CONCRETE CRACKING IN COASTAL AREAS
Problems and Solutions

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ABSTRACT

The paper discusses cracking and corrosion of reinforced concrete (RC) structures in coastal zones where aggressive action of salt burdened air is the primary cause of concrete deterioration. Case studies are presented, along with discussion of possible remedies including local demolition, reconstruction and epoxy injection as well as concrete treatment.

INTRODUCTION

The occurrence of concrete cracking and deterioration in coastal areas is more severe than in any other terrestrial environment. This is caused by a salt-burdened air zone, which may extend inland three to five kilometres from the shoreline. Cracking in concrete buildings is a common problem, with cracks often affecting aesthetics as well as the perception of construction soundness.

For many years, the causes of concrete deterioration have always been the object of concern and research. This interest is increasing due to the high cost associated with the repair and maintenance of the built environment. The sources of concrete distress can be grouped into four broad categories [1]: unsuitable materials, improper workmanship, severe environment, and structural weakness.

Most of failures due to concrete deterioration could have been avoided if the well-established principles of construction practice [2,3,4,5] had been followed. Human negligence is more of a factor than scientific ignorance.

The case studies presented here illustrate some typical cases of concrete cracking resulting from reinforcement corrosion due to a coastal environment in combination with improper workmanship (e.g., handling/placing of concrete) or unsuitable materials (e.g. sea-water contaminated aggregates, improper mix proportions).

CHEMICAL CONSIDERATIONS

An idealised diagram of the reactions that occur when a bar surrounded by concrete corrodes is shown in Fig. (1).

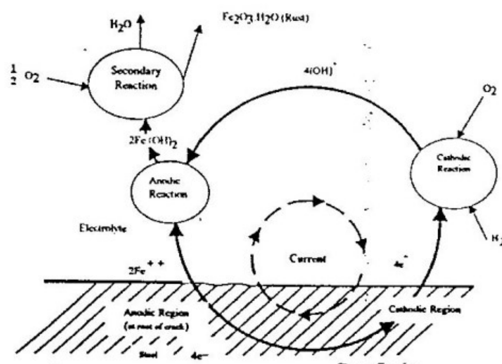

Fig. 1. Corrotion reaction (idealised)

When steel becomes depassivated in the region of a crack, it is rendered anodic relative to the areas that remain protected. Metal ions pass into solution in the electrolyte, and the resulting excess of electrons are attracted to the cathodic regions. Here, they associate with oxygen and water to produce hydroxyl ions. These transfer to the anode where they associate with metal ions to form ferrous hydroxide, which in the presence of oxygen is rapidly converted to rust. The details of the reaction process which are illustrated in Fig. (1) are as follows:

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(a) The anodic reactions

$$2Fe \rightarrow 2Fe^{2+} + 4e^-$$

$$2Fe^{2+} + 4(OH)^- \rightarrow 2Fe(OH)_2$$

$$2Fe(OH)_2 + 0.5\ O_2 \rightarrow 2FeO(OH)$$

$$2FeO(OH) \rightarrow Fe_2O_3.H_2O \text{ (rust)}$$

(b) The electrons produced by the anodic reaction are transferred to the cathodic region allowing the cathodic reaction to proceed.

$$2H_2O + O_2 + 4e^- \rightarrow 4(OH)^-$$

In this way the corrosion cycle illustrated in Fig. (1) is completed

The precise nature of the corrosion product will depend on various factors including the availability of oxygen and the one shown in Fig. (1) is not the only possibility. The important point to note is that the rate at which the reaction can occur is controlled by the availability of oxygen at the cathode and the resistance of the electrical path through the concrete between the cathode and the anode. Thus the rate of corrosion depends on the availability of oxygen not at the crack but in the surrounding concrete away from the crack and hence on the rate at which oxygen can diffuse through the cover.

From a chemical standpoint, therefore once corrosion has started, the influence of the crack on the rate of corrosion is small. therefore, the assumption that the rate of corrosion is independent of crack width thus seems reasonable.

CORROSION DAMAGE IN PRACTICE

When the reinforcement rusts the corrosion products generally occupy considerably more volume than that of the steel destroyed.

