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Corrosion Resistant Steels for Reinforced Concrete Structures: A Review of Current Status

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ABSTRACT: Worldwide, the corrosion of reinforcing steel in concrete structures continue to be their single biggest durability problem. The mechanisms of this deterioration are well understood and documented, so that new structures can be designed and built to withstand corrosion. Nevertheless, despite this available knowledge, many recently built structures continue to suffer corrosion damage.

One method of combating the problem has been to specify austenitic stainless steel reinforcing. Unfortunately, this material has always carried a precious metal price tag that has precluded its use in all but extreme environments and consequently, it has never been produced in southern Africa. A more cost-effective solution is the use of ordinary black reinforcing steel that has been hot-dip galvanised. Existing concrete literature cites several seemingly convincing reasons not to specify hot-dip galvanised reinforcing in concrete and consequently, it has seldom been used in South Africa historically.

Recently, a corrosion-resisting alloy called 3CR12 has been produced and marketed in South Africa as reinforcing steel. Because of its relatively low chromium content, 3CR12 reinforcing steel costs a fraction of its high-alloy, austenitic counterparts and its corrosion products do not exhibit as much deleterious expansion as ordinary steels.

This paper explores the potential of hot-dip galvanised and 3CR12 reinforcing steels with reference to 20 structures built throughout South Africa during the past three decades. It provides possible explanations of why actual performance sometimes deviates from conventional expectations and it dispels ten common misconceptions. Lastly, it provides some guidance for appropriate specification

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Biography

Roderick Rankine is the Education and Training Manager of the School of Concrete Technology – a division of the Cement and Concrete Institute. Prior to that, he was a member of the academic staff at Wits University where he received his doctorate. He also holds an ACT diploma from the Institute of Concrete Technologists UK and is currently an honourary lecturer at Wits University and author and coauthor of more than 40 papers published in accredited journals, international conference proceedings and books.

The School of Concrete Technology is a non-profit making organisation that is committed to the responsible delivery of the highest standard of education in concrete technology and construction throughout southern Africa and internationally. The School currently enjoys provisional NQF accreditation and offers a number of formal and correspondence courses to a range of audiences (from anyone who is functionally literate to professional consultants both locally and abroad).

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1. Introduction

Corrosion of reinforcing steel is currently recognised as the single most critical threat to the durability of reinforced concrete structures. Since the early days of reinforced concrete, structures have experienced problems of loss of structural integrity due to the corrosion of their reinforcing steel. This problem manifests itself not only in marine structures but also inland. The enormous cost of repair measures has resulted in recognition of the need to improve the durability of new structures. One method of combating corrosion of reinforcement is to specify cover concrete properties such as minimum binder content, maximum water: binder ratio, permeability and sorbtivity. While this approach is to be applauded, we should not forget that there are reinforcing steels available that offer some inherent protection against corrosion for the inevitable instances where the quality or depth of cover concrete is less than adequate.

2. Mechanisms whereby Steel Reinforcement Corrodes in Concrete

Ordinary steel reinforcing that is adequately embedded in good concrete will not easily rust. This is because the concrete affords protection to the steel both physically and chemically. Firstly, the physical cover of concrete over steel slows down the reaction kinetics by restricting the flow of oxygen and water as well as any aggressive substances that promote corrosion. Secondly, because fresh concrete is highly alkaline

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(pH approximately 13), a stable oxide film (gamma ferric oxide) forms on the steel surface. This passive oxide film is impermeable and therefore able to insulate the steel from water and oxygen and thus prevent corrosion. However, there are two ways in which this film is destroyed:

2.1 By Loss of Alkalinity

Anything that decreases the pH of the concrete in contact with the steel much below 12 will cause a breakdown of the gamma ferric oxide film. The most common reaction occurs when carbon dioxide from the atmosphere reacts with calcium hydroxide in the concrete (pH of 12,4 in saturated solution) to form calcium carbonate which has a neutral pH according to equation 1.

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O \qquad (1)$$

This reaction, sometimes called "carbonation", causes a decrease of pH (carbonation front) starting at the concrete surface exposed to air and progressing inwards at a rate roughly proportional to the square root of time. In other words, it starts off penetrating very quickly and then slows down markedly. For example, if it took 16 years to penetrate 10mm, then it would take 64 years to penetrate to a total depth of 20mm and 144 years to penetrate to a total depth of 30mm and so on. The reaction is also fastest in climates that are neither exceptionally dry nor exceptionally moist since a water film is required for the diffusion of carbon dioxide into the paste.

Thus, loss of alkalinity is the primary process responsible for corrosion of reinforcing steel in inland regions.

