Ordinary and Long-Term-Durability of Reinforced Concrete Structures

by M. Collepardi

Synopsis: Durability of reinforced concrete structures (*RCS*) seems to be poor when compared to that of ancient un-reinforced structures. When ordinary durability (service life of 40-50 years) is needed, the poor behavior of *RCS* stems from human negligence in adopting the well consolidated and available experiential knowledge. However, for long-term durability requirements (service life of 100 years and more) the inherent vulnerability of the steel-concrete system must be taken into account.

The inherent vulnerability of *RCS* substantially depends on the following "weak points"of concrete:

(*i*) Poor tensile strength

(*ii*) High modulus of elasticity

(*iii*) Microcracking caused by restrained thermal and drying shrinkage or loadings in service.

This paper critically examines some possible future scenarios to achieve long-term-durability in *RCS*, including:

a) Improvement in the corrosion behavior of the reinforcement through the use of corrosion inhibitors, protection of the reinforcement with a coating, change in the composition of reinforcing bars, cathodic protection.

b) Increase in the tensile strength and/or ductility of concrete mixtures based on rubber-like polymer additions.

c) Flexible surface coatings for concrete protection in order to bridge the unavoidable cracks of the rigid concrete substrate.

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INTRODUCTION

Paradoxically modern concrete structures, with metallic reinforcements, are less durable than the ancient un-reinforced concrete structures.

Some Roman plain concrete structures are still in excellent state even after 2000 years or more. Those which today appear in form of romantic ruins owe the lost of their integrity more to extra-ordinary traumatic and cumulative events of the past - earthquakes, fires, wars - rather than to degradation processes inherent to the material itself. For the front cover of the Proceedings of the Kumar Mehta Symposium(1) the editors selected a picture of the *Pantheon* dome in Rome, a still sound, intact and majestic building made of concrete with lime-pozzolan mixture as binder and crushed bricks or natural pumice as lightweight aggregate. On this picture the editors placed an inscription referred to this concrete: "*But concrete can be durable*".

The long term durability of this ancient cementitious material highlights even more the relatively poor behavior - in terms of durability - of the modern reinforced concrete structures (*RCS*), most of which have lost their original serviceability in less than one century and in some cases in less than a few decades. When referred to modern reinforced concrete the above inscription should be changed into "*Can it be durable?*"

To find a possible answer to this question, the author of the present paper will address the following three aspects of the problem:

- Meaning of durability of modern concrete structures
- Deterioration causes in *RCS*
- Conceivable scenarios to design and achieve long-term-durability in *RCS*.

WHAT DOES DURABILITY MEAN?

The durability of a reinforced concrete structure is the capability of the structure of maintaining its original **functional and structural characteristics** for the expected service life and exposure conditions it was designed for. It does not necessarily coincide with the durability of concrete, the latter being the capability of the material by itself of keeping the original **properties** for a certain period of time. In fact the durability of *RCS* depends not only on the durability of the concrete, but also on aspects of design (cover thickness, density and positioning of reinforcing bars, surface protection, if any) and on the **execution techniques** (transport, placement, compaction, and curing of the concrete mixture).

Norms and recommendations are available in Europe (2), America (3), and Japan (4) for the durability of concrete and *RCS* exposed to various aggressive environments including humid air, sea water, freezing- thawing, and de-icing agents, when a service life of 40 to 50 years is required. In the present paper this will be termed **ordinary durability** compared to the **long-term-durability**,which refers to a longer service life, of a minimum of 50 years up to 200 years (5) and even more. Long-term-durability is needed, for instance, in infrastructural works of particular social importance which require great investments (e.g. underwater tunnels, long span bridges, highway networks, etc.) or structures of particular architectural interest (e.g. monumental works, churches, state buildings, etc.). Significant examples of the latter structures are the *Grande Arche* in Paris and the *Opera House* in Sydney.

Wondering whether these monumental buildings will last, for instance, for at least 500 years is more than legitimate, if we compare the experienced service life of reinforced concrete buildings in the present century with that of ancient monumental works built in this millennium.

Michelangelo - who is perhaps the most famous world-wide sculptor and painter, but also was a very fine architect - designed *Palazzo Farnese* in Rome in the 15th century. This building is still in service as the residence of the French Embassy in Italy. Can we hope for a five-century-service-life in modern reinforced concrete architectural works such as that achieved by many Renaissance buildings in Italy as well as in other countries in Europe? Although Michelangelo was more an artist than an engineer, he always took into great account the quality of the materials he used to achieve the longest possible durability for his masterpieces - the marble for the *David* statue in Florence, the colors and the mortar substrate for the *Cappella Sistina* in Vatican as well as the stones, bricks and mortars for the *Palazzo Farnese* or the *Capitolium Square* in Rome.

Is perhaps the present experiential knowledge on the construction materials lower than that available to Michelangelo and to other architects of the past? If not, why are the durability problems of *RCS* debated in hundreds of papers, seminars, conferences, and books? According to the author of the present paper, the answer to this key-question can be found by examining two fundamental durability problems in the specific field of *RCS*:

a) **Human negligence** in adopting the well consolidated and available experiential knowledge for ordinary-durability *RCS*.

b) **Inherent vulnerability** of the steel-concrete system for long-term-durability *RCS*.

