JCSE The Journal of Corrosion Science and Engineering
ISSN 1466-8858 Volume 16, Preprint 3 submitted 3 January 2013

The Principle of the Critical Stress for Limiting Corrosion of Steel Reinforcements in Concrete

M.J. Molyneaux
141 Brooklands Road, New Plymouth, New Zealand
mike.molyneaux@xtra.co.nz

Abstract

Standard corrosion textbooks imply that once corrosion of reinforcing steel in concrete has started it will continue without limit unless some engineering intervention is undertaken. However field observations show that this type of degradation can be self-limiting. If the concrete has sufficient strength and the design of the reinforcing bars are suitable, then any active corrosion will eventually be stifled. This will only happen if the stress that builds up in the concrete to accommodate the volume of corrosion product reaches the critical limiting stress before the concrete cracks. Three case studies are presented to illustrate the limiting conditions for this type of corrosion.

KEY WORDS: concrete cracking; steel reinforcement; corrosion limiting stress; damage assessment; crack prevention:

1. Conditions for Limiting Corrosion of Steel Reinforcement

It is commonly observed that corrosion of steel in marine environments will be restrained when the corrosion products become trapped and tightly wedged in a strong, unyielding crevice. The limiting conditions were systematically studied and first reported by Molyneaux in 2008 [1]. The same phenomenon can be observed in the case of reinforcing steel in concrete structures. Cathodic protection is recognised to be a cost effective solution for preventing corrosion of steel reinforcements [2], and often presented as an essential part of restoration [3]. Other methods recommended in two authoritative textbooks on corrosion [4 and 5] are the use of galvanizing, coatings, stainless steel and the addition of corrosion inhibitors or chemically inert fines to the concrete that retard salt water ingression through the concrete. However, there is no mention of applying the (apparently unknown) principle of the corrosion limiting conditions to remedy or design out the problem.

2. Field Observations of Corrosion

Field observations and tests were carried out to investigate corrosion rates of steel embedded in concrete and the possibility that corrosion could also be restrained by the build up of corrosion product trapped at the steel/concrete interface. In particular, the influence of the alkaline environment of concrete was of interest. The structures had been exposed to the splash zone of a marine environment for a period of over fifty years. Three cases are presented to illustrate the principle of a critical limiting stress (pressure) that eventually stifles further corrosion.

Case 1

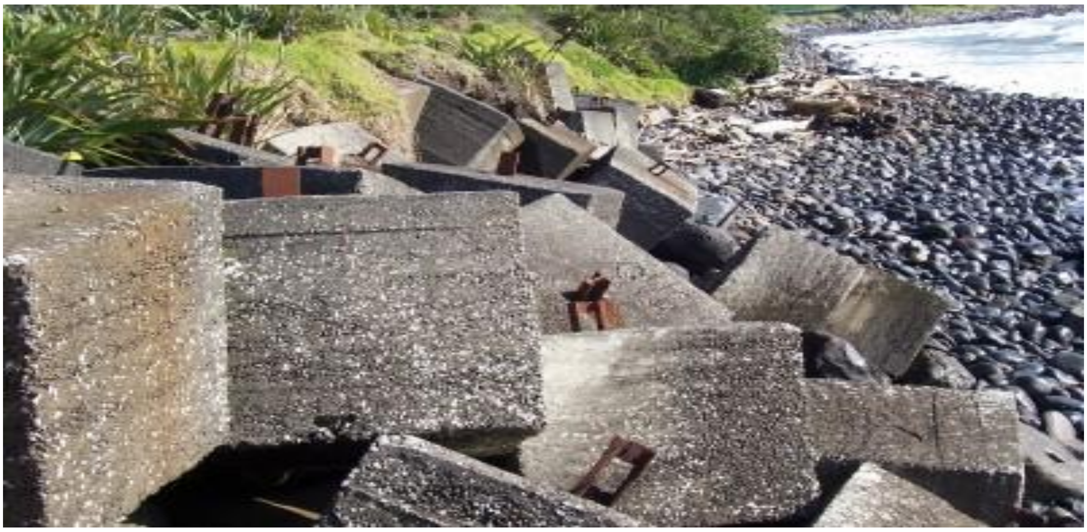

Figure 1: Concrete blocks designed to prevent coastal erosion

Case 1 studied a large collection of approximately 2 ton concrete blocks. The casting dates marked on the blocks show that they were cast in the period between February 1949 and March 1951. Carbon steel lifting bars [pieces of rail with an original thickness of 25mm at the load bearing end and 12.5mm thick web] were embedded in each block with one end protruding by approximately 200mm. In general and as expected, the forces exerted by the increasing volume of corrosion product that formed around the steel bars had opened up large cracks in the concrete.

