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Strategies for resisting corrosion of reinforcement in concrete

P.C. Chowdhury

Civil engineers are now-a-days being offered a variety of reinforcing steels to resist corrosion of steel in concrete. Two in particular, "CRS" and "MMFX", will be discussed in this write-up. However, the author stresses that reinforced concrete construction professionals need to refocus their attention on concrete, the material they know best, rather than on the metallurgical mysteries expounded by specialists from another discipline. After all, as every civil engineer worth his salt knows, concrete is the first line of defence in the fight against corrosion and good concreting practices need no justification other than themselves.

Much has been written on the subject of corrosion resistance and the details of the corrosion process itself will not be discussed here. This write-up will concern itself mainly with what the civil engineer can do to avoid the problem of rebar corrosion.

There exists a point of view that states that corrosion of reinforcement is *not* important. This deliberate over-statement of the case may, hopefully, provoke civil engineers to re-examine their position. It is dismaying to see, in print, the opinions of some engineers pointing a casual accusing finger at what is vaguely referred to as the metallurgy of present-day steels as compared to the supposedly corrosion-free steels of yester years. Some even go as far as to suggest a nostalgic reversion to mild steel rebars as if strength plays some sort of zero-sum game with corrosion resistance. The cause for concern with such statements are not that they are made but that these are, all too often, subjective opinions unsupported by experimental or statistical data or by reference to authoritative sources. *Appendix* I lists some quotes from experts that may serve to rectify several widely-held but erroneous beliefs on corrosion.

Consider the sequence of events leading to corrosion of rebars. There is a first stage before the *onset* of steel corrosion and there is the second stage of *actual* steel corrosion. It is the onset of rebar corrosion that determines the design-life[1] of a structure which is never meant to extend into the second stage where rebars are actively corroding and spalling concrete endangers life and limb. Both the logic of focusing on the onset of corrosion as well as the search for the most cost-effective approach to the overall corrosion problem lead to a very obvious and very old conclusion: focus on to the concrete that covers the steel. Here lies the magic formula for lasting structures of yester-years, a simple formula known to every civil engineer in theory, but sacrifised at the altar of poor practice which is ensure a uniform cover of compact concrete with a low w/c ratio.

However, there are concrete structures vulnerable to chloride-induced corrosion in some adverse environments (for example, offshore oil platforms, bridge decks treated with de-icing salts) where a designer must consider measures beyond good concreting with adequate cover. The cost-effectiveness of each option has to be evaluated on a case-to-case basis but the usual alternatives, in order of increasing cost, are : galvanising, epoxy coating, stainless steels and cathodic protection. But what must be avoided is the "lazy-engineer syndrome" which tends towards needless specification of a corrosion resistant process or product for the steel to compensate for foreseeable and avoidable deficiencies in the cover concrete.

Role of concrete

Over the years, civil engineers will have noticed that voices lost in the wilderness are beginning to be heard again and the issue has come full circle: the key to avoid corrosion of the embedded steel is to have the proper thickness of concrete that is well-compacted and impermeable[2,3]. This simple prescription will take care of the vast majority of structures including those in coastal areas. Some interesting research has been reported about the use of corrosion inhibitors but they will not be discussed here.

The durability of concrete depends on its composition and strength, properties of its constituents, how it is cast, compacted and cured. Strength alone is an unreliable indicator of durability since it characterises an entire cross-section whereas durability is controlled mainly by the concrete skin. It is now accepted that the key is the cover concrete's resistance to the penetration of aggressive media through the mechanisms of permeation, diffusion, absorption and capillary action.

Even after the local break down of the passivating layer on the steel surface – due to carbonation or chloride ingress or both – there are two requirements for the steel to corrode:

(i) sufficient moisture to serve as a low-resistance electrolyte

(ii) sufficient oxygen to support the cathodic corrosion reaction.

While concrete that is continuously saturated with water ensures low ohmic resistance between anodic and cathodic sites, access of oxygen will not be sufficient to support corrosion. Similarly, oxygen can permeate through the open pore system of dry concrete but lack of electrolyte prevents corrosion. Corrosion resistance through increasing the resistivity of concrete is one of the mechanisms through which fly ash or slag additions impart durability to concrete even though they reduce the alkalinity of the cement paste.