Both these aspects (Table 1) are discussed in the next section.

DETERIORATION CAUSES OF RCS

Human negligence: In *RCS* exposed to aggressive environments a service life of 40-50 years (ordinary durability) may not be achieved when one or more of the following recommended actions are not performed:

- *Selection of adequate materials* in terms of specified cements, sound and well graded aggregates, chemical and mineral admixtures.
- *Proper mixture-design* in terms of water-cement ratio (*w/c*) and air-void system as needed for strength and durability requirements dependent on environmental exposures.
- *Adequate construction-design* in terms of concrete cover thickness, position and density of reinforcements, form and dimension of structural elements.
- *Careful execution techniques* in terms of workability and transport-related slump loss of the fresh concrete, placement, compaction and curing of the concrete mixture.

Two types of human negligence may occur. The first type - the most frequent - involves the adoption of a high *w/c* in relationship to the aggression level of the environment, the absence of an air-entraining agent in structures exposed to freez-thaw cycles, the selection of a thin cover in reinforced concrete structures exposed to carbonation or chloride penetration, the addition of uncontrolled amounts of mixing water on the job site because of concrete slump loss, the inadequate or missing curing after demoulding. All these forms of negligence occur due to the gap existing between the available know-how in the concrete durability science (6) and the relatively poor knowledge of concrete technology of design-engineers, architects and especially contractors. Neville (7) has highlighted this gap and ascribed it to the poor attention paid by schools and universities to teaching concrete technology compared to that devoted to structural design. According to Neville "*Inadequate knowledge of factors influencing the behavior of concrete has harmful consequences in the operations of manual and technical staff. This situation exists because learning about concrete is considered almost below the dignity of the person undertaking sophisticated structural calculations*" (7).

The second type of human negligence is related to some aspects of cement production and concrete manufacture processes which can objectively be managed with some difficulties in the pratical field experience. One of these aspects deals with the selection of sound aggregates, not prone to alkali-silica-reaction (*ASR*), when concrete must be produced on a large scale - as it is usual for real life *RCS*: so far, reliable and quick tests to detect potential *ASR* in each individual grain of a big batch of aggregates are still not available. The routine use of fly ash and other supplementary cementitious materials remains the best way of preventing *ASR* in concrete structures where there is the risk of using alkali - reactive aggregates and an alkali-free portland cement is not available (8, 9).

An other and more recent aspect of the second type of human negligence (Table 1) deals with the risk of delayed ettringite formation (*DEF*) occurring when high clinker sulfate content is used in the production of modern portland cements (10). According to the available standard tests only the total sulfate content of cement - and not that of the clinker phase - may be checked. Therefore, the *DEF*-induced concrete distress can be managed with difficulty. This type of deterioration has been growing, in prestressed concrete structures and particularly in concrete ties, since the last decade. This is due to two concurrent events besides the exposure to humid environment (Fig. 1): the unwitting increase since the 80s in the sulfate content of the clinker phase related to the use of sulfur-rich wastes and fuels in the kiln, and the increase in microcracking related particularly to the high, uncontrolled and non uniform stress distribution in prestressed and/or steam-cured concrete structures (11). Therefore, this type of human negligence could be eliminated through a better control in the clinker production process by cement producers, and in the stress distribution in the *RCS* by design engineers.

Inherent vulnerability of RCS: In contrast to what happens in the laboratory, real life structures are subjected to static and dynamic loads. Moreover, the additional deterioration which is observed in real life *RCS*, compared to that of the specimens stored in a laboratory room, is due to the following "weak points" of concrete:

(*i*) Poor tensile strength.

(*ii*) High modulus of elasticity which is responsible for the transformation of restrained thermal and hygrometric length changes into relatively high tensile stresses.

(*iii*) Microcracks formed as a consequence of (*i*) and (*ii*).

These microcracks represent preferential paths for the penetration of aggressive environmental agents - such as air, water, sulfate, chloride, alkali ions - through the mechanisms of diffusion and capillary absorption through the cracks. This means that the concrete cover can be penetrated by the aggressive agents independently of the porosity of the cement matrix. This promotes the corrosion of the metallic reinforcement, characterized by a disruptive expansion which accompanies the change of the metal (Fe) into the corresponding oxides (rust). Once this process is initiated, the microcracks of the concrete cover grow becoming macrocracks and then, after an initial induction period, the duration of which depends on the aggression level of the environment, the degradation process increases very rapidly (12).

When ordinary durability is required - as for *RCS* with an expected service life of 40 to 50 years - the presence of microcracks in the concrete cover and their transformation into macrocracks plays, in general, a role of negligible importance provided that all deterioration causes related to human negligences are avoided (Table 1) and very severe aggressive environments are excluded. On the other hand, when long term durability is needed - as for *RCS* with an expected service life of 100 years or more - one cannot ignore the mechanism of formation of microcracks in the concrete cover and their subsequent transformation into macrocracks due to the corrosion of the reinforcement. Moreover, even when ordinary-durability *RCS* are required, microcracking of concrete should be avoided in case of very severe environmental exposure (e.g. tidal zone in maritime works or frequent freezing-thawing accompanied by de-icing salt treatments). The metallic reinforcing bars, specifically used to counteract the poor tensile strength of concrete and the possible failure of plain concrete structures subjected to tensile or flexural stresses in service, paradoxically have become the main reason of concern for the long-term-durability behavior of *RCS*. Concrete structures, even when microcracked by restrained thermal or drying shrinkage, could substantially perform as long-term-durable structures, in the absence of reinforcing bars, provided that low *w/c*, adequate air void system, effective compaction, and proper curing were adopted.

