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Corrosion inhibitors and other protective systems in concrete repair: concepts or misconcepts

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Abstract

In recent times in many parts of the world, reinforcement corrosion has become the main factor in early, premature deterioration, and sometimes failure, of concrete structures. One of the major factors contributing to this deterioration process is the environmental and climatic conditions to which a concrete structure is exposed. When the severity of environment is compounded with poor quality concrete and/or defective design and construction practices, the process of deterioration becomes interactive, cumulative and very rapid, and a cancerous growth that cannot be easily stopped.

The poor durability performance of many concrete structures is causing disruption and expenditure on remedial works which owners and society cannot afford and do not wish to see repeated.

A glimpse of reinforcement corrosion and some of the protection options is presented in this paper. The effect of corrosion inhibiting admixtures in concrete and concrete repair is discussed in detail. The complex issue related to the effectiveness of inhibitors in repairs is addressed, based on analysis of the differences between electrochemical activities in new and repaired structures. The paper concludes that as long as one continues to blindly use protection methods applicable for newly constructed structures for concrete repairs, the business of "repairing the repairs" will be on the rise. A broader understanding of the electrochemical differences between new and repaired concrete is necessary for effective protection of reinforcement in repaired structures.

Keywords: Alkalinity; Corrosion protection; Durability; Inhibitors; Reinforcement

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> *I sometimes think that the construction industry is like the person who seeks the wonder cure: the elixir that will provide eternal life with no effort at all on their part. Wouldn't it be wonderful if by the simple expedient of adding ingredient X all would be solved? There would be no need to worry about cover, compaction, curing or even the concrete itself. Life is not that simple… C.D. Pomeroy*

1. Introduction

It is an unfortunate fact that very large amounts of existing concrete structures worldwide are in a state of deterioration/distress. At the same time, it must also be recognized that many repaired concrete structures are severely deteriorated only a few years after being repaired.

The performance of repaired concrete structures remains a matter of utmost concern to all those involved with their design, construction, maintenance and use. Few problems aggravate the public and lead to their dissatisfaction with our ability to provide for the structure's use than the disruption of its use a few years after repairs. Contrary to the expectations, the problem of corrosion in concrete repairs has become widespread not only with respect to severe environmental conditions but also with respect to moderate environmental condition.

The concrete repair industry is thus facing a major challenge: How to halt the decay of the world's physical infrastructure. It is therefore important that we critically examine the issue of corrosion and corrosion protection in today's concrete repair and explore how it can be improved in the near future, i.e.: how to make today's repairs durable for tomorrow. A basic understanding of

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the processes leading to premature corrosion in repaired structures still eludes the concrete repair community. This applies not only to the processes of corrosion of reinforcement in repaired structures and deterioration/distress of concrete, but also to a variety of the proposed solutions—corrosion protection techniques, materials and systems. They have a highly empirical history of use, and their performance in many cases is questionable.

This paper offers some random thoughts in the area of reinforcement corrosion and protection in concrete repair. It encompasses the elucidation of the basic processes of corrosion of steel in repair, electrochemical incompatibility, and how these processes may lead to eventual failure of the composite repair system. The paper is also about how we can, or cannot, successfully address these problems with the aim of prolonging lifetime of existing concrete structures. After all, we must pause periodically from our busy schedules to review where we are and where we might be going. Of course, there are some thoughts in this paper which may lead others to agree or disagree. But it is only when ideas receive a forum that progress can be made, and that is the goal of this paper.

It is not possible here to provide a critical review of numerous aspects of corrosion and corrosion protection, the problems are too extensive and various mechanisms too complicated for a critical discussion in a single paper. General aspects of steel corrosion in concrete and its protection have been treated by a number of authors and will not be addressed here.

Research has substantially improved our knowledge