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Risk of rebar corrosion in cracked RC flexural member, incorporated with fly ash

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In this write-up, citing the results of an elaborate study conducted in Europe in the past, it is brought out that flexural cracks upto a width of 0.4 mm has insignificant influence on rebar corrosion rate in cracked reinforced concrete (RC) structure and thus by adherence to the crack width restrictions stipulated in the code(s), elimination of additional risk of rebar corrosion in concrete is ensured. Effect of fly ash incorporation on durability of concrete is then discussed and role of fly ash in enhancing the service life of RC members cracked under design flexural loading, against rebar corrosion is highlighted.

Fly ash as a cementitous material is used extensively all across the world and is known to enhance the sustainability of concrete by alleviating concerns related to environmental pollution and green house gas emissions. Incorporation of fly ash as a mineral admixture in concrete directly, facilitates reduction in water demand for the same workability, and, achieve improvement in microstructure through pozzolanic reactivity[1,2]. However, pozzolanic reaction of fly ash with lime (CH) liberated from reactions of C_2S and C_3S with water may result in a small reduction in alkaline content of concrete. Alkalinity of concrete, together with other factors, is known to contribute to protection capacity of concrete against rebar corrosion. Thus, there may be some apprehension that reduction in alkalinity mentioned above, especially in concrete members subjected to flexural loading, may render them vulnerable to rebar corrosion due to micro-cracking that is assumed to take place under such load. The under-lying concerns behind the above apprehension are scientifically examined in this write-up and relevant conclusions are drawn. To do so, the role of flexural cracking on rebar corrosion is initially discussed in the following section.

Flexural cracking and rebar corrosion

To investigate the role of flexural cracking on corrosion of rebar an elaborate study was conducted in Europe in past[3]. Various European laboratories were involved in the testing scheme. In one set of tests reported (Munich exposure tests), beams were loaded to obtain flexural cracks up to 0.4 mm width and then they were subjected to:

- normal urban environment,
- heavily polluted industrial atmosphere
- marine environment exposures.

The beams were observed after 1, 2, 3 and 10 years and development of the corrosion was studied by measuring the depth of corrosion at each crack. Two additional factors namely cover depth of 25 mm and 35 mm were also included in the investigation. After two years of exposure, cracks less than 0.1 mm wide rarely exhibited corrosion, whereas, corrosion was always present in cracks wider than 0.25 mm. However, after 10 years, influence of crack width on the extent of corrosion was negligible as indicated by reduction in area of rebar. In the case of 10 years of exposure to most severe marine environment, the loss of sections were about 2 percent, independent of crack width and cover depth. General conclusions drawn from the investigation, on the influence of cracking on corrosion, were as follows.

(i) Corrosion is likely to initiate at the location where the rebar intersects the crack.

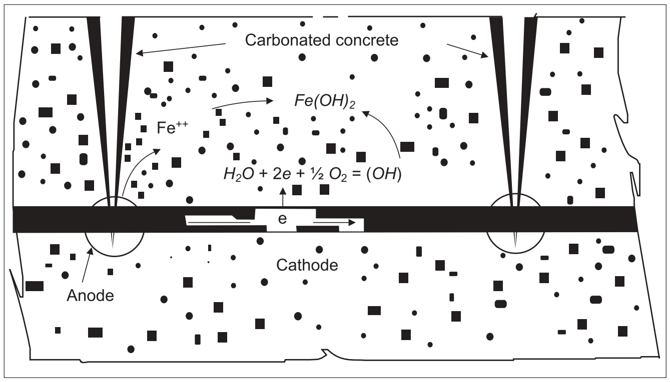

Fig 1 Corrosion process in cracked concrete

(ii) In short term, that is, of the order of two years, there is likely to be significant influence of crack width on the amount of corrosion found near the crack.

(iii) In long term, that is, of the order of 10 years, the influence of crack width on the extent of corrosion is negligible. Thus, for crack running perpendicular to reinforcement, crack width has no significant influence on the extent of corrosion that would occur during the life of the structure.