The next section examines some conceivable scenarios to produce long-term-durability *RCS*, in alternative to those currently used for ordinary durability *RCS*.

FUTURE SCENARIOS FOR LONG-TERM-DURABLE RCS

For new *RCS* to be competitive, in terms of durability, with ancient unreinforced buildings, three main scenarios are possible:

a) Improvement in the corrosion behavior of the reinforcement

b) Higher tensile strength and/or more ductility of special concrete mixtures

c) Flexible surface coating for concrete protection.

a) Reinforcement with improved corrosion behavior: The improvement should consist in a significant reduction of the corrosion process of the reinforcement, even when, due to exposure to aggressive environments, the reinforcement is **embedded in a micro-cracked cement matrix**. In other words, even in the absence of the passivating action of the cement-matrix, the reinforcement should resist **by itself** the corrosion promoted by CO_2 or Cl^- ions and fed by humid air (O_2 and H_2O). The corrosion rate - in terms of reduction in the cross section of the reinforcement - should be as low as few μm/year in order to achieve two important objectives:

(*i*) Reliable safety, from a structural point of view, of *RCS* exposed to aggressive environments for a long period of service life

(*ii*) Absence of any disruptive action of the reinforcement which could transform microcracks into macrocracks in the concrete cover and then be detrimental to the long-term-durability of the *RCS*.

Based on the available experiential knowledge (13), the following options are theoretically available for the long-term protection of reinforcing bars:

- Use of corrosion inhibitors as concrete admixtures
- Protection of the reinforcement with a coating (epoxy or galvanized steel)
- Change in the composition of reinforcing bars to more durable alloys (e.g. stainless steel)
- Cathodic protection methods.

However, so far none of the above protection methods appear to be sufficient to provide corrosion protection unless a crack-free long-term durable concrete is used (Table 2). For instance, the use of corrosion inhibitors does not protect the reinforcement from corrosion when cracked *RCS* are exposed to sea water or any other Cl^- source (14): in spite of a low-porosity cement matrix, concrete microcracks and cracks (> 0.1 mm wide) act as preferential paths for the aggressive agents which hence have direct access to the surface of the reinforcement close to the crack tip.

Coated reinforcements, and in particular epoxy coated reinforcements (*ECR*), can lead to an "extra life" in the functionality of *RCS* (15) by prolonging the service life defined as the time span from the construction of the structure to the total loss of its functionality (Fig. 2). However, due to the diffusion of water molecules through the coating and the subsequent loss of its adhesion to the steel surface (16) an underfilm corrosion can occur in sound uncracked *RCS* and, to a greater extent, in microcracked structures.

The use of galvanized, copper-clad (17) or stainless steel (18) can prolong the service life due to the shift in the Cl^- threshold over which corrosion of reinforcing bars can be promoted. This threshold can change from 0.4% by mass of cement in ordinary steel to about 1.2% or 3.5% for galvanized or stainless steel respectively. However, in very severe exposure conditions (such as tidal zones, concrete structure semi-immersed in a Cl^- rich ground or *RCS* in contact with de-icing salts) where high chloride content can be accumulated, the threshold value can be reached in a relatively short time particularly in microcracked *RCS*. Therefore galvanized or stainless steel appears to be successful for long-term durability *RCS* provided that the constructions are exposed to carbonation only in the absence of chloride.

Cathodic protection of the reinforcement (19), under the action of an impressed electrical current, seems to be the most promising method even if, for the high financial investment in its installation, so far it is more used in rehabilitation works rather than in new constructions* . Theoretically, the protection of *RCS* from corrosion is just a question of a sufficient decrease in the electrochemical potential of the reinforcement (cathode), whatever Cl^- penetration occurs through the cement matrix or the preferential paths of

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* According to Pedeferri (19) "cathodic prevention" should be referred to new RCS, whereas the "cathodic protection" term would be related to the rehabilitation of deteriorated constructions.

microcracks. However, the decrease in the cathodic potential raises both the maintenance cost in service life and the risk of other concurrent electrochemical processes (e.g. cathodic reduction of $2H^+$ to H_2 and consequent embrittlement of steel in prestressed concrete structures). Presently, the main concern for the cathodic protection method is in the proper distribution of the auxiliary anode which should be applied close to the cathodic steel reinforcement. With respect to the past experience in the traditional cathodic protection of steel in soil or in sea water, there are clear logistic problems which are specific to *RCS*. In particular, due to the concrete resistivity, the flow and distribution of cathodic current from the anode to the steel reinforcement network can be obstructed. Therefore, the reinforcement in close proximity of the anode receives more current and is over-protected, whereas more distant reinforcements receive only a small fraction of the impressed current and remain under-protected (20). In conclusion, it seems that cathodic protection can be a successful and reliable method to provide long-term durability for new constructions, provided that a specific and taylor-made electrochemical design is adopted concurrently with the structural design of the *RCS*.