Only part of the chlorides in concrete — the free chloride ions in the pore solution — contribute to the corrosive action on rebars; the immobilised chloride ions are combined in or bound to the different hydration products of the cement. At a given total chloride ion content, the higher the hydroxyl (OH^-) concentration, more the free chlorides present[4]. Early publications indicated contradictory trends for binding capacity when slag or fly ash was blended with OPC. However, it is now becoming clear that replacing *at least* 50 percent of OPC with dispersed mineral additions (for example, fly ash, silica fumes, ground granulated blast furnace slag) not only decreases the permeability of the concrete but also favourably interferes with the chemical reactions during hydration and in the corrosion reaction[5]. Replacing OPC with these pozzolanic materials results in less cement paste and hence less shrinkage and less cracking. High volume fly ash concrete (HVFA) foundations have developed no cracks after a year, even without any "temperature" steel[6]. Such concretes also minimise the hydroxyl (OH^-) ions so that the pore water does not "conduct" and resistivity of the concrete can increase to the extent that HVFA concrete behaves almost like a ceramic insulator. Corrosion resistance by this mechanism[7] is quite different from the traditional reliance on the alkalinity of the cement paste.

Even governments have seen fit to intervene in favour of such blended cements because disposal of waste products like fly ash and blast furnace slag have become a public issue. The Japanese national policy based on the "Green Purchase Law" (in force since April 2002) specifies Portland blast furnace slag cement as an environment-related item with priority given to procurement in public works. An important paper by Rajkumar drew some conclusions that are particularly relevant to local conditions in India[8]. It was based on extensive data available with NCCBM (National Council for Cement and Building Materials) which constantly monitors the various types of cement produced in India. It makes out such an overwhelming case favouring concretes containing upto 70 percent GGBS for increasing service life several fold that one wonders how civil engineers have been influenced by so-called CRS rebars which offer an improvement factor of 1.5 to 1.6. As an example[8], replacing 65 percent OPC with GGBS reduces the diffusion of chloride ions by a factor of 10 ! In another example, it has been shown that proper curing practice alone can improve performance in terms of rebar corrosion by a factor of 12.2[9]! Elsewhere, it has been found that increasing the cover from 10 mm (it is frequently less where rebars sag) – to 45 mm reduces the free chlorides available at the steel surface to less than one percent[8].

Examples abound where a bounty of high improvement factors have been shown to reward attention to almost every aspect of good concreting practice taught to every civil engineer even at the diploma level. And yet we have experienced and highly qualified civil engineers turning a blind eye to the obvious solution and willing to pay a premium for CRS rebars which at best (that is, as claimed by manufacturers) offer only *fractional* improvement of 0.5 to 0.6 (50 to 60 percent) ! To someone from outside the field of civil engineering, the choice does not present any dilemma: in fact, if with poor concreting, corrosion of ordinary rebars lead to spalling after five years, investing in CRS rebars might buy a reprieve for another three years; on the other hand, investing in better concreting practice – the very "dharma" of any civil engineer – can extend the service life beyond 50 years or, if HPC is specified, even longer. That's good "karma" for all of us!

Steel

As stated earlier, there are scenarios which call for corrosion protection measures beyond the ambit of concrete. These may include special structures, like monuments or places of worship, which are designed to last for centuries. Or they may be structures that are specially vulnerable to corrosion either because of the aggressive environment to which they are exposed or because aesthetics or difficult conditions dictate a departure from known good practices of construction. A good example is the famous Bahai Lotus Temple in Delhi where the cover is minimal at the tapering ends of the lotus "petals". In this case, the Canadian architect and the British structural consultants decided to specify galvanised torsteel bars.