2.2 By Ingress of Chlorides

Chlorides that penetrate the concrete cover and migrate to the surface of the reinforcing steel are able to undermine and strip the gamma ferric oxide film even if the pH is high. Unfortunately, these chlorides are not consumed by chemical reactions associated with corrosion. Once they have caused damage in one area they migrate freely and damage other areas. In southern Africa just about all chlorides originate from the sea and are often transported a few kilometres inland by wind borne sea spray. Chloride attack is therefore generally limited to coastal regions but may also occur elsewhere when reinforced concrete is exposed to chloride bearing industrial environments. In cold countries it may also occur inland where de-icing salts are used on roads.

Once corrosion is initiated by either mechanism, the products of corrosion (the oxides and hydroxides) occupy considerably larger volumes (typically three or more times greater) than their steel derivative. This effectively causes a swelling of the reinforcing which exerts tensile stresses on the adjacent surrounding concrete. Because concrete has a relatively low tensile strength, it cracks and spalls off the structure affording the underlying steel no protection whatsoever. At this stage, there is usually no risk of any loss of structural integrity but many structures are nevertheless condemned because of the safety hazard posed by falling chunks of spalled concrete and the associated liability to third parties. Given sufficient time, the reinforcing steel will continue to corrode until its cross sectional area diminishes sufficiently to the point at which structural integrity is compromised.

The techniques to prevent corrosion of ordinary reinforcing steel are no secret. They have been well documented for several decades and any competent civil engineer knows the rules commonly referred to as the "Four C's". They are essentially that the concrete must have a low water to **Cement** ratio, that the concrete must be well **Compacted** and free of excess voids, that it must be well **Cured** and that the depth of concrete **Cover** must be adequate. It is important to understand that for the concrete cover to succeed in protecting the steel from corrosion, all four C's need to coexist simultaneously. Neglect of any individual factor will compromise the durability of the steel. An analogy would be the chain that is as strong as its weakest link.

The corrosion protection of the steel can be further augmented by the use of extenders such as fly ash, ground granulated blastfurnace slag GGBS and silica fume as part of the total binder content. Specified and used appropriately, these extenders reduce the permeability of the concrete and some may even bind and incapacitate chloride ions.

3. If Prevention of Reinforcement Corrosion is so simple, why are Corrosion Problems still so Prevalent?

The answer to this question is complex and has its roots in practical realities that may not be immediately apparent to some clients and designers. Firstly, inadequate concrete cover is universally regarded as the single biggest factor leading to corrosion of reinforcement - both where loss of alkalinity is concerned and where chlorides are concerned. It is not uncommon to measure cover depths of less than 5mm where 40mm or more had been specified. Reasons for this might include the fact that both the steel fixer and shutterhand have reasonable dimensional tolerances to work within given the nature of the materials they deal with as well as the difficult circumstances under which they must often operate. If the steel-fixer builds his reinforcing cage to the maximum dimensional tolerance (SABS 1200 G)[1] and the shutterhand builds his forms to the minimum dimensional tolerance (SABS 1200 G)[1], we could immediately lose 50mm of concrete cover. Unless the designer makes some provision for this possibility, the chances are that the minimum cover specification may be violated. Furthermore, when a threat of insufficient cover is identified early on in a project, the client's desire to save money often precludes the appointment of a resident engineer and his urgency to take occupation of his structure may overshadow the possibility that problems of reinforcement corrosion might manifest in several years' time. Moreover, contractors are not usually paid for achieving the desired cover, nor are they penalised for failing to achieve this cover.

The second biggest problem arises from inadequate curing. Until very recently, tests[2] to measure concrete properties associated with curing were uncommon and not generally specified.

If extended concretes are not properly cured, the substitution of cement with the extender may actually result in inferior quality cover concrete.

Problems of inadequate compaction and an unsuitable water:binder ratio usually emanate from the use of unsuitable mix proportions. These unsuitable mixes are often too stony and therefore difficult to place. Site personnel frequently resort to adding unauthorised quantities of water in an effort to make the concrete placeable. By appointing a good concrete laboratory (during the planning phase of a project) to design an appropriate concrete mix, using the best possible combination of available ingredients, it is usually possible to obviate these problems. Most authorities concur that a water:binder ratio of less than 0,5 and a minimum binder content of at least 300 kg/m^3 should be specified to combat reinforcement corrosion.