b) Special concretes with higher tensile strength and/or ductility: Long-term durability (crack-freedom) can be provided in *RCS* by an increase in the tensile strength and/or a decrease in the modulus of elasticity of the concrete (21). In fact, concrete cracks when the tensile stress induced by restrained thermal or drying shrinkage exceeds its tensile strength. Due to creep of the material, some of the stress is relieved and it is the residual stress - after the stress relaxation from creep - that determines whether or not cracking will occur (Fig. 3). In general high compressive strength concretes are intrinsically prone to microcracks, even to a greater extent than ordinary strength concrete, since the increase in the compressive strength is accompanied by an increase in the elastic modulus which is higher than that in the tensile strength. Therefore, unless some specific ingredients are used to manufacture special concretes, pursuing a crack-free concrete with high tensile strength (Fig. 4) or low elastic modulus (Fig. 5)does not seem to be a practicable approach

These special concretes exist in form of polymer-modified concrete mixtures characterized by a monolithic co-matrix in which the organic polymer matrix and the cement gel matrix are homogenized (22). In general, polymer modified concretes show a significant increase in tensile and flexural strengths and a negligible improvement in compressive strength. This is due to the contribution of the polymer phase interpenetrating throughout the cement phase. Figure 6 illustrates the influence of the addition of styrene-butadiene rubber (*SBR*) latex on the flexural strength of concretes with and without steel fibers (22). It seems that polymer modified concrete, particularly with steel fiber additions, is a promising material for preventing microcracks induced by restrained length changes and therefore for long-term-durability *RCS*. However, it is seldom employed because it is very expensive with respect to traditional concrete mixtures. Only in some special applications, such as bridge deck overlays or patching work, the polymer modified concrete has been used in Japan (23), USA (24) and Europe (25).

c) Flexible surface coating for concrete protection: Because of the high cost of polymer modified concrete, ductile and elastic polymer modified mortars have been developed to act as a flexible skin as thin as 1-2 mm on the surface of the concrete rigid substrate. Due to the relatively low thickness of these coatings, the cost increase related to the coating application is much lower with respect to polymer modified concrete employed in bulk for *RCS*. On the other hand, the cost increase of the coating application becomes negligible for long-term-durability *RCS* if one only thinks about the reduction in the cost for the rehabilitation of these structures particularly when subjected to very severe environmental exposures.

The original idea pursued by Swamy et al. (26) was to employ a flexible coating combining an acrylic, elastomer (based on an aqueous 2-ethylhexyl polyacrylate emulsion) with mineral filler and inorganic pigments. Subsequent developments by Coppola et al. (27) led to flexible mortars made from the same acrylic polymer aqueous emulsion combined with cement and fine aggregates. In these materials, thanks to the consumption of the water of the emulsion by reaction with the cement, the hardening time is reduced. These coatings are by themselves resistant to the aggressive agents present in the environment (water, CO_2, Cl^-, and $SO_4^{=}$ ions), are sufficiently flexible so that they can deform and bridge the un-avoidable cracks in the rigid concrete substrate, and can maintain these characteristics in time regardless of the environment in which they are placed.

Experimental results on the performance of these flexible coatings are available as a function of the exposure time in laboratory room, underwater, and outdoor natural environment (26, 27). It should be pointed out that, as for field experience with reinforcements with improved corrosion behavior, also in this case the available data refer to exposure times of only a few years. In conclusion, no direct field experience of real long-term durability (> 50 years) is available at this time. However, in contrast to what happens with the new types of reinforcement embedded into the concrete matrix, the long-term behavior of surface flexible coatings can be directly monitored and, in case of failure, the treatment can be repeated or modified.

CONCLUSIONS

Modern reinforced concrete structures are less durable than the ancient un-reinforced concrete structures because of the corrosion risk of the metallic reinforcement embedded in a rigid concrete.

Human negligence in adopting available experiential knowledge on proper design, placing, and curing of concrete is considered to be responsible for the lack of ordinary durability (up to 50 years of service life). However, the lack of human negligence is only a pre-requisite to achieve long-term durability (100 years or more).

Initial microcracks, produced by restrained thermal and drying length changes or loadings in service, act as preferential paths for the environmental aggressive agents and transform into macrocracks. This is detrimental to the long-term durability of reinforced concrete structures even when proper concrete mixtures are designed, placed, compacted, and cured.

The shift from ordinary to long-term durability can be achieved through one of the following developments:

- improvement in the inherent corrosion resistence of the reinforcement
- increase in the tensile strength and/or ductility of the concrete
- use of flexible surface coatings to bridge the cracks of the concrete substrate and protect it from penetration of the environmental aggressive agents.