The cost-effectiveness of alternative strategies need to be assessed for each case. The usual choice, in order of increasing cost, is between: hot-dip galvanising, fusion bonded epoxy coating, ferritic or austenitic stainless steels (clad or solid) and impressed-current cathodic protection. The first two are coatings on ordinary (or "black") rebars and considerable literature is available on these topics, but fall beyond the scope of this feature. So also with stainless steels and these also will not be discussed in this write-up. Excluded also from the scope of this write-up are the many options which are more appropriate for repair and renovation works, for example, re-alkalisation, electro-chemical extraction of chlorides, sacrificial zinc anode embeddment. Here, the emphasis is on solid steel rebars of special composition to resist corrosion in concrete.

Corrosion-resistant steel (CRS)

Leaving aside the strategy of preventing corrosion through better concrete, the solution of choice has been to coat the rebars. Such coatings have ranged from cement slurries to epoxies and zinc. The popularity of coatings can be attributed to their economy; they are cheaper than the usual alternative: stainless steel rebars. Coatings suffer from the obvious disadvantage that they may be physically damaged or electrochemically penetrated so that the base steel is again vulnerable to the usual corrosion process. Steelmakers, the world over, have spared no effort to avoid both the vulnerability of coatings and the high cost of stainless steel by concocting low-alloy steels but a cost-effective solution has been elusive.

In the 1980s, a major Japanese steelmaker patented a 3.5 percent tungsten steel which performed well in laboratory tests but it never saw the light of commercial use[10]. The reason could well be because results of corrosion tests in the field do not necessarily corroborate those of accelerated lab tests, as pointed out by investigators from TISCO/NML[11]. Several steel mills, in India and abroad, have understandably experimented with various compositions of "weathering steels" to see if their proven resistance in exposed conditions might be applicable to the situation where embedded steel was *not* exposed to the weather. After extensive in-house and independent tests, all the reputed steelmakers of the world have abandoned this search because of the consistently poor performance of "weathering steels" when buried. However, some producers in India have chosen to ignore the available evidence on record and opened a pandora's box by commercially releasing similar products without adequately warning prospective users about known risks.

According to conventional wisdom, the elements that improve the corrosion resistance of steel are phosphorus, copper, chromium and nickel; the usual corrosion resistant low-alloy steels limit these elements to a combined total of less than one percent. But surprisingly, recent research indicates that less than five percent chromium can be *harmful* in the presence of chlorides. *Chromium-free* "weathering steels", with 10 times the corrosion resistance of Cor-Ten, are now being used for exposed bridge structures in Japan[12] and we may expect arrival of similar chromium-free steels to replace low-chromium steels in India also. The first "weathering steel" was introduced in 1933 by US Steel; this original Cor-Ten A had a high phosphorus content (0.1 percent). However, since phosphorus is highly detrimental to both fracture toughness and weldability, US Steel replaced this in the 1960s with Cor-Ten B and Cor-Ten C having normal low levels of phosphorus (0.04 percent maximum) in the full knowledge that these new grades were *less* corrosion resistant than the original[13]. By contrast, most of the CRS rebars offered by main producers in India correspond closely to the much older high-phosphorus Cor-Ten A. Only one of the main producers openly admit [14] that their CRS rebars are made out of "weathering steel"; some hide behind a combined total of undisclosed corrosion resistant elements; others fight shy of being clubbed with "weathering steels" to escape the damning evidence of their performance record when used as rebars. However, *Appendix* II sets out the internationally accepted range of compositions encompassing all "weathering steels" and users would be well advised to ask for a full chemical composition for comparison with known weathering steels, for example, IS 11587, ASTM A588 etc.

The Cor-Ten type of weathering steels are not intrinsically resistant to corrosion but can develop a protective layer of adherent rust after prolonged exposure to the atmosphere and, to quote ASTM, "exposed to the washing action of rain and the drying action of the wind or sun or both". Manufacturers of such weathering steels, like US Steel and British Steel, are unanimous in their recommendation that such steels are *not* corrosion resistant when buried, even in soil. When embedded in concrete, such steels are positively dangerous in the presence of chlorides, being subject to pitting and crevice corrosion as against the more general attack suffered by ordinary 'black' rebars. *Appendix* II quotes some extracts from both European and American sources on this subject. These negative conclusions from abroad are indirectly confirmed by results from tests conducted in India and quoted by an Indian manufacturer. The improvement factor for corrosion resistance in *concrete* of one such steel has been determined[15] to be under 2 as against an improvement factor of 5 to 8 for a weathering steel with near-identical composition (Cor-Ten A) exposed to *atmosphere*, that is, the performance is far inferior under concrete cover than in open air![16]

