the high alkalinity of the pore solution with the concrete. A stable oxide layer is formed on the steel surface, which prevents the anodic dissolution of iron. Loss of durability in reinforced concrete only occurs if this stable oxide layer is rendered unstable due to ingress of chlorides to the steel /concrete interface or carbonation of the concrete reducing alkaline of the pore solution at the steel/ concrete interface (Zivica, 2003). Diffusion of carbon dioxide from atmosphere or as a permitted additive in form of calcium carbonate in cement can react with the cement hydrates in presence of water to form calcium carbonate and depassivates the oxide layer. On the other hand, the intrusion of chloride ions in reinforced concrete can cause steel corrosion if oxygen and moisture are also available to sustain the reaction. Chloride ions may be introduced into the concrete through intentional inclusion as an accelerating admixture, accidental inclusion as contaminants on aggregates; or penetration by deicing salts, industrial brines; marine spray, fog or mist. The usual corrosion products are oxide, hydroxide, carbonate, sulfide etc.

Although steel can corrode by chemical attack, the most common form of corrosion in an aqueous medium is electrochemical. In most cases electron transfer occurs under electro-chemical action in

which there is a transfer operation taking place either between two dissimilar metals or between different areas upon a single material. The zone that releases electrons is called anode while the zone accepting those electrons is termed as cathode as in other electrical circuits. Reaction of anodes and cathodes are broadly referred to as "half-cell reaction". It works with an anode, where electrochemical oxidation takes place; a cathode, where electrochemical reduction occurs; an electrical conductor, and an aqueous medium. At the anode which is the negative pole, iron is oxidized to ferrous ions, shown in equation (1), whereas reduction takes place at the cathode. In an acid medium the reaction taking place at the cathode is the reduction of hydrogen ions to hydrogen. However, concrete is highly basic and usually has an adequate supply of oxygen, so the cathodic reaction occurs according to equation (2).



(1)



(2)

A great deal of research was conducted to investigate corrosion behavior of concrete materials and prevention methods. However, most previous research was focused on undamaged (pristine) concrete and comparatively little work was performed to quantitatively describe how these properties change in the presence of damage or

sustained loading, which frequently occurs in field applications. Penetration of chlorides and diffusion of carbon dioxide are increased at the places of cracks, which further increases corrosion. Another consequence of crack formation is the development of galvanic cells with anodic and cathodic areas with corrosion at unprotected (anodic) areas. Pitting corrosion and galvanic macro cell formation generate small losses of steel, but create areas with concentrations of strains (Raupach, 1996). It is, therefore, extremely important to know the mechanism of corrosion process at the initial stage, so that it can be minimized to a greater extent and the heavy losses incurred due to corrosion may be greatly reduced.

The purpose of this study is to assess the effect of corrosion in embedded reinforcement after the subjection of pre-load through accelerated corrosion test. Durable reinforced concrete must be designed to resist carbonation and to exclude chlorides from any source. With the view point that a denser paste matrix would offer a better resistance against corrosion initiation, the corrosion behavior of normal concrete and high performance concrete flexural members is compared. By definition, a high performance concrete (HPC) refers to that type of concrete which is treated in such a manner so that the concrete ensures optimum resistance against various degradation processes in a particular type of climate or environment. The HPC was prepared by including supplementary cementitious materials in this study. The results may provide engineers insight into

design, condition evaluation, and service life prediction of reinforced concrete structures.

2. Experimental program:

2.1 Materials, mix design and sample preparation

Three batches of concrete were constructed, one was reference concrete beam (Ref) incorporating ordinary Portland cement (OPC) as binder, while the other two were high performance concrete beams, treated by supplementary cementitious materials of slag and fly ash, in batches SL and FA, respectively. The mix proportion is shown in Table 1. Stone chips were used as coarse aggregate with maximum size of 20 mm and coarse sand with a fineness modulus of 2.7 was used as the fine aggregate. Both coarse and fine aggregate were saturated with 1% water before mixing. In Batch SL, 35% OPC was replaced by slag, while 25% OPC was replaced by fly ash in Batch FA. The replacement was on the basis of volume batching. Water-to-binder ratio (w/b) was kept 0.5 in all batches. The beams, having dimensions 100 mm (4 in) wide by 150 mm (6 in) high by 1170 mm long, were reinforced with a single standard No. 5 (16 mm diameter) Grade 60 reinforcing steel bar. The clear cover below the bottom surface of reinforcing steel was 20 mm. To avoid excessive corrosion at the ends of the reinforcing bar, the ending 60 mm range of the bar was coated with epoxy. Specimens were moist cured for 28 days in an 85% relative humidity room at an average temperature of 24°C before being subjected to loading.