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Table 1- Main causes of deterioration in reinforced concrete structures (*RCS*)

DETERIORATION CAUSES IN RCS:			
HUMAN NEGLICENCE*:		INHERENT VULNERABILITY OF RCS**:	
First Type	Second Type	Concrete	Steel reinforcement
• Inadequate materials: - cements - aggregates - chemical & mineral admixtures • Unproper mix-design: - *w/c* - air void system • Inadequate construction design: - cover thickness - position & density of rebars - form & size of elements • Careless execution techniques: - slump & slump loss - placement - compaction - curing	• ASR monitoring in field: experience - alkali-reactive aggregates - high alkali cement • DEF induced distress: - high sulfate clinker - microcracking - exposure to water	• poor tensile strength • high modulus of elasticity • prone to microcracking produced by thermal and drying shrinkage • microcracks as preferential paths for aggressive environmental agents (humid air, Cl^- and SO_4^{--} ions)	• corrosion when exposed to humid air or Cl^- ions penetrating through microcracks • expansive-disruptive nature of the corrosion process causing macrocracks in the concrete cover

**it must be avoided for ordinary durability of RCS in aggressive environments.*

***it should be avoided for long-term durability of RCS or ordinary durability of RCS in very severe environmental exposure.*

Table 2 - Improved protection of the reinforcement and related limits in succeful applications

Type of protection:	**Limits in successful applications**
• Corrosion Inhibitors	• They do not work in microcracked RCS
• Epoxy Coated Reinforcement	• Loss of adhesion due to water diffusion and under-film corrosion
• Galvanized Steel	• Corrosion occurs with Cl^- over 1.2% by cement weight
• Stainless Steel	• Corrosion occurs with Cl^- over 3-4% by cement weight
• Chatodic Protection	• Tailor-made electrochemical design is needed for the specific distribution of the reinforcements

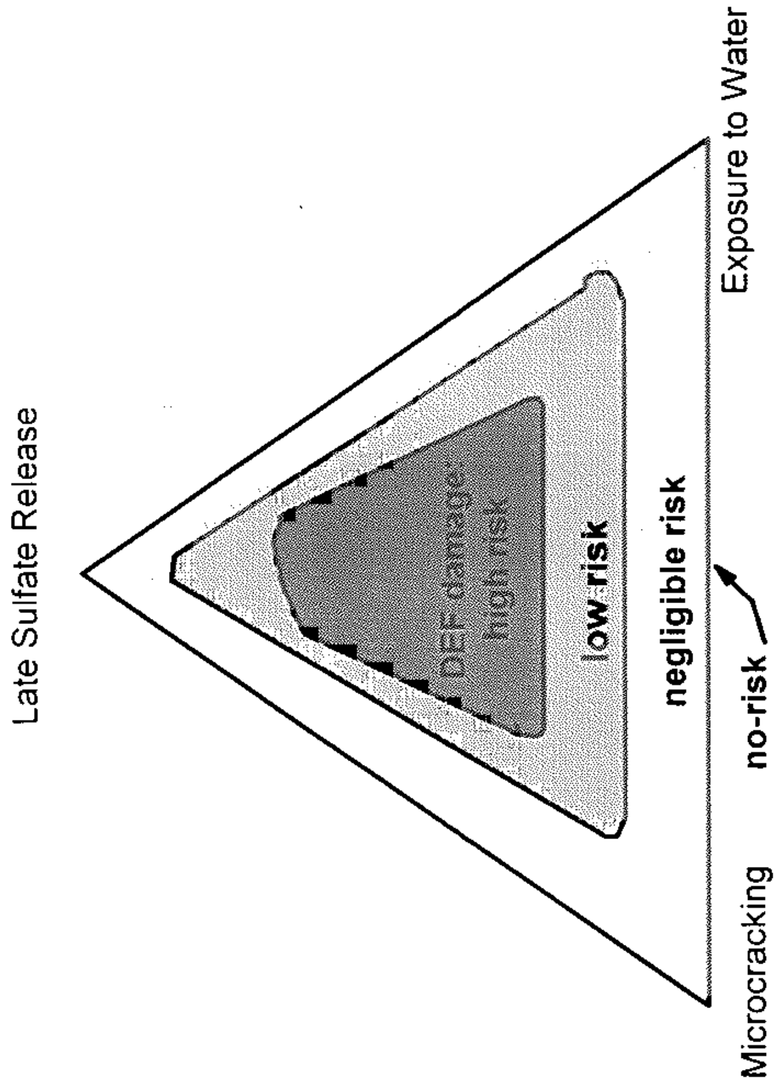

Figure 1 - A holistic model showing DEF-damage as a function of late sulfate realase, microcracking, and exposure to water (11).