Many organisations are active in research into the corrosion performance of reinforcing bars in concrete but only a few have the financial muscle to commit the huge resources involved in methodical long-term exposure tests. Foremost among these are the Building Research Establishment (BRE) in U.K. and the Federal Highway Administration (FHWA) of the US Department of Transportation. The latter was responsible for the seminal work to determine the feasibility of using organic coatings, especially epoxies, to protect rebars in concrete[17]. Over the years, they meticulously evaluated 47 different coating materials. The tests, which considered flexibility, abrasion resistance, bond strength and creep characteristics as well as corrosion protection, eventually identified four epoxy coatings for further evaluation in experimental bridge construction.

Fusion bonded epoxy coating (FBEC) was well accepted and extensively used in USA until some deficiencies were noticed a decade later in some bridges in Florida where FBEC rebars had been specified. The resulting controversy regarding the effectiveness of epoxy-coatings prompted FHWA to launch a 5-year research project to evaluate all corrosion resistant bars. They tested 60 different bar types including several solid metallic bars. The screening tests were conducted in several phases of increasing severity.

In 1996 they published the results of the first two years (of this 5-year study) covering 24 bar types including 10 solid metallic alloy reinforcing bars[18]. This report refers to a 1993 paper claiming that TISCO had developed a "CRS" rebar that had significantly greater corrosion resistance than "black" steels[19]. A TMT-type rebar with similar steel composition was specifically included in this FHWA research study. The findings (see *Appendix* II *(iv)*): "CRS" exhibited essentially the same performance as "black" bars in all the tests and CRS was eliminated from further participation in the more stringent tests over the following three years. These results simply echo the BRE findings of seven years earlier, *Appendix* II, for weathering steels and underline the futility of trying to circumvent scientific conclusions by re-labelling a nominally 'different' product.

There has been a half-hearted attempt to escape the negative conclusions of BRE's 10-year exposure study by taking advantage of an apparent misprint in the paper. The pitting corrosion observed by the British investigators have been sought to be explained away by the very high sulphur content (0.21 percent) appearing in one of the tables. Such a metallurgical improbability may have escaped the notice of the civil-engineer-authors but it is common knowledge among steel technologists that, even in the 1980s, any steel – except those deliberately resulphurised to improve machinability – with sulphur in excess of 0.06 percent would have been rejected as an unacceptably "dirty" steel. Even IS 1786 in the 1970s did not permit rebars with sulphur content over 0.055 percent!

In spite of all this evidence against the use of CRS rebars, there are civil engineers who go along with the suggestion to specify it for their projects on the specious plea that although the improvement factor is a mere 1.5 to 1.6, it is okay as a low additional cost measure. They forget the risk of pitting corrosion indicated by both theory and practice. Even otherwise, here is a recent cautionary tale about marginal improvements touted by manufacturers. Some years ago, the US tobacco megacorp Philip Morris introduced "light" cigarettes and many smokers switched to these in the belief that they were really reducing their health risk. The manufacturer's legal contention that the harmful tar etc were factually, if marginally, less in the "light" cigarettes compared to regular ones, could not save them from the recent award of $10.1 billion as damages for deceiving smokers into a false sense of security. With growing consumer awareness in India, this case has lessons not only for manufacturers promoting products of doubtful efficacy but also for architects or engineers who specify such products to clients.