The explanation of the above behaviour was provided by Schiessl[3,4]. Carbonation is governed by ingress of moisture and atmospheric carbon-dioxide. In sound concrete, the carbonation may not even penetrate more than a few millimeters depending upon wetting and during cycle[4]. Schiessl observed that for exposure to environment other than marine environment, rate at which carbonation penetrated down the crack is a function of crack width. At the wider crack, carbon dioxide would penetrate into the section more rapidly in its vicinity, and, provided sufficient moisture is available, carbonation would occur quickly compared to thinner crack, hence small initiation period in the former case. Thus, cover and crack width both would have an influence on the time of initiation of corrosion. Once initiated, provided sufficient moisture and oxygen are available at the rebar surface, the rate of corrosion is independent of cover, crack width and even the presence or otherwise of the crack present. This can be explained through two considerations, one physical and another electrochemical. As regards the physical consideration, it was observed through resin impregnation studies that the crack width at the intersection of rebar and concrete is constant and independent of cover depth and crack width at the surface. The rib spacing in the deformed bar controlled this width. The electrochemical consideration is more relevant for the purpose of this article and is explained through *Fig* 1.

As shown in *Fig* 1, at the anodic region in the vicinity of cracked concrete, dissolution of iron (*Fe*) takes place after its depassivation due to carbonation. At the cathodic region of rebar surrounded by un-cracked concrete, cathodic reaction involving oxygen (*O*) and water (H_2O) will take place. The flow of charged ions (OH^-, Fe^{++}) shown in *Fig* 1 would be dependent on the electrical resistance of the un-cracked concrete. The process of rebar corrosion involves several simultaneous mechanisms of charge and mass transfer governed by laws of electrodynamics and conservation of mass, etc[5]. These are:

(*i*) dissolution of *Fe* at anode to Fe^{++} in the solution, and, transfer of electron through the bar to cathode;

(*ii*) transfer of electron from rebar to solution at their interface at cathode, and, cathodic reaction involving the electron, oxygen (O_2) and water (H_2O) at cathode

(*iii*) diffusion of oxygen and water through concrete at cathode for replenishing the quantity consumed in the cathodic reaction;

(*iv*) transfer of charge, (OH^-, Fe^{++}), that is, flow of current through un-cracked concrete to common reaction site forming $Fe(OH)_2$ etc.

The rate of reaction, that is, corrosion rate at any stage is controlled by kinetics of the slowest of all the above processes. In this case of rebar corrosion, the kinetics of the electrochemical corrosion reaction is controlled by rate of oxygen diffusion at the cathode and resistivity of un-cracked concrete media. Hence, rate of propagation of corrosion is independent of crack width or even the presence of crack or otherwise. The absolute rate of corrosion is also very small for cracked beams with otherwise sound concrete. As confirmed from the above study, only about 2 percent average loss of steel was noticed for 10-year exposure to most severe environment. It may be mentioned that a minimum acceptable level of rebar loss is 10 percent for justifying repair[6]. Thus, even though the initiation period for corrosion is small at isolated locations of the rebar, overall service life of the reinforced concrete (RC) members will not get affected and it can be as desired by the designer. The flexural micro-cracks thus have little effect on rebar corrosion related service life of concrete members.

Codal recommendations

The European study refered earlier was carried out for appraisal of the permissible limits of crack width as a means of design against corrosion by means of crack control, in CEB recommendations[3].These recommendations are 0.3 mm in normal exposure, 0.2 mm in internal exposure to humid or aggressive atmosphere and 0.1 mm for exposure to particularly aggressive environment. The IS 456 : 2000 recommendations are almost on the similar line. The permissible crack dimension (width) stipulated to control corrosion by limiting the possibilities of entry of moisture and salts, depending upon exposure conditions as recommended by ACI 224R are given in *Table* 1[7]:

Table 1: Permissible crack widths as per ACI 224R[7]

Exposure condition	*Permissible crack width, mm*
Dry air	0.41
Moist air	0.70
De-icing salts	0.18
Sea water spray/wetting and drying	0.15
Water-retaining condition	0.10

The ACI committee 224 R-90 report cites the article authored by Beeby and recognises the fact that flexural micro-cracks have insignificant effect on corrosion of rebar[3,7]. However, as a cautious approach, the above permissible crack widths mentioned earlier for the use of the designer is recommended. Repair strategies of cracks are also based upon above ACI recommendations, for example, crack width less than 0.3 mm usually does not require repair other than that for aesthetics purpose when exposed to ordinary moist air environment[8].