4. The Role of Corrosion Resisting Reinforcing Steels

Despite the fact that it is possible to make durable reinforced concrete structures using ordinary reinforcing steel, there may be justification for using special corrosion resistant steels in the following circumstances:

1. In extremely aggressive environments.
2. Across joints in structures where it may be impossible to insulate reinforcing from water.
3. Where the structural elements are too slender to permit ideal depth of cover eg. precast units.
4. Where local skills are poor and supervision is intermittent.
5. Where steel is partly embedded and partly exposed ie. cast-in holding down bolts.
6. Where clients are serious about the durability of their structures and willing to pay a small premium (in relation to the cost of the project) for a structure that will have low maintenance costs.
7. Where the design life of a structure is substantial, for example, worldwide specifications for public infrastructure increasingly require a design life of 100 to 150 years.

In southern Africa, there are currently two choices of corrosion resistant reinforcing steel. Hot dip galvanized reinforcing and 3CR12, a steel alloy containing a chromium content on the threshold of that required for classification as a stainless steel alloy. Very little if any epoxy or powder coated reinforcing steel appears to have been used in southern Africa and these coatings are therefore beyond the scope of this paper.

4.1 Hot Dip Galvanized Reinforcement

Hot dip galvanized reinforcing steel is not currently available "off the shelf". Ordinary mild steel or high yield reinforcing steel must be purchased from a reinforcing steel supplier, transported to a hot-dip galvanizing works for galvanizing and then collected at a later date and returned to the reinforcing supplier for cutting, bending and fixing.

The hot dip galvanizing process (SABS ISO 1461) essentially entails degreasing, followed by pickling the bars in a solution of dilute acid to remove rust and millscale, followed by a fresh water rinse, followed by the application of a fluxing agent, followed by immersion into a bath of molten zinc and finally the option of passivation in a chromate solution. In the zinc bath, steel reacts chemically with the zinc. The exposed surface of galvanized steel consists of a thin outer layer of pure zinc upon a series of layers of zinc iron alloys with increasing iron content. The protection afforded to the bar by the zinc layer is proportional to the thickness of the zinc (which is typically at least 80 microns). The hot dip galvanized coating is effective at combating corrosion of the reinforcing steel in several ways. Firstly, it delays the initiation of corrosion and cracking of the concrete because the zinc surface is more reactive than the steel below. This is essentially cathodic protection and the steel bar can only start to corrode once all the zinc immediately surrounding that part of the bar is consumed. Secondly, even when the concrete has lost its alkalinity, the galvanizing remains effective since the zinc remains passive at pH levels well below those required to sustain passivation of uncoated steel. Thirdly, galvanized reinforcement can tolerate higher chloride migration levels than uncoated steel[3]. Furthermore, the corrosion products of zinc are relatively soluble and not as expansive or disruptive to the concrete as those of ordinary steel.

Hot dip galvanized reinforcement has been successfully used in the thin precast concrete panels of the Johannesburg Civic Centre (1968) and the New Groote Schuur Hospital (1989) in Cape Town. It has also been successfully used in numerous marine applications including Dairy Beach Pier in Port Elizabeth, the reconstruction of the diving platform at Seapoint (early 1990's) and three tidal pools in Camp's Bay (1992), Strandfontein (1995) and Koegel Bay (1989). It has been deployed throughout several bridges on Baden Powell Drive Cape Town including the Weltevreden Road bridge, the bridge over the Strandfontein Stream

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and a footbridge at the intersection of Eisleben Road. It has also be used in retrofitting existing structures for example in bridge widening projects including the N2 Liesbeek Bridge (1989) and the Belmont Road Bridge in Rondebosch (1995). Galvanized reinforcing has also been specified to construct the "Water Taxi" canal linking Cape Town's V&A Waterfront Basin with the Convention Centre and the Aquarium. The author visited all of these structures in January 2003 and could find no evidence of reinforcement corrosion whatsoever, even in places where an electro-magnetic cover meter showed that the concrete cover was clearly inadequate.

4.2 3CR12 Reinforcement

In 1978, a South African company, Middelburg Steel and Alloys, patented a low chromium steel alloy which had evolved from type AISI 409 alloy, used extensively in automobile exhaust systems. Unlike AISI 409, 3CR12 was capable of being rolled into thick sections without the formation of a deleterious coarse-grained microstructure. Because of the low alloy content, 3CR12 was cheaper than those grades previously used as stainless steel reinforcing. During the mid 80's, a four and a half year accelerated corrosion test was conducted by Callaghan[4] of the CSIR and in 1989 and 1990, an explorative research project[5] was undertaken to investigate how best to utilise 3CR12 as reinforcing steel. Subsequently, 3CR12 has been made available as reinforcing steel (in all standard diameters from 8mm to 32mm) through a partnership between Columbus Stainless, Trident Midrand Steel (a subsidiary of the Aveng group) and Iscor Long Steel Products. The physical properties of 3CR12 are presented in Table 1. Like most chromium steels, 3CR12 does not possess a definite yield point followed by a horizontal yield plateau and the strain hardening. Instead, it exhibits a gradual transition from elastic to plastic behaviour and therefore instead of reporting a yield strength, the manufacturer reports the material's 0,2% proof stress. 3CR12 reinforcing bars are supplied annealed with ribbed deformations to enhance concrete bond and are easily distinguished by their bright silver appearance that is imparted by a shot peening process, that removes millscale, using stainless steel balls. 3CR12 owes it corrosion resistant properties to a stable chrome oxide film that forms on the bar surface. There is always enough oxygen available for this oxide film to form on steel encapsulated in concrete exposed to the atmosphere. Like all chromium steels, 3CR12 responds favourably to increases in pH above 12,5 by becoming more Nobel, thus even exhibiting greater resistance to corrosion[6].