Microcomposite steel (MMFX)

As mentioned earlier, stainless steel rebars are acknowledged to be suitable even in the worst exposure conditions but the high cost cannot always be justified. To cut costs, efforts have been made to use ferritic grades but the performance decreases more than the cost does. Even among the austenitic grades, where grade 304 (18 percent *Cr* + 8 percent *Ni*) is the norm, some projects have considered it cost-effective to specify premium grades like 316 (with molybdenum) where exposure conditions are particularly severe or where down-time for repairs can be prohibitively expensive. Another way of cutting costs has been to clad "black" rebars with a skin of stainless steel but reductions in costs have been insufficient to make this an attractive option. In the 1990s, Cromweld Steel (UK) introduced "3CR12", a low-carbon steel with 12 percent chromium, that was claimed to give "stainless performance with mild steel utility". Later, Columbus Steel (South Africa) tried to develop it for rebar production but with no demonstrable success. With the unsatisfactory CRS rebars at the other end of the cost spectrum, there has always been room for another product to occupy the middle ground.

Making a bid for this slot is a candidate calling itself "microcomposite steel", which claims very high corrosion resistance due to its unique micro-structure. According to its inventors, the basic problem of steel is that it contains microscopic "fingers" of two different components, ferrite and carbide, that act like a tiny battery when an electrolyte is present ; the corrosion of steel is due to the micro (electric) currents produced by these micro-galvanic cells. Their proprietary chemical composition (reportedly a low carbon steel with about 8 percent chromium) and production process (controlled rolling followed by a direct quench) results in a microstructure of "untransformed nanosheets of austenite between laths of dislocated martensite" in a virtually carbide-free steel. In the absence of continuous paths of carbides, micro-galvanic cells are minimised and corrosion is controlled. An added bonus is its higher strength (yield strength of about 700 MPa) fracture toughness. It is noteworthy that this superior energy absorption under dynamic/impact loading goes hand-in-hand with a suprisingly low (7 percent average) elongation in the tensile test. Such a concept appears to run counter to the recent amendment to IS 13920 that reposes unquestioning faith in (static) elongation for ductility in a seismic (dynamic) situation.

This steel is the outcome of R&D work by scientists at the University of California at Berkeley, led by Prof. Gareth Thomas, who first patented the process in 1985. The steel was trade-marked FERMAR and was subject of various tests, mainly in the laboratory. In 1988, the inventors, joined by other promoters, formed MMFX Steel Corporation of America to commercialise the over 25 years of R&D at Berkeley. The strategy of MMFX is to side-step the notoriously unprofitable task of owning and operating steel mills by contracting with existing mills to use their excess capacities. The success of this strategy remains to be proven. The jury is also still out on the long-term performance of this new steel that costs about the same as epoxy-coated rebars but is much easier to handle.

Civil engineers in India should ask themselves if it would not be more appropriate to exploit the recent advances in concrete rather than specify FBEC or stainless steel or FRP to simply counteract avoidable deficiencies in workmanship and supervision.

MMFX rebars are currently being produced at five locations – all in USA. At least 17 of the state DoTs (Department of Transportation) in that country are evaluating it for use in bridge decks. It has also been used in some building elements in a Florida residence and a Colorado commercial building. The US Navy is considering the use of MMFX rebars in the construction of ocean piers. Civil engineers eagerly await the comparative performance results of many long-term studies including one by NCHRP (National Cooperative Highway Research Programme) in USA. However, very recently in February 2003, MMFX2 rebars have gained the essential qualification for use in general construction throughout the United States through certification by ICBO (International Conference of Building Officials).

The available literature on this new steel is almost exclusively from MMFX Corporation and, quite expectedly, they all paint a very rosy picture. The results of independent tests may not be available for some years but some reservations are discussed to balance the picture. It is not the intention to unjustly criticise a product that may fulfill all it promises but to bring to light some unanswered questions that appear very relevant, especially in an Indian context.