Practical experience

Corrosion cracking and spalling occurs randomly near locations of moisture ingress and not selectively at the tension zone of flexural members. Had flexural micro cracking been a serious factor governing the corrosion, then, corrosion cracks and spalling would have appeared predominantly in tension zone of flexural members and would have occurred less in axially loaded columns, top surface of beam at its mid span and on nonstructural members like sunshades, etc. General experience confirms that corrosion does not necessarily and predominantly occur at flexurally-vulnerable locations in RC structural members. In a recent visual condition survey of buildings in IIT Delhi campus, locations exhibiting distresses had been photographed for arriving at a condition rating for each of the buildings[9]. Several cases of corrosion cracking and spalling had been reported. An examination of these photographs revealed that out of 99 cases of severe corrosion cracking and spalling of concrete, only 17 can be considered to be located at flexurally vulnerable locations, for example, bottom of the beam at mid span, etc. Most of the cracking and spalling observed were on lightly loaded nonstructural members such as sunshades, facial beam etc. which faced the brunt of exposure to moisture and temperature variation and not on heavy beams or columns. Further, even in structural beams cracks and spalling were observed more often in compression zone rather than tension zone. Proximity to moisture ingress was the major factor that governed the location of corrosion distress in RC structures, rather than vulnerability to flexural micro-cracking.

Thus, it can be inferred that design flexural micro-cracking has very little influence on service life of RC members with respect to rebar corrosion.

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Effect of fly ash on some properties of concrete

Long term permeability of fly ash concrete

Structural concrete is specified in terms of its grade and a measure of workability (slump/compaction factor, etc), besides some other aspects. Hence, 28-day mean strength should be as required by the grade irrespective of the type of cementitious materials used. Hence, strength of OPC concrete and fly ash incorporated concrete shall be the same at 28 days age and for that the water/cementitious ratio need not be same, for example, if W/C represents this ratio for only OPC concrete, for fly ash admixed concrete, for same 28 days strength, this ratio may be $(W\text{-}\Delta W)/(C'+kF)$; where, W is the water content needed for specified workability for the given aggregates in OPC concrete; C is the OPC content in OPC concrete; ΔW is the reduction in water content for same workability when admixed fly ash is used in the cementitious materials, C' is the new cement content, k is a factor that represents the effectiveness of fly ash and is less than unity, and, F is the fly ash content.[1,2,10] For fly ash blended portland pozzolana cement (PPC) concrete the above ratio for same strength would be, W'/C'' where W' is the water content required for same specified workability and that may be same as W, and, C'' is the cement content. Thus, water to cementitious ratio need not be same but strength at 28-day age shall be same. Considering fundamental principles, the strength of concrete is mainly governed by flaws in its micro-structures, namely, pores at the interfacial transition zone (ITZ), capillary and gel pores in the bulk paste, compaction pores and deliberately introduced air entrained pores, etc[11]. For the same strength, porosity and mean (log mean) pore sizes shall be similar at 28 days for OPC as well as fly ash concretes. Hydraulic diffusivity that governs the moisture ingress and permeability of concrete are fundamentally related to the inter-connected porosity, pore size distribution, mean pore size and tortuosity, etc.[12] Thus, at the age of 28 days, fly ash concretes and OPC concrete have similar permeability and resistance to moisture ingress. With age, say at about 1 year, due to pozzolanic reaction the pores in the fly ash concrete are refined to finer sizes and porosity gets reduced vis-à-vis OPC concrete. Therefore, for the same grade of concrete, long term permeability of un-cracked fly ash concrete is lower and resistance to moisture penetration is significantly higher compared to OPC concrete. Further, for same exposure condition electrical resistivity of fly ash concrete is 3-5 times more than that of OPC concrete[4,13].

Alkalinity and pH of fly ash concrete

Hydration reaction of 100 gm of C_2S and 100 gm of C_3S, two main compounds of cement, with 21 gm and 24 gm of water liberates 22 gm and 49 gm of calcium hydroxide (CH) respectively[10]. According to Papadakis, reaction of silica with CH may take the following form[14]

$$2S + 3CH \rightarrow C_3S_2H_3 \qquad \ldots(1)$$

Thus, 100 gm of silica requires 185 gm of calcium hydroxide to produce 285 gm of $C\text{-}S\text{-}H$ gel. For common OPC composition amount of silica required to consume all the CH liberated can be calculated to be about 15 percent of the OPC. Fly ash having 55 percent silica, about 25 percent fly ash in cementitious is required to consume most of the CH produced. However, there are other reports that indicate that even 30 percent of fly ash by mass of OPC consumes only 14 percent of the CH produced[15].