Table 1: Mixture Proportion (kg/m³)

Batch	Cement	Slag	Fly ash	Stone chips	Sand	Water
Ref	470	-	-	1180	470	235
SL	305	150	-	1180	470	230
FA	355	-	85	1180	470	220

2.2 Pre-loading setup:

The specimens were subjected to four-point loading test by a hydraulic jack. Destructive flexural test was performed with similar batches of beams to obtain the average ultimate flexural strength. It was found to be 24.2 kN. Then 80% of the average ultimate flexural strength was applied on the beams under corrosion investigation for the purpose of pre-loading. The load-deflection diagram is shown in Figure 1. Loading was applied in three successive steps. At the first step, the beams were subjected to 50% of their ultimate load and the load was kept stagnant for 10 minutes. Afterwards, the load was increased to 60% and 80% of their ultimate load in the second and third steps, respectively, and was projected sequentially in a similar manner.

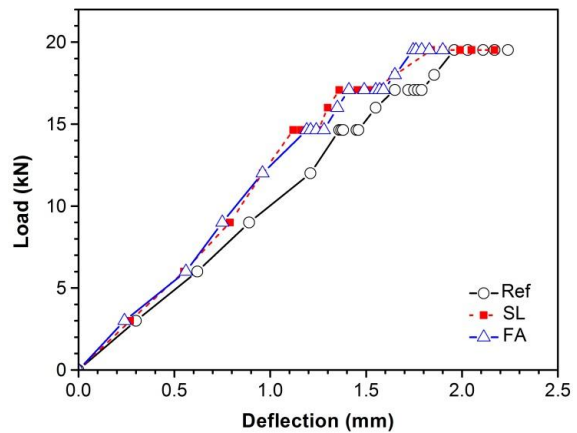


Figure 1: Load-deflection diagram in pre-loading phase

2.3 Corrosion measurement

2.3.1 Galvanic current measurement

The corrosion process of the reinforcing steel in the present study was monitored by the use of galvanic current. A copper plate was placed in a 5% NaCl solution and electrically connected to the reinforcement through a shunt-resistor (2 ohms). The schematic of the corrosion cell is shown in Figure 2. This type of corrosion cell, composed of two dissimilar metals in contact and sharing a common electrolyte (concrete pore solution), is called a galvanic cell (Devalapura, et al., 1994). Among the two dissimilar metals, the metal with the more negative standard potential value serves as anode, while the noble metal with the less negative standard potential value serves as cathode (Berkeley and Pathmanaban, 1990). In this project, mild steel ($E = -0.61$ Volts) served as anode and copper ($E = -0.36$ Volts) served as cathode.

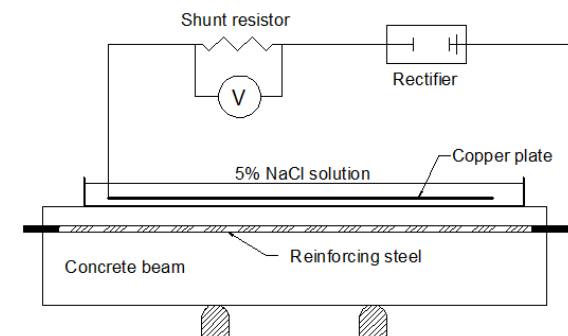


Figure 2: Schematic of galvanic current measurement

The amount of galvanic current, that flows between the galvanic couple – mild steel and copper, indicates the degree of corrosion activity in the cell. The galvanic corrosion current can be calculated from equation (3).