Around the time that the new steel was patented in USA, Mukand Iron & Steel Works Ltd. signed a collaboration agreement with Advanced Design Materials Corporation of USA for the manufacture of high-tensile rebars based on "dual phase" technology. As a result of this collaboration, in 1986 , Mukand's R&D introduced *SUPERSTEEL-60* rebars in this country, predicting that this new technology will bring about a techno-economic revolution in the construction industry not only in India but all over the world[20]. Their promotional literature referred to the steel, variously, as "dual phase" (ferrite + martensite) steel and "FERMAR", the trademark of the Berkeley-developed steel. Much later, in 1996, the inventor of this steel published a paper in India acknowledging the cooperative programme with Mukand Steel[21]. This paper referred to the steel, variously, as "dual phase", "FERMAR" and "DFM"(dual –phase ferritic martensitic). The recent NCHRP study also refers to "DFM" reinforcing steel supplied by MMFX Corporation. This plurality of terminologies create some confusion: do FERMAR, MMFX, MMFX 2, DFM etc refer to steels with different compositions and/or micro-structure or are they, for all practical purposes, the same? This question assumes some importance in the light of the fact that Mukand's introduction of *SUPERSTEEL-60/FERMAR* into India 17 years ago was not a success story. In the absence of any published literature about the proprietary compositions or independent tests on their corrosion performance, there is no way of drawing any lessons from past experience as a pointer to the future.

Conclusions

Resort to expensive alternatives to conventional rebars are called for only in special cases. Offshore oil platforms of RC construction or bridge decks subjected to de-icing salts are rarities in India. Specification of such alternative rebars are frequently motivated by a reluctance to address issues related to good concreting; issues that are fairly basic but require proper site supervision rather than capital expenditure. In a country where labour is, relatively, still very cheap, it should surely be of more lasting benefit to invest available capital in training that labour rather than needlessly burying more expensive rebars in *low* performance concrete (LPC).

Civil engineers in India should ask themselves if it would not be more appropriate to exploit the recent advances in concrete rather than specify FBEC or stainless steel or FRP to simply counteract avoidable deficiencies in workmanship and supervision. It would be sad if through a mere lack of will to implement the simple and well known principles of mixing and placing even ordinary concrete, the subcontinent acquires the dubious distinction of being associated with LPC when others are moving on to HPC and building RC structures with a design life of 1000 years! After all, even if civil engineers may be mystified by metallurgical claims and counter-claims about the properties of austenitic versus ferritic steels or strain-hardening versus quench-hardening , they must surely feel more at home with concrete, a material that is truly and uniquely their own.

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Appendix I : Extracts from publications on corrosion of rebars

(i) In the 1980s, there was increasing concern over the rate of deterioration of some concrete structures [in U.K.] …In most instances, deterioration of concrete could be linked to *failure to implement existing technology; for example, due to lack of supervision*…Almost all forms of deterioration are the result of water ingress...

— *Materials in Construction* by G.D.Taylor (1994)

(ii) Many authors have traditionally ascribed the effect of residual stress within the [cold worked] metal, which serves to increase the corrosion tendency. But the residual energy produced by cold working, as measured in a calorimeter (usually < 7 cal/g), is less than sufficient to account for an appreciable change in free energy, and hence this intuitive concept is probably wrong.

— *Corrosion and Corrosion Control* by H.H. Uhlig and R.W. Revie (1985)

(iii) ......existence of two different types of martensite: slipped (in practice *low-carbon* steels) and twinned (*medium- and high-carbon steels*)…the microstructure in question should be scrutinised closely… This [twinned] martensite in the steel is the microstructure *most susceptible to both stress corrosion and hydrogen embrittlement.*

— *Strong Tough Structural Steels,* Iron & Steel Institute, Special Publication 104 (1967)

(iv) When martensite is [tempered], decomposition to ε iron carbide of unknown composition takes place. This two-phase structure sets up galvanic cells which accelerate the corrosion reaction. Some finely divided cementite also appears by decomposition of the e phase. After tempering … cementite acting as cathode offers maximum peripheral surface adjoining ferrite, and galvanic action is at a maximum …

— *Corrosion and Corrosion Resistance* by H. H. Uhlig & R. W. Revie (1985)

(v) Adequate protection to reinforcement can generally be achieved by the use of properly designed concrete mixes, producing dense impermeable concrete with adequate concrete cover to reinforcement. Materials such as PFA and GGBS enhance the resistance of the concrete cover to chloride ingress and offer an *economic option for increasing service life.*