Figure 2: Example of cracks in the concrete surrounding the steel bars

Figure 2 shows an example of cracking that had propagated across the face of the block. In other cases cracking was only visible part of the way across the faces and in a minority of cases the concrete appears to have resisted cracking and remained virtually undamaged. Seven smaller blocks shown in figure 3 had round steel bars or tubes (32mm outside diameter) protruding from opposite surfaces. The concrete surrounding five of these round bars was undamaged, the other two were cracked.

JCSE The Journal of Corrosion Science and Engineering
ISSN 1466-8858 Volume 16, Preprint 3 submitted 3 January 2013

Figure 3: Example of corroding round bars in undamaged concrete

Some round bars (see figure 3) had been worn down almost flush with the concrete through erosion/corrosion due to the impact of stones in the surf and the smooth curved surface of the embedded bar (visible at the steel/concrete interface) appeared to be virtually uncorroded after nearly sixty years exposure to the sea water. The shape of reinforcing bars was obviously related to the incidence of cracking – round being less conducive to cracking.

It is possible that invisible micro-cracking had taken place in those apparently uncracked blocks but the significant point to note is that even if invisible micro-cracking had taken place, propagation could not have progressed at the same rate as some of the other examples. An explanation for the great diversity in corrosion rates in concrete is required. The corrosive environment had been equally aggressive in all cases, as evidenced by the observation that in every case those parts of steel protruding out from the concrete had been converted into thick layers of rust, in some cases leaving only a short stub of metal and rust, in other cases the steel had completely converted to rust scale. There was no apparent relationship between the incidence of cracking and the severity of rusting/metal loss of the protruding steel. In all cases the depth of cover [thickness of the concrete] over the steel bars is actually zero at the point where the bars protrude from the concrete. This means that in every case, salt water would have attacked embedded parts of steel near the surface of the concrete with equal aggressiveness early in the life of all these structures. So the difference in cracking observed cannot be explained on the basis of different local chemical environments in the concrete immediately surrounding the steel bars. The most obvious explanation for the cracking incidence [besides the shape of the bars and presence of porosity and/or casting defects around the edges of the bars] is a factor involving the strength of the concrete. More specifically, this factor relates to the capability of the concrete to absorb a certain critical (limiting) level of stress and strain without cracking. The most significant finding is that corrosion of steel in concrete can be limited by the build up of iron oxide and stress generated by the additional volume [iron oxide] at the steel/concrete interface. Corrosion is stifled when the stress exceeds a certain limiting pressure without cracking the concrete.

Case 2

Figure 4: Cracked concrete block with piece of concrete displaced

The second case examined another similar collection of blocks cast between August 1947 and February 1948. Each block had a pair of steel rails (from a railway line) fully embedded at least 100mm deep in the concrete. A rectangular furrow across the centre of one face (where a wooden baton was originally embedded) left only approximately 25mm concrete

JCSE The Journal of Corrosion Science and Engineering
ISSN 1466-8858 Volume 16, Preprint 3 submitted 3 January 2013

cover where the wood had been. Most blocks were severely cracked and the cracks appeared to originate from the rails but very few had begun to break apart. The impact of stones tumbled by waves recently broken and displaced a chunk of concrete from one of these, revealing details of the steel corrosion inside. The edge of the rail was well exposed at one place. More concrete was chipped away with a chisel for closer examination. It was significant to observe that while the top and the outer surfaces of the rail were covered with hard magnetite at least 0.25mm thick, on the inward facing surfaces of the rail (the recess area) the magnetite was much thinner [approximately 0.1mm thick].

Figure 5: Steel rail with thin magnetite on inward facing surface [x10 magnification]

Another broken block with part of the rail exposed had been descaled by sand erosion. Again, the top edge of the rail was uneven and roughened/pitted through corrosion and metal loss while the inward facing surfaces (the recess area) was still straight, flat and smooth – virtually uncorroded. The depth of cover was the same for these different parts of the rail but the concrete cast in the recess area between the inward facing parts of the rail had been compressed (wedged in place) as corrosion product was formed on the steel surfaces thus providing the pressure needed to stifle further corrosion of these surfaces. In contrast, the geometry of expanding corrosion scale at the top and outer edges of the rail creates tensile stress in the surrounding concrete. The considerably lower tensile strength of the concrete gave way to cracking and ongoing corrosion. These observations indicate

JCSE The Journal of Corrosion Science and Engineering
ISSN 1466-8858 Volume 16, Preprint 3 submitted 3 January 2013

the role of stress and concrete strength (rather than chemistry) in either restraining or permitting corrosion of steel reinforcements.