$$I = \frac{V}{R} \text{ ----- (3)}$$

2.3.2 Application of external current

After being subjected to same level of loading (Figure 1), the beams were connected in parallel for the application of an external direct current through an adapter. The complete test setup is shown in Figure 3. The external current was applied in two phases. After 40 days of successive ponding of the concrete surface near the tension zone, a stagnant voltage (9 volt) was applied, in the first phase, to the group of three beams (Ref, SL and FA) for 10 days to initiate the corrosion process. Afterwards, the external direct current was increased at a constant rate to the specimens through an adapter to accelerate the corrosion propagation process. The adapter had one end connected to the reinforcing steel in the specimens while the other end was connected to the copper plate via a shunt resistor. Then, the voltage

was gradually increased (3 volt for each consecutive day) to 30 volts within 8 days in order to obtain a decent degree of corrosion propagation.

$$\text{Weight loss} = \frac{TC \times EW}{F} \text{ ----- (4)}$$

Where,

TC = Total electric charge (coulombs)

EW = Equivalent weight that is oxidized (gm)

F = Faraday's constant (96490 coulombs)



Figure 3: Test setup for accelerated corrosion

3. Results and discussions:

3.1 Effect of pre-loading on corrosion initiation

The effect of pre-loading on corrosion initiation and propagation is shown in Figure 4. It compares the corrosion current density and corrosion induced cumulative weight loss (%) between a pristine (undamaged) beam and a pre-loaded beam under the same exposure conditions (5% NaCl ponding). The loading level was 60% of the ultimate load (Figure 1). Measurements were taken twice a day so that corrosion process could be monitored as a function of time. External voltage application was started after 28 days of moist curing and 40 days of NaCl ponding. A stagnant voltage of 9 volts were kept constant for the first 10 days of the observation and the corrosion current reached to $0.317 \mu\text{A}/\text{cm}^2$ in the pre-loaded beam, which was considered to be the threshold for corrosion initiation (Gonzalez, et al., 1980). A rapid change in the corrosion propagation was observed after 11 days when the applied voltage was successively increased. The rapid corrosion propagation might have resulted from larger and higher number of cracks and microcracks that generated in the concrete during loading, which permit chloride penetration for corrosion propagation.

It can be further observed that the specimen without loading had approximately a constant current density, in the range of $0.04\text{-}0.26 \mu\text{A}/\text{cm}^2$, which indicated that no corrosion of the reinforcement had occurred during the 18 days of accelerated corrosion process.

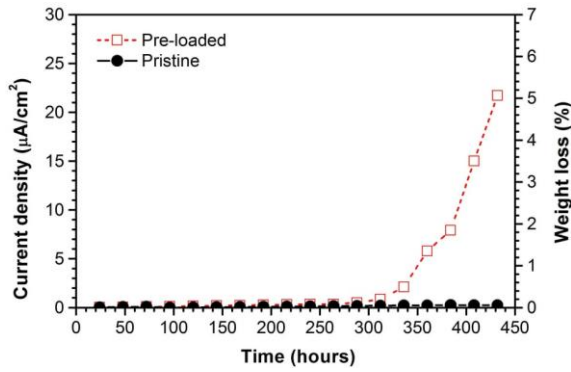


Figure 4: Influence of pre-loading on corrosion process

3.2 Corrosion behaviour of HPC

The accelerated corrosion process between the reference concrete and the high performance concrete beams was compared in Figure 5. It can be seen that the effect of preloading on corrosion propagation was not distinct at the beginning of the corrosion acceleration; but it became more obvious at the later stage. It was possible that some micro-cracks in the concrete that were generated during the pre-loading phase might be closed or became smaller and less connected when the load was removed, thus slowing down further chloride penetration and reducing rate of corrosion propagation (Yoon, et al., 2000). A critical crack width below which the crack does not affect the corrosion process of reinforcing steel was suggested to be approximately between 0.1 and 0.3 mm (Vidal, et al., 2004). Moreover, the relatively smaller cracks might have been sealed by the corrosion products and postponed corrosion propagation.

Among the three specimens, Beam FA where 25% of the OPC was replaced by fly ash had shown lower corrosion current density and cumulative weight loss than the other two specimens. Fly ash has a very rounded particle shape, including some partly broken hollow spheres known as cenospheres (as opposed to the extremely jagged particle shape of cement) and is of lower density (specific gravity usually 1.9 to 2.4 compared to 3.15 for cement). When cement hydrates, it releases free lime. This lime is the softest, weakest and most chemical attack and leaching susceptible of all the constituents of concrete. The fly ash combines chemically with the free lime to form compounds similar to those produced by the rest of the cement. This reaction is quite slow (7 days before it produces much effect), and generated little heat during the setting process, which might have contributed towards a lesser microcracks development during the early days of hydration. Concrete porosity in such concrete could be reduced significantly with increased curing times and, corresponding corrosion resistance is improved.