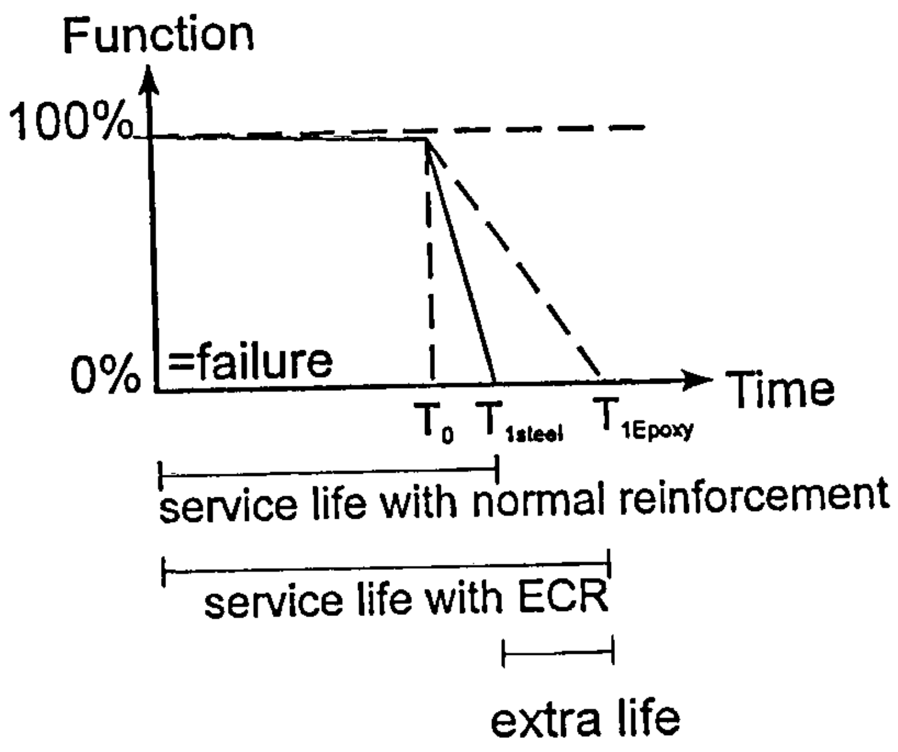

Figure 2 - Design-concept for use of epoxy coated reinforcement (ECR) as a corrosion protection system (15).

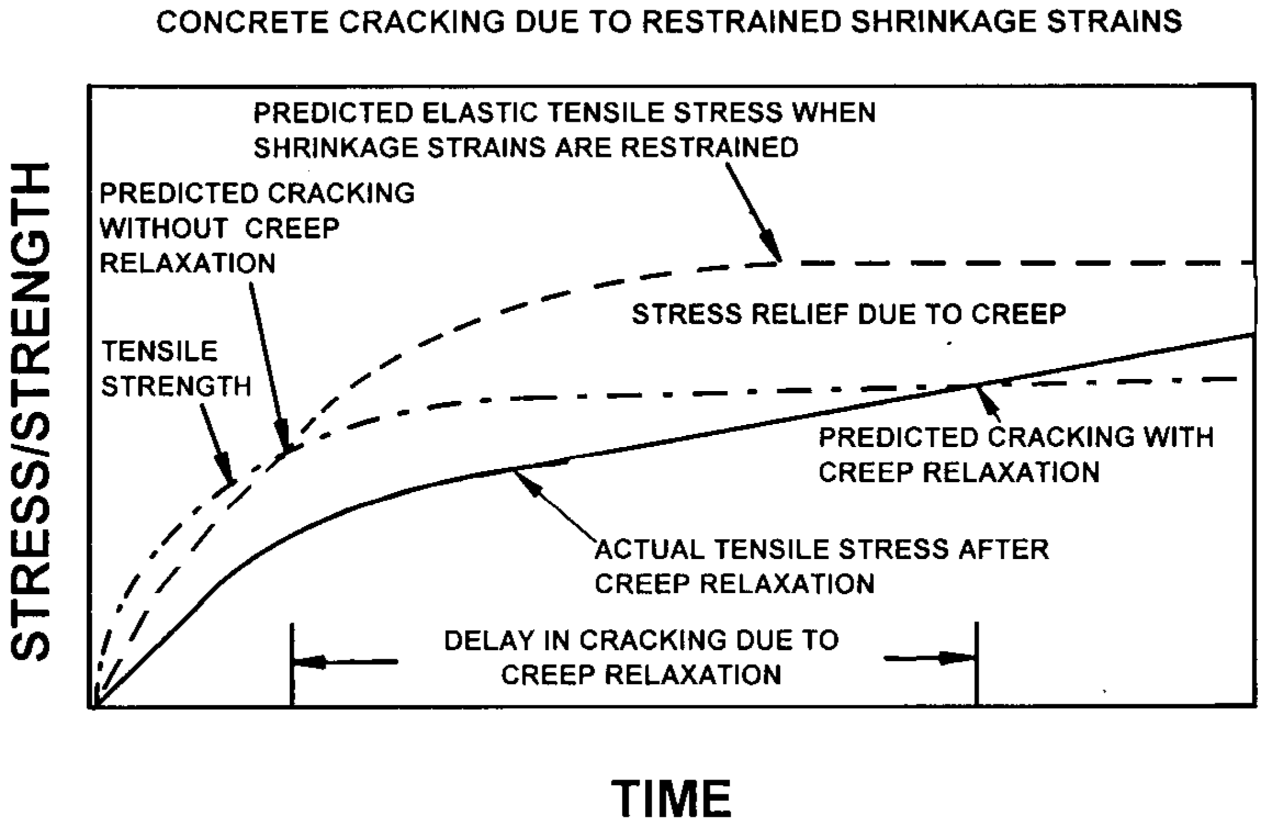

Figure 3 - Craking of concrete due to the lower tensile strength with respect to the tensile stress [adapted from (19)]