3CR12 reinforcing has been successfully used in four pedestrian-over-rail bridges on the KwaZulu Natal coast at Warner Beach, Kelso Station, Ilfracoomb and Temple Road. It was also used on part of the iron ore terminal in Saldanha Bay and has been specified for special applications in Coega Port.

Table 1. The physical properties of 3CR12 reinforcing steel compared with high yield reinforcing steel made in accordance with SABS 920.

	Yield strength or 0,2% proof strength (MPa)	Max tensile strength (MPa)	Elongation (%)
3CR12 minimum	450	520	14
3CR12 typical	540	680	25
High Yield minimum	450	-	14
High Yield typical	470	700	26

Table 2. A cost comparison between ordinary high yield steel reinforcement, hot dip galvanized high yield steel reinforcement, 3CR12 reinforcement and 316 austenitic stainless reinforcing steel (not available in SA).

	Diameter (mm)	Johannesburg (Rands / Ton)	Cape Town (Rands / Ton)	Durban (Rands / Ton)	Relative cost (to regular bars)
Uncoated high yield steel	10mm 12mm 16mm	4990 4923 4788	4990 4923 4788	4990 4923 4788	1
Hot dip galvanized high yield steel	10mm 12mm 16mm	7601 (1,5) 7021 (1,4) 6783 (1,4)	8752 (1,8) 7933 (1,6) 7650 (1,6)	8901 (1,8) 8047 (1,6) 7752 (1,6)	See columns left in brackets
3CR12 Ribbed and peened	10mm 12mm 16mm	14300 (2,9) 13420 (2,7) 13420 (2,8)	14760 (3,0) 13760 (2,8) 13760 (2,9)	14750 (3,0) 13575 (2,8) 13575 (2,8)	See columns left in brackets
Austenitic 316 Stainless reinforcing	Not available in SA	N / A	N / A	N / A	8

The costs are given in Rands per tonne inclusive of VAT and are applicable from 1 July 2004. Prices exclude cutting and bending. The price of hot dip galvanized bars includes an amount of R160 per tonne for transport (up to 100km each way) to and from the galvanizers and the price of the 3CR12 reinforcing in Johannesburg excludes any delivery charge presuming that it will be fabricated by Steeldale. Prices were obtained from each of the relevant suppliers in the form of written quotations for a ten tonne consignment made up of 3 tonnes of 10mm, 3 tonnes of 12mm and 4 tonnes of 16mm bar.

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5. Cautionary note

5.1 Hot Dip Galvanized Reinforcement Should Not be Heated for Bending

If the reinforcing bars are heated in an effort to make them easier to bend, there is a risk that the zinc coating will melt and penetrate the grain boundaries between the individual crystals of steel. This phenomenon may be termed intergranular zinc embrittlement and it can give rise to deleterious cracks within the body of the bar.

6. Conclusion

By consistently using sound design and construction practices, it is possible to make durable reinforced concrete structures without resorting to the use of corrosion resistant reinforcement - even in corrosive environments. However, in the real world, there will inevitably be instances where the quality and depth of concrete cover to the steel reinforcement prove to be inadequate. It is in these places that steel reinforcement will corrode and lead to deterioration of the structure. Hot dip galvanized and 3CR12 reinforcing steels offer considerable protection against this type of deterioration both in coastal environments and inland. Moreover, they do so at a fraction of the cost of their austenitic stainless steel forefathers traditionally regarded as ultimate insurance against corrosion. Although many structures reinforced with these galvanized and 3CR12 bars appear to be in good condition, most of them are no more than 12 years old and there is no way of accurately predicting their serviceable lives.

While corrosion resisting reinforcing steels may offer a reduced risk of corrosion, their use should not be taken to imply that less care is required in ensuring that the concrete is properly designed, compacted and cured. Maximum durability will only be achieved if the quality of the concrete cover and the corrosion resistance of the special steels are regarded as complimentary rather than alternatives.

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