The magnitude of this increase in volume varies somewhat from situation to situation, but a value in the region of 2 to 3 times the volume of metal removed would not be unreasonable. As a result, the corrosion products from quite small reductions in the cross-sectional area of a bar will produce internal stresses sufficient to disrupt the surrounding concrete. The typical indications of corrosion in reinforced concrete structures are wide cracks along the line of bars, spalled-off corners or substantial spalled areas on slabs. In most practical circumstances this spalling occurs well before the reinforcement has become significantly weakened.

Once the cover has been spalled off, rapid corrosion of the exposed steel will take place. The indications are that corrosion of exposed bars may occur at about 10 times the rate at which it occurs at cracks, sufficient to cause significant weakening of bars in a short time relative to the design life of a structure. The primary objective of design against corrosion is thus design against spalling rather than design against unacceptable loss of reinforcement area. The parameters that are likely to influence spalling of the concrete can be derived very simply. The internal forces generated by corrosion will depend on the depth of corrosion, the corroded length and the bar diameter. The ability of the concrete to resist these forces will depend on the location of the bars (a corner bar will be weaker than one in the centre of a slab), the tensile capacity of the concrete and the cover.

Another variable mentioned above, as being likely to critically affect the possibility of spalling is the length of bar over which corrosion occurs. In situations where the initiating source of corrosion is a crack perpendicular to the line of the bar, the corroded length is likely to be small, typically up to about 3 bar diameters. Far larger corroded lengths will occur where a crack follows the line of a bar. In such a situation, the corroded length will be roughly equal to the length of the crack.

Furthermore, the crack will reduce the resistance of the surrounding concrete to spalling. Longitudinal cracks can result from a variety of sources, e.g. in a beam many of the cracks perpendicular to the main bars will form along the line of stirrups. Similarly, cracking in slabs often at least partially follows the lines of reinforcement.

In a contribution to the investigation of corrosion damages at cracks also coring programme of actual structures have been carried out by different researchers and investigators [6] and found that very little corrosion occurred where cracks crossed bars but the transverse bars were considerably more heavily attached.

There is a fundamental difficulty associated with the valuation of data from actual structures. Since corrosion causes longitudinal cracking, it is not really possible to tell whether a particular crack caused the corrosion or whether the corrosion caused the crack. Nevertheless it does seem clear that a crack perpendicular to the line of the bar does not constitute a corrosion risk in practice, while the existence of longitudinal crack may.

CAUSES OF CRACKING

Seawater attack.

Seawater contains approximately 3.5 percent by weight of soluble salts, namely 3% NaCl, 0.3% $MgCl_2$, 0.18%$MgSO_4$, 0.04%$MgBr_2$ and others in significant amounts.

It has been found out [7] that the aggressive action of sea water on concrete does not result from the presence of magnesium (Mg^{++}) or sulphate (SO_4^{--}) ions that directly attack the portland cement hydration products [8]. In fact, sulphate attack due to the formation of expansive ettringite is inhibited in the presence of chloride (Cl^-) ions. Chlorine is responsible for the greatest damage of steel reinforcement because of its corrosive attack and the fact that makes the major salt constituent of sea water.

Deterioration of conventional reinforced concrete structures affected by rusting reinforcement results from the disruption of concrete due to the expansive products of corrosion. It is not a result of a reduced mechanical strength of steel itself. Only for the case of prestressed concrete does the soundness of the tendons become a concern [9].

Corrosion of steel reinforcement.

Fig. (2) represents the mechanism of corrosion of steel reinforcement.

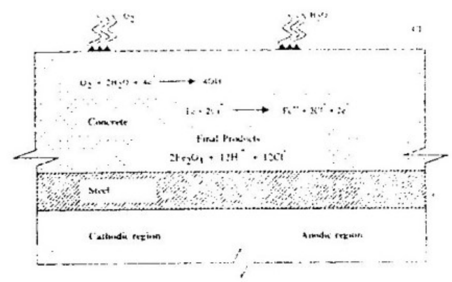

Fig. 2 Corrosion of steel reiforcement in concrete in the presence of chloride

It is apparent that three conditions are to be fulfilled to make the electrochemical process possible, namely, disruption of passive gamma- Fe_2O_3 film, a supply of oxygen and the possibility of current flow.