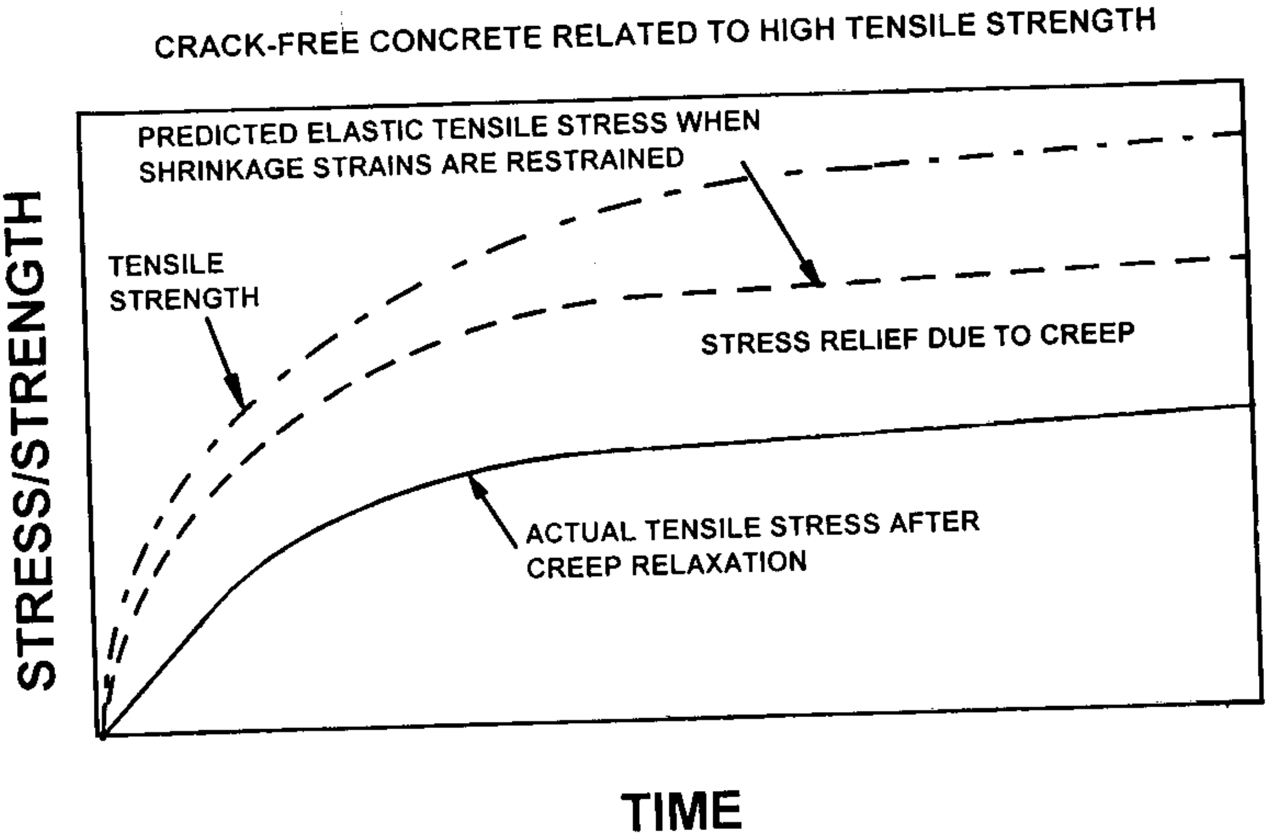

Figure 4 - Crak-free concrete due to the tensile strength increase with respect to tensile stress.