— *Civil Engineering Materials ed.* by N. Jackson & R.K. Dhir (1996)

(vi) Within pH 4 – 10, any small variation in composition of a steel and its heat treatment, or whether it is cold worked or annealed, has no bearing on corrosion properties provided the diffusion barrier layer (e.g. hydrous ferrous oxide) remains essentially unchanged… This means that whether a high- or low-carbon steel, or similarly a low-alloy steel [(e.g. 1 – 2 percent alloying elements], wrought iron, cast iron, or cold-rolled mild steel is exposed to fresh water or sea water, all the observed corrosion rates in a given environment are essentially the same. Many laboratory and service data obtained with a variety of irons and steels support the validity of this conclusion. ... These observations answer the once vociferous argument that wrought iron, for example, is supposedly more corrosion resistant than steel.

— *Corrosion and Corrosion Resistance* by H. H. Uhlig & R. W. Revie (1985)

(vii) Corrosion rate of iron and steel … is controlled by diffusion of oxygen to the metal surface. Hence, whether a steel is manufactured by the Bessemer, oxygen furnace, or open-hearth process, and whether it is a wrought iron, or a cast iron, *makes little or no difference*… In general, *the least expensive steel or iron… should be specified for those environments* [in natural waters or in soil].

— *Corrosion and Corrosion Resistance* by H. H. Uhlig & R. W. Revie (1985)

(viii) Steels containing a *few tenths of 1 percent of copper* are more resistant to the atmosphere but show *no advantage over copper-free steels in natural waters or buried in the soil* …

— *Corrosion and Corrosion Resistance* by H. H. Uhlig & R. W. Revie (1985)

(ix) An amount *upto 5 percent chromium* … was reported to decrease weight losses in

seawater at Panama Canal at the end of one year. A sharp increase in rates was observed between 2 to 4 years ; *after 16 years the chromium steel lost 22 to 45 percent more weight than did the 0.24 percent carbon steel*. Depth of pits was less for the chromium steels after one year *but comparable to pit depths in carbon steel after 16 years*. Hence, for long exposures to seawater,, *low-chromium steels apparently offer no advantage over carbon steels* .

— *Corrosion and Corrosion Resistance* by H. H. Uhlig & R. W. Revie (1985)

(x) ....evident that concrete cover and composition have a much greater influence [on corrosion] than crack width …… problem of reinforcement corrosion in crack zones cannot solely be solved by crack width limitation …; *corrosion protection must be assured primarily through adequate concrete quality and cover.*

— Laboratory studies and calculations on the influence of crack width on chloride-induced corrosion of steel in concrete by P. Schiessl & M. Raupach, *ACI Materials Journal*, January-February 1997.

[N.B.: Some of the original text in Appendix I is italicised to show the author’s emphasis]

Appendix II : European/US verdict on corrosion resistant steel rebars

(i) “The resistance of steel to atmospheric corrosion can be somewhat improved by low alloying additions of elements such as chromium, phosphorous and copper to produce the so-called *weathering steels*. These usually contain 0.25 - 0.5 percent Cu, 0.04 - 0.15 percent P, 0.2 – 0.9 percent Si, 0.3 – 1.2 percent Cr and upto 0.6 percent Ni. On exposure to the atmosphere, the rust on weathering steels give a degree of protection, *provided the conditions are favourable*.”

— *Basic corrosion technology* by Prof. Einar Mattsson, Director, Swedish Corrosion Institute, Stockholm, Publisher, Ellis Horwood, 1989

(ii) “Weathering steels require adequate oxygen supply to develop corrosion resistance. Hence, these steels are not specified in anerobic conditions such as stagnant marine conditions, concrete embedment, or where the oxygen supply is low. In addition, due to lack of protective film being developed, these steels are subject to pitting and crevice corrosion in the presence of chloride.”

— a personal communication by American Concrete Institute’s Managing Director of Engineering, June 1996 [in reply to an enquiry about the current validity of the recommendation of ACI Committee 222 that “weathering steels commonly used for structural steelwork do not perform well in concrete containing moisture and chloride and are not suitable for reinforcement ’’ as stated in "Corrosion of Metals in Concrete", ACI Publication 222R-89.