Concrete made with PPC (20 percent fly ash) exhibited no reduction in pH (measured on powdered concrete) compared to OPC concrete, and, concrete made with 25 percent admixed fly ash in the total cementitious, exhibited a pH of above 12 in the laboratory[13,16]. However, due to the consumption of *CH* by silica, some reduction in reserve alkaline content in fly ash concrete is expected. It may be pointed out at this point that lowering of reserve alkaline content can affect the concrete in terms of faster rate of carbonation, if at all it does, only in presence of moisture that can enter through ingress from out side in a relatively porous concrete[4]. In case of concrete of low permeability this lowering is inconsequential. It may be worthwhile to mention here that in a recent study meant for investigating the role of cement content in specifications for concrete durability, Dhir *et al* have concluded that at the same *W/C* ratio, reduction in cement content by up to 22 percent had no adverse effect on most concrete (durability) properties, rather, the concrete exhibited improvement[17].

Flexural cracking and rebar corrosion in fly ash concrete

Considering the case of fly ash concrete RC member, cracked due to flexural loading, vis-à-vis that cast with OPC and similarly cracked, the behaviour of the former compared to later member would be similar as that of a member with wider crack vis-à-vis a member with thinner crack, discussed earlier. In the short term, say a year or two, one may observe more corrosion penetration at the intersection of rebar and crack, in case of fly ash concrete member compared to that in an OPC concrete member. However, the situation is likely to reverse in this case, in the long term. This is because the rate controlling mechanisms again would be oxygen diffusion at the cathode and electrical resistivity of the un-cracked concrete at cathode as shown in *Fig* 1. The oxygen diffusivity of fly ash concrete would be much lower in the long term and electrical resistivity of fly ash concrete under similar exposure is few times greater than that of OPC concrete. Thus, in the long term, a member cracked due to flexural loading and cast with fly ash concrete would exhibit much lower corrosion penetration at the intersections of cracks and rebar, than a similar member cast with OPC concrete having same cracks widths.

It can be inferred from above discussions that, even for flexural members with micro cracks in the tension zone, fly ash concrete members has much longer service life against rebar corrosion, vis-à-vis OPC concrete members.

Additional discussion

In a recently published article, 22 case studies on rebar corrosion distressed RC buildings/group of buildings in northern region of India are reported[18]. For the cases analysed, the age at investigation varied from 5 to 50 years[18,19]. It was observed that in most of the buildings, concrete was chloride contaminated through ingredients, probably through the mixing water and unwashed land-quarried sand. The cement used was OPC only. Regression of the age at investigation, that is, initial repair cycle (T_R, years) data with ultra sonic pulse velocity [USPV] (V, km/s), strength (f, MPa) and cover depth (c, mm) resulted in following equation indicating that service life of concrete members depends largely upon USPV that is a measure of soundness of concrete, strength and cover depth.

Even for flexural members with micro cracks in the tension zone, fly ash concrete members has much longer service life against rebar corrosion, vis-à-vis OPC concrete members.

$$T_R = 9.39V + 0.65f + 0.24C - 14.0 \quad ...(2)$$

Thus, the generally porous and poor quality concrete (not locally poor only at isolated location or crack) and low cover depths are mostly responsible for lower service life. Similar inferences were also drawn by other workers in past as well[20]. Main factors causing early corrosion repair is the poor quality control at site and poor construction practices. Adoption of mechanisation in large scale, for example, automated batching plant to control the mix proportions and ensuring appropriate cover depth etc., can improve the situation significantly. Use of pozzolanic material like fly ash can only enhance the service life of concrete members and make the concrete eco-friendly and more sustainable.

Conclusion

Two major conclusions are drawn from above discussions, namely:

(i) design flexural micro-cracking has very little influence on service life of RC members with respect to rebar corrosion,

(ii) RC members cast with concrete incorporating fly ash, has much longer service life against rebar corrosion, even for flexural members with micro cracks in the tension zone, vis-à-vis OPC concrete members.

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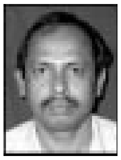

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