The pH of concrete, usually above 12.5, is strongly related to the presence of free calcium hydroxide ($Ca(OH)_2$). Any process (e.g., carbonisation) that can reduce alkalinity will also cause a breakdown of the protective ferric oxide film formed over the steel. However, even at high alkalinity, this film is destroyed by penetration of the aggressive chloride ions, which may promote corrosion at the anode.

After the reaction, chloride ions are released for reuse. Thus, the corrosion process is an oxygen diffusion limited system: the reaction can progress only as fast as oxygen is supplied. Finally, concrete must allow a current flow between anodic and cathodic areas. This current flow is controlled by the electrolytic resistance of the matrix and is inversely affected by moisture content, temperature, soluble salts content and permeability. However, water saturation may prevent oxygen transport with a resulting decrease in corrosion rate [10].

In terms of corrosion areas, it appears that anodic and cathodic reactions occur in different places some distant apart (i.e. micro-cell type corrosion). The separation depends upon cover depth, steel layers, chloride levels, etc, and the formation of these cells is not necessarily permanent.

Corrosion of non-ferrous metals.

Metals other than steel may also be embedded in concrete for various construction purposes (e.g. conduits, railing posts, galvanised lath, etc.). Aluminium has the worst stability and can corrode rapidly in moist concrete since its passive film is destroyed in high alkalinity. This corrosion phenomenon is aggravated in the presence of Cl-ions, or when aluminium is in contact with reinforcing steel, in which case it becomes a sacrificial anode.

Non portland cements.

Gypsum type cements are occasionally used in building construction as rapid-set binders, for repairs or railing installation. This produces matrices with a pH value below 12, which is not sufficient to protect embedded steel. In addition, due to the localised use, the likehood of macro cell formation resulting from pH differential may increase.

Corrosion prevention.

From Table 1, where both the elements necessary for steel reinforcement corrosion in concrete and the conditions favouring it are summarised, it can be inferred that the most effective corrosion prevention actions are:

Impermeable concrete-making concrete as impermeable as possible would prevent penetration of chloride, moisture, and oxygen. Permeability is generally associated with the water-cement ratio, which affects pore structure, number, factors such as bleeding and segregation. This will further impoverish the quality of the concrete surface.

Table 1. Corrosion of steel reinforcement in concrete

Elements for corrosion	Circumstances Favouring	Corrosion prevention action	
		Specific	Common
Passive Film disruption	Carbonation Chloride Penetration Permeability/cracks	High pH	Impermeable Concrete Appropriate Cover surface Coating
Oxygen Supply	Permeability/ Cracks aeration		
Current flow	Permeability/Cracks, Moisture, Soluble salts, temperature	Different Metals Separation	

Cracking due to placement, curing, or loading also affects permeability, even there is no clear evidence that cracking and crack size lead to more severe corrosion [11]. It can be simply stated that cracks do not help, particularly when they extend to the reinforcement bars and run parallel to them.

Appropriate cover - It is well-established [11] that increasing cover depth decreases corrosion for the simple reason that the penetration path to the steel is proportionally lengthened.

Surface treatment - Surface treatments for concrete have the objective of improving the matrix impregnability. However, they cannot be considered as an alternative to good quality concrete, particularly where active cracks are encountered. Epoxy-coated reinforcing bars are occasionally used in the

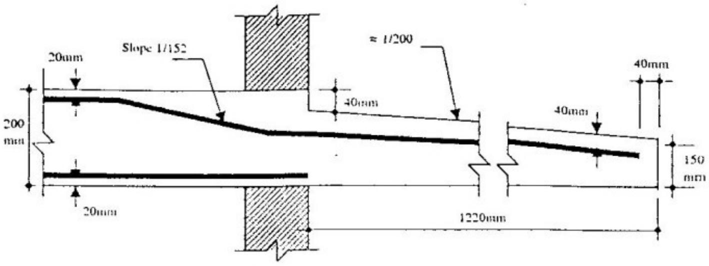

Fig. (3) Balcony detail according to AC 308-83

construction of infrastructures rather than buildings.