Case 3

Figure 5: Octahedron pillars reinforced with a cage structure

In the third case, four octahedron pillars were reinforced with 8 x19mm diameter vertical rods, spaced 80mm apart, with 3mm diameter wires wrapped horizontally around the rods and spaced 32mm apart to form a cage structure as shown in figure 5. In spite of the fact that the depth of cover over the rods was only 40 mm [in some areas even slightly less] the design generally offered good resistance to cracking and spalling. The middle sections of the pillars were all totally undamaged as far as visual examination could tell. The top and bottom ends of all four pillars had been chipped and cracked through the action of rocks thrown up by waves, exposing the reinforcing steel to weathering. It is assumed that there were originally also thin wires at the ends and that those had been completely destroyed through erosion/corrosion. The greater extent of damage on these ends would have been due to the original square edges that constituted boundary conditions with stress concentrations that the middle parts do not experience. The original dimensions of the uncorroded steel were measured after chipping away the concrete at one point – shown by an arrow in Figure 5. The concrete covered wires themselves are only slightly oxidized and too thin [in relation to the depth of cover] to cause progressive cracking and spalling. Any

JCSE The Journal of Corrosion Science and Engineering
ISSN 1466-8858 Volume 16, Preprint 3 submitted 3 January 2013

tendency of expanding iron oxide from the corroding rods to split the concrete in the middle sections had been restrained by the thin wires that are perfectly placed to bind the concrete and resist further corrosion.

This principle of a critical stress that limits steel corrosion explains why the steel rod and wire cage reinforcement design provides such good resistance to concrete cracking and spalling – the thin wires secure the concrete around the larger rods protecting them from cracking and allowing corrosion to continue.

3. Measurements and analysis of findings

The magnitude of the corrosion limiting stress can be estimated from the strength of the concrete and the geometry of the structure under study. The methods of stress analysis described by Roark [7] are applied. Because the modulus of elasticity for steel is much higher than concrete, most of the deformation [strain] occurring in reaction to the additional volume of corrosion product is distributed in the concrete material around the steel bar while the bar itself undergoes negligible shrinkage strain. The analysis is simpler for round bars, so in this paper the analysis will only be applied to that shape. The pattern of the stress field surrounding a round bar fully enclosed in concrete is similar to the case of a round hole in a flat plate.

Stress analysis shows that the stress field extends into the bulk of the concrete material to distances [in the radial direction] of up to three times the radius of the bar. The concrete experiences compressive stress in the radial direction and tensile stress in the circumferential direction. [8] This situation is comparable to the behaviour of concrete in the splitting tensile test situation where compressive stress and strain in the vertical direction induces tensile stress and strain in the horizontal direction. In the case of a round bar, the compressive stress exerted by iron oxide on the surface of the steel bar [in the radial direction] will be comparable to the pattern of stress generated during a splitting tensile strength test.

An estimate of the critical stress for limiting corrosion was made from field observations as follows. The first step was to estimate the compressive strength of the blocks in the field under study from hardness readings taken on these blocks. Research [9] shows a good correlation between these two properties of concrete – compressive strength and hardness. Four concrete test cylinders that had been tested in accordance with ASTM C39/C39M were selected to provide a range of compressive strength values for calibration. A set of hardness readings (Load deflection “LD” values) was taken on each of the test cylinders using an Equotip portable hardness tester. The LD values were recorded without converting

JCSE The Journal of Corrosion Science and Engineering
ISSN 1466-8858 Volume 16, Preprint 3 submitted 3 January 2013

to a hardness number. These values were then compared with a similar set of readings taken on the blocks and the four pillars in the field study. Each pillar was tested, as well as a sample of ten blocks containing steel rails and seven blocks containing steel rods or tubes. Twenty readings were taken on each block and twenty for each of the four pillars. The surface material of all the blocks was well eroded, allowing easy access to select only the smooth flat regions of cement as appropriate sites for the test, i.e. avoiding the stone aggregate. In all cases spurious low readings were discarded as well as any uncharacteristically high readings presumed to be sites where stone aggregate lay just below the surface. The range of readings (excluding those discarded) is given in table 1.

A linear calibration graph was drawn & extrapolated through the 4 points representing the test cylinder data. The graph correlated hardness readings (LD values) and compressive strength test results for the four cylinders. The mean hardness (LD values) for each concrete block in the study was used to estimate its average compressive strength from the calibration graph.

Table 1: Tests and estimations of compressive strength

Description of test material	Range of hardness readings [LD values]	Mean hardness [mean LD values]	Compressive strength [Mpa]
Hardest test cylinder as calibration reference	464– 586	542	49.1 [tested]
Softest test cylinder as calibration reference	449 – 534	478	34.5 [tested]
Hardest block with steel round bar encased	499 – 547	531	45 [estimated*]
Softest block with round bar encased	436 – 505	488	37 [estimated*]
Hardest block with steel rail encased	481 – 604	525	46 [estimated*]
Softest block with steel rail	410– 588	503	40

encased			[estimated*]
Hardest pillar with steel round bar encased	549 – 679	612	65 [estimated*]
Softest pillar with steel round bar encased	522 – 635	591	61 [estimated*]

The compressive strength values for the blocks are within the range expected for ordinary Portland cement concrete, more specifically in the upper range. The pillars are marginally stronger.