The concrete beam with slag replacement (SL), showed lesser weight loss in accelerated corrosion than the reference concrete Beam-Ref (Figure 5). Concrete using slag normally has a greater resistance to chemical attack, and is particularly suggested for marine works, however, it generally develops strength more slowly than OPC concrete. Its greater fineness confers resistance to bleeding in the fresh state and lower permeability when hardened. A large amount of ‘free lime’ (CH) is liberated during the hydration of cement. Slag reacts with that hydrated lime, forming a secondary calcium-silicate compound. At the same time, a lot of homogeneous hydration products like ettringite and CH are also formed, which have larger specific surface than that of OPC. In addition, when slag (with high CaO and MgO content) hydrates, it provides OH⁻ ions and alkalis into the pore fluid, which react with SiO₂ and break down the glass phase of slag, which accelerates the process of hydration. Increased corrosion resistance came from the accelerated hydration resulting a densified paste matrix and reduction of permeability, which inhibited penetration of chloride ions.

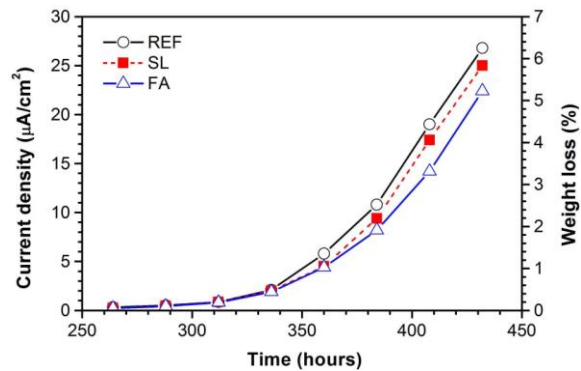


Figure 5: Corrosion process in high performance concrete

4. Conclusion:

Accelerated corrosion processes in high performance concrete beams under preloading condition were investigated in the present study. It involved 28 days of moist curing, 40 days of 5% NaCl ponding and 18 days external current application from corrosion initiation and propagation. Two high performance concrete beams were prepared by replacing a portion of the cement and compared their corrosion resistance performance with a reference concrete beam for the same exposure condition. Test results revealed that corrosion initiation followed linear trend for a constant supply of external current however switched to an exponential trend when the applied current was increased. Concretes having fly ash and slag showed better corrosion resistance in terms of lower current density and lesser cumulative weight loss. Subjection of preloading showed significant influence on corrosion initiation and should be considered for service life modelling.

References:

- [1] Berkeley, K. and Pathmanaban, S. (1990). Cathodic protection of reinforcement steel in concrete. Butterworths and Company Publishers, Limited, Borough Green, Sevenoaks, Kent TN15 8PH England.
- [2] Devalapura, R., Kamel, M., and Arumugasaamy, P., (1994) "Nondestructive Techniques for Corrosion Evaluation of Steel in Concrete, Corrosion and Corrosion Protection of Steel in Concrete", Proceedings of International Conference held at the University of Sheffield, Sheffield, UK, Vol. 1, pp. 300-309.
- [3] Gonzalez, J.A., Algaba, J., and Andrade, C., (1980) "Corrosion of reinforcing bars in carbonated concrete", British Corrosion Journal, Vol. 15 (3), pp. 135-139.
- [4] Raupach, M., (1996) "Chloride-induced macrocell corrosion of steel in concrete— theoretical background and practical consequences", Construction and Building Materials, Vol. 10 (5), pp. 329-338.
- [5] Vidal, T., Castel, A., and Francois, R., (2004) "Analyzing crack width to predict corrosion in reinforced concrete", Cement and Concrete Research, Vol. 34 (1), pp. 165-174.
- [6] Yoon, S., Wang, K., Weiss, W.J., and Shah, S.P., (2000) "Interaction between loading, corrosion, and serviceability of reinforced concrete", ACI Materials Journal, Vol. 97 (6), pp. 637-644.
- [7] Zivica, V., (2003) "Corrosion of reinforcement induced by environment containing chloride and carbon dioxide", Bulletin of Materials Science, Vol. 26 (6), pp. 605-608.