High pH - The need for a high pH level, which is responsible for the steel passive film, does not necessary call for high cement content, even if increasing cement percentage seems to decrease corrosion rate. Gypsum-type cements and concrete additives (e.g. phosphates) that produce a low pH, do not passivate the steel.

Different metals separation-Contact of steel reinforcement with other embedded metals of different electrical potential can create galvanic currents and sacrificial anodes. If contact cannot be prevented, the metal surfaces should be treated with an isolating coating.

CASE STUDIES

Insufficient cover. The first case study illustrates the consequences of not providing sufficient cover to the reinforcing steel. Fig. (3) represents a sketch of a balcony with typical details in accordance with ACI 318-83 specification [2]. Violations of these specifications commonly occur in two areas:-

(1) Top reinforcing steel is usually bent on the site to conform with different requirements for cover between building interior and balcony (in the given example - 20mm and 30mm cover respectively). It should be assured that: (a) enough cover is provided under the stepdown; (b) reinforcement slope does not create excessive stress in the confining concrete; and (c) loss of negative moment capacity due to the lower steel position is accounted for.

(2) Cover requirements should be enforced at the balcony edge for both longitudinal and transverse reinforcing bars. Fig. (4) also presents clearly another example that this precaution was not taken for these sun-breakers. Approximately ten years after construction, the edges of the sun-breakers deteriorated to the extent that cracked concrete had to start spalling off as it is seen in Fig. (4). The proximity of the ocean to the building is the main cause of deterioration of the sun breakers as it is seen from the photograph. Had the construction been located inland, reinforcement corrosion and concrete cracking would have considerably delayed. These sun breakers can be repaired using epoxy-based concrete.

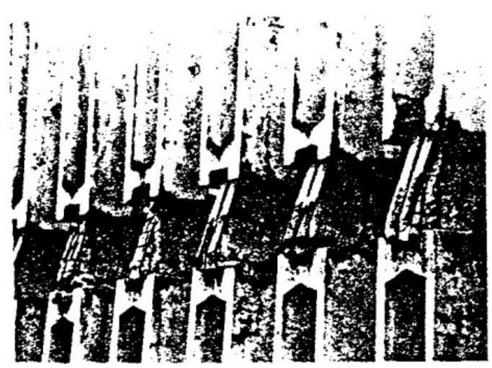

Fig. 4 Sun-breaker edges without appropreate cover

Architectural accessories. Sun exposure and scenery are the reasons for many balconies on the buildings in coastal areas to deteriorate. A construction fault can become extremely costly, involving incorrect selection and installation of balcony parapets.

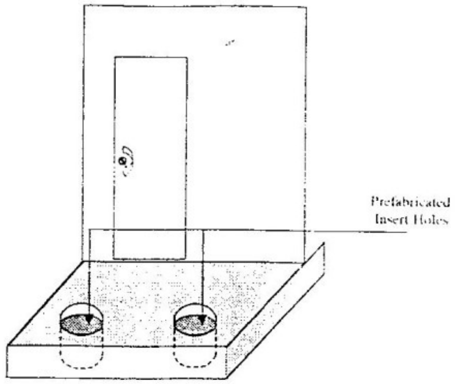

Fig. 5 Prefabricated insert holes in the balcony

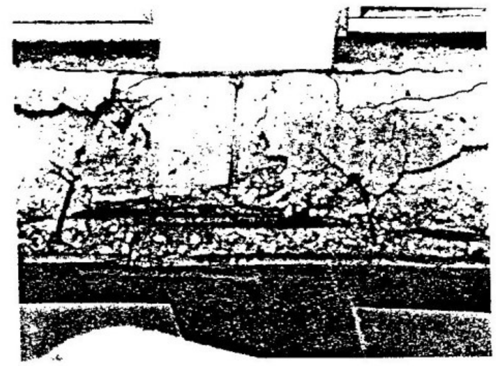

Fig. 6 Spalling of concrete resultimg from contaminated aggregate

When aluminium railings are chosen, the post surfaces to be embedded in concrete must be protected (e.g. epoxy coating) to prevent contact with the reinforcing steel. Prefabricated insert holes as shown in Fig. (5), present a solution to avoid metal contact problems. The grout-mortar used to anchor the posts should be non-shrinking. Fast setting gypsum-based mixtures should be avoided because of their low pH values.
The aluminium spacers are embedded in concrete. The spacers are originally provided to facilitate installation of this railing. Since the concrete had irreparably cracked the entire edge of the continuous balcony has to be sawed off. The repair has to be completely glued in a new cast in place concrete edge to the existing sound concrete of the balcony.