The second step was to calculate the expected splitting tensile strength of the blocks from their estimated compressive strength values. The ratio between splitting tensile strength and compressive strength is typically 0.1 for ordinary concrete made from Portland cement [10]. Calculations indicate that splitting tensile strength for the blocks would be approximately 4.0 to 4.5 MPa and for the pillars 6 to 6.5 MPa.

4. Discussion of results

Most of the concrete blocks (having lower strength) had cracked but in contrast the pillars (having marginally higher strength) were generally resistant to cracking. Because corrosion was unlimited in concrete blocks in this range of strength between 4.0 to 4.5 MPa but was stifled in concrete in the higher range of strength, namely 6 to 6.5 Mpa, we can conclude that the limiting compressive stress that stifles corrosion would be the same order of magnitude as that of these pillars. This figure is comparable with the corrosion limiting pressure [approximately 6.6 MPa] calculated for crevice corrosion between two steel surfaces. [1]

As mentioned in section 3, there are stress concentrations (boundary conditions) in the concrete surface around protruding steel that require adjustment of the simple calculations applied in this paper. However since the reinforcements in the bulk of the pillars were completely encased, the estimation described above would be realistic without adjustment. The tensile strength values of the blocks were simplistically estimated on the basis of a 1:10 ratio between splitting tensile and compressive strength. These estimated values are published only as a guideline for further research along the lines of related experimental work [6].

The result of this analysis (where corrosion takes place in the alkaline environment of concrete) is comparable with the case of crevice corrosion in steel alone. The corrosion limiting stress for different environments is not significantly different. This indicates that a mechanical mechanism is involved in restraining corrosion rather than a factor deriving from the chemical constituents and concentrations of the corrosive environment.

5. Research Significance

Several experimental studies have been done to quantify corrosion induced stress levels and crack propagation rates for steel reinforcements in concrete but the limiting stress conditions have not been noted or measured (6). A review of these and other authoritative texts on the subject indicates a common mistaken belief that once initiated, corrosion of steel reinforcements in concrete structures will continue without limit unless cathodic protection or chemical inhibition is applied. The principle of corrosion limiting conditions due to internal stress caused by trapped corrosion products has not been published and exploited in the design of concrete reinforcements and in damage risk assessments or failure predictions. The principles outlined in this study are also relevant to understanding the durability of paint coatings on ordinary steel in immersion conditions and the restoration of damaged concrete structures.

6. References

[1] 'The limits of carbon steel corrosion inside crevices', M. J. Molyneaux, *Corrosion & Materials, Australasian Corrosion Association* **33**, 2, 2008

[2] 'Technical Note No 3: *Cathodic Protection of Steel in Concrete, the International Persepective'*, J. P. Broomfield and B. S.Wyatt, *Corrosion Protection Association,* 2008.

[3] 'MMO-Coated Titanium Anodes for Cathodic Protecion - Part 2', D.H. Kroon, and L. M. Ernes, *Materials Performance,* **46**, 6, pp24-28, 2007

[4] 'Crevice Corrosion', R.M. Kain, *ASTM Handbook of Corrosion* **13**: pp108-113 1987

[5] 'Controlling Crevice Corrosion', L. L, Sheir, R. A. Jarman and G. T. Burstein, *Corrosion Vol 1, 3rd Ed* **1**,pp164-169, 1994

[6] 'Concrete Cover Cracking with Localized Corrosion of Reinforcing Steel', A. A. Torres Acosta and A. A. Sagues, *Proceedings Fifth International Conference, ACI* , SP-192-36. 2000

[7] 'Roark's Formulas for Stress and Strain' W.C. Young, and R.G. Budynas, *McGraw-Hill (7th Edition),* 2002

[8] 'Simplified Mechanics and Strength of Materials', H. Parker, and J. Ambrose [Editors] 5th Ed. *John Wiley & Sons, INC,* 1992

[9] 'Correlation between concrete strength and combined non-destructive tests for concrete', R. Domingo & S. Hirose, *Japanese Society for the promotion of Science.* 2004
[10] 'Evaluation of Ratio between Splitting Tensile Strength and Compressive Strength for Concretes up to 120 MPa and its Application in Strength Criterion', C. Nihal Arιoglu, Girgin & E. Arιoglu, *ACI Materials Journal,* Jan/Feb 2006