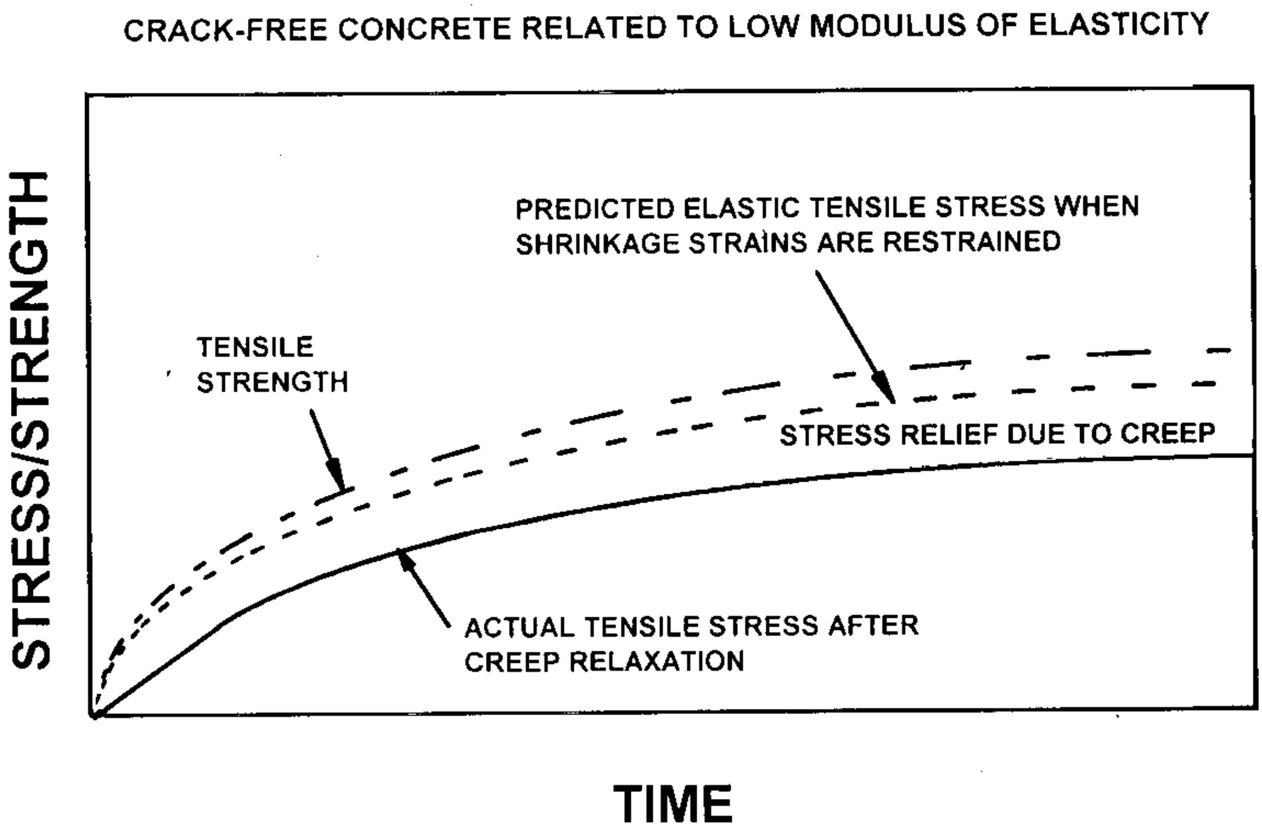

Figure 5 - Crak-free concrete to the tensile stress decrease with respect to tensile strength.

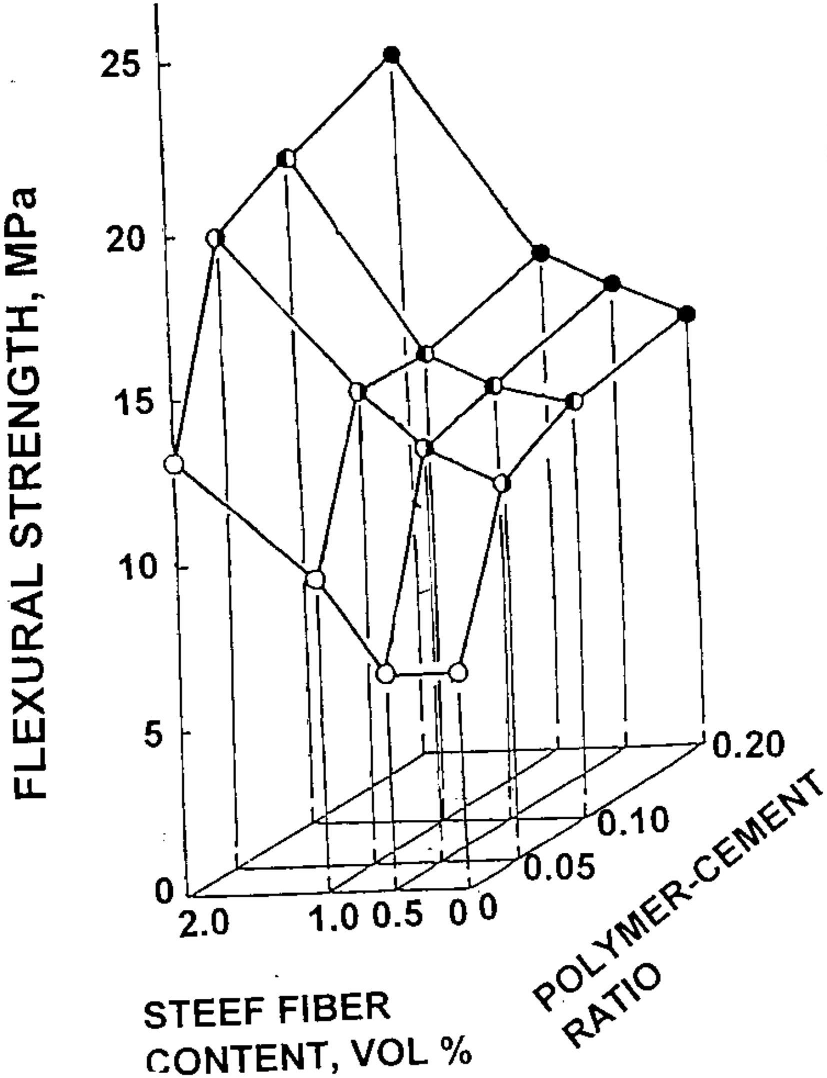

Figure 6 - Steel fiber content and polymer-cement ratio versus flexural strength of latex-modified (SBR) concretes (22).