Poor quality concrete. Poor quality concrete was used in the following examples. Fig. (6) shows extensive damage due to cracking and spalling of concrete originally made with seawater contaminated aggregate. It may be interesting to note that the peeling off of the concrete cover (Fig. 6) is not the result of careful demolition work, but the effect of chemical decomposition within the concrete mix, as time passes on.

Chloride ions could be present within a mix at any geographical locations: however, this problem is more prevalent in the coastal zones where the aggregate may be mined from saltwater-saturated or coral stones quarries. When salt water contaminated aggregate is the only available source, extensive washing with free water should be mandatory.

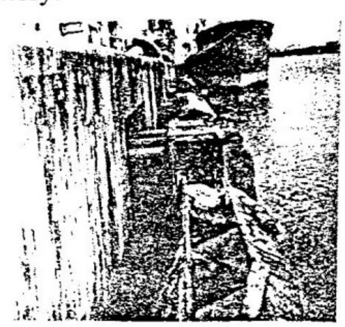

Fig. 7 Corrosion of steel bars in concrete piles at the port area

Figs. (7) and (8) show location and condition of concrete steel bars in concrete piles and broken off fender system due to corrosion at a sea port area. Concrete around the piles and fenders has badly deteriorated and cracks due to reinforcement corrosion, even though appropriate cover was provided during construction. In this case poor quality of the concrete mix, confirmed by low compressive strength results was responsible for chloride penetration and subsequent rapid steel corrosion.

Fig. 8 Broken off fender system due to corrossion of support areas

Fig. (9) shows a newly erected reinforced concrete building not far away from the seashore. The building has sun breakers as well as exposed external staircases. Would this building structure sustain these aggressive environmental conditions plus those caused by human negligence?

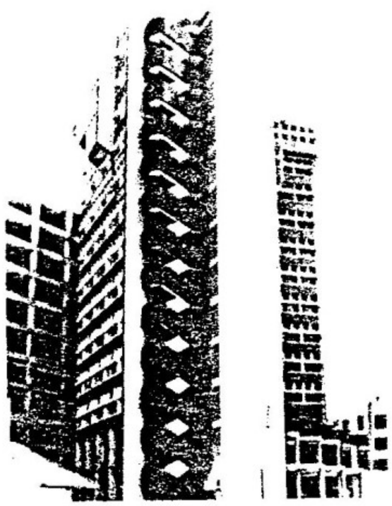

Fig. 9 A newly constructed reinforced concrete building -a few meters away from the sea

Repair. For most of the situations encountered, the only feasible repair solution consisted of the following steps:-

1. Local demolition of deteriorated concrete until sound material is exposed. Concrete is to be removed all around the reinforcing bars.

2. Application of a protective epoxy coating to the reinforcing bars.

3. Plastering with epoxy based mortar.

4. At times, treatment by application of VANDEX CRS systems on exposed concrete surfaces may be appropriate although very expensive hence measures should early be taken during design and construction to make sure that the environmental effects are kept at bay from the building.

The practice of crack sealing with epoxy method is done by the operator who injects a

vertical crack by means of a hand pump. Normally, this is not appropriate for cracks produced by reinforcement corrosion. Epoxy injection should be performed on stable cracks, between sound surfaces, only after the cause of the crack has been neutralised. The aim of this type of repair is to restablish continuity in the matrix. Thus, a careful investigation of the cause(s) of cracking should precede any rehabilitative effort.