(iii) “When embedded in concrete, conventional steel gain their corrosion protection from the reactivity reducing effects of high levels of alkalinity. Weathering steels gain their improved atmospheric corrosion resistance from the development of an adherent and dense oxide film. However, when exposed to damp saline conditions, the long term reduction in corrosion rate may not be marked. Thus embedment of these steels in concrete, particularly that contaminated with chloride, is of interest. The results of the present work indicate that, contaminated with chloride upto a level of 0.96 percent, little difference in performance is seen between high-yield and weathering steels. Increasing the chloride content above 0.96 percent does, however, create conditions sufficient to promote the corrosion of the weathering steels. The corrosion takes the form of pitting which has occurred more deeply than on the high-yield steels, but overall weight loss on weathering steels is less than their high-yield counterparts, indicating reduced general attack. Pitting was, however, sufficiently severe to indicate that weathering steel tested would be unsuitable for use as a corrosion resistance alloy in heavily chloride-contaminated concrete. In the absence of chloride contaminantion, high-yield steel performs as well as weathering steel; hence the additional costs cannot be justified in terms of improved durability.”

— *Durability or corrosion resisting steels in concrete* by Treadway, K.W.G. et alia, Proceedings of the Institution of Civil Engineers, Part I, 1989 [reporting the results of an extensive 10-year exposure study conducted by Building Research Institute, U.K.]

(iv) Corrosion-resistant steel alloy reinforcement was submitted *(to FHWA for testing)*. The material was based upon that reported by Jha, Singh and Chatterjee *(all from TISCO)*.

… The material was THERMEX treated *(TMT)*.

The CRS bars exhibited essentially the same PR *(Polarisation Resistance)* performance as black bar *(in pH 7 tests)*.

The CRS products exhibited similar corrosion rates to black bars after the 168-d*(ay)* test period *(in pH 13 solution)*.

The CRS exhibited 4X markings *(in a range of 0X for best and 5X for worst)* based on visual assessment.

The values *(of half-cell potential changes for CRS)* are approximately the same as that determined for BL *(black i.e. conventional rebars)* bars……..The values appear to be dependent on the chloride ion concentration, indicating that the metal is influenced by the presence of this ion.

From review of PR data it was found that the following bars were potential candidates for further testing : …….*(CRS did not qualify)*………From review of visual data, it was found that the following bars were potential candidates for further testing : ……..*(again CRS did not qualify)*…..Bars common to both these lists *(selected for further testing)* are :……*(CRS was eliminated on all counts)*…….”

— *The corrosion performance of inorganic, ceramic-, and metallic clad reinforcing bars and solid metallic bars in accelerated screening tests* by D.B.McDonald et alia (1966), Publication no. FHWA-RD-96-085 [presenting the first 2 years results of an exhaustive 5-year study on 24 bar-types including one coded “CRS”, a TMT-type rebar with steel composition based on TISCO’s claims]

[N.B. – In Appendix II, parenthetic bridging text in *italics* are not part of the quoted publication but are provided by the author for continuity]

Dr P.C. Chowdhury graduated in mechanical engineering from the University of Surrey and was awarded a doctorate in applied science by the University of Newcastle-upon-Tyne in 1974. In 1965, he did a five-year engineering apprenticeship in the aero-engine division of Rolls Royce Ltd, England. He continued as a research associate in the department of Naval Architecture & Shipbuilding in Newcastle University before returning to India in 1974. After working in the Aircraft Design Bureau at Hindustan Aeronautics Ltd in Bangalore, Dr Chowdhury was seconded to the newly established national classification society, Indian Register of Shipping in Mumbai, to initiate R&D activities and to formulate the new rules for design and construction of merchant ships. After 7 years in shipping, he joined Torsteel Research Foundation at its head office in Calcutta. He has been in charge of the Foundation’s activities in north India for the last two decades. Dr Chowdhury’s experience has been multi-disciplinary and his current interests are centered on steel as a construction material.

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