CONCLUSIONS

The following conclusions can be drawn from the presented case studies:-

1. Cracking of exposed concrete in coastal areas is mainly a result of reinforcement corrosion, which is caused by either the penetration of chloride from seawater spray or the use of contaminated aggregate.

2. Appropriate cover and good quality concrete most efficiently prevent reinforcement corrosion. Compliance with the provision in the codes of practice and standard construction practice guarantee durable concrete.

3. Careful specifications for selection and installation of accessories such as railings and planters should be provided to ensure durability of concrete. This is often overlooked by most of engineers.

4. Repair should follow the correct identification of the problem and should be executed on sound concrete. the most commonly used rehabilitation technique for concrete deteriorated due to metal corrosion is local demolition and reconstruction.

REFERENCES

1. Waddel, Joseph, J., "Basic Steps of a Concrete Repair Program," **concrete International:** Design and Construction. V.2, No. 9 Sept. 1980, pp. 30-33.
2. AC1 Committee 318, "Building Code Requirements for Reinforced Concrete (ACI 318-83)." American **Concrete Institute,** Detroit, 1983, 11 pp.
3. ACI Committee 315, "Details and Detailing of Concrete Reinforcement (ACI 315 - 82)," **American Concrete Institution**, Detroit, 1980, 50 pp.
4. The Institution of Structural Engineers, "Durability", Manual for the Design of Reinforced Concrete Building Structures. **The Institution of Civil Engineers**, United Kingdom, December, 1985, 25 pp.
5. BS 8110 Part 1. "Structural Use of Concrete", Code of Practice for Design and Construction, **British Standard Institution,** 1985, 3/6 pp.
6. Beeby, A.W., "Corrosion of Reinforcing Steel in Concrete and its Relation to Cracking", The Structural Engineers. Journal of the Institution of Structural Engineers, Volume 56A. No. 3, March 1978, pp.77-81.
7. Perkins, H.P., "Repairs to Concrete Marine Structures", Concrete Structures: Repairs, Waterproofing and Protections, Applied Science Publishers Ltd., 1976, Chapter 5, pp.180-206.
8. Perkins, H.P., "Protection of Concrete Structures Against Chemical Attack", Concrete Structures: Repairs, Waterproofing and Protections, Applied Science Publishers ltd., 1976, Chapter 6, pp.207-254.
9. Neville, M.A. "Admixtures", Properties of Concrete, Longman Scientific and Technical Publishers, 1981, pp. 100-106.
10. Slater, John, E., "Corrosion of Metal in Association with Concrete". STP-818, ASTM, Philadelphia, 1983, pp.83.
11. Beedy, A.W., "Cracking, Cover and Corrosion of Reinforcement, Concrete International, Design and Construction, V.5 No.2, Feb. 1983, pp.35-40.
12. Mwakasala, J.N.T., Dr. Mrema, A.L.: Dr. Rubaratuka, I.; Report, "Technical Investigations on Defects and Failures in Reinforced Concrete Buildings", No. 51-93-60, Department of Civil Engineering, University of Dar es Salaam, May, 1994.
13. Omollo, K.W.; Dr. Mrema, A.L.; Dr. Mpinzire, S.R., Report, "The Repair of Concrete Structures"W, No. 40-96-60, Department of Civil Engineering, University of Dar es Salaam, June, 1996.
14. Lukaza, J., Dr. Rubaratuka, I.; Dr. Mpinzire, S.R.; Report, "Appropriate Designs of roofs in Tropical Regions", Case Study in Dar es Salaam, Department of Civil Engineering, University of Dar es Salaam, June, 1996.
15. Salim, Mohamed, A; Dr. Rubaratuka, I.; Report, "Improving the Durability of Reinforced Concrete Structures", Report, No. 84-97-60, Department of Civil Engineering, University of Dar es Salaam, May 1997.

16. Advisory Note, "A guide for Use of Epoxide Resins with Concrete for Busdine and CWIL Engineering". Cement and Concrete association UDE 678.6?7.026; 693.548 625.75.03, No. 12.

17. VANDEX CRS, "Concrete and the Environment Manual", CONCRETE REPAIR AND PROTECTION SYSTEM, Vandex International Ltd., Box 1369, CH-3601 Thun/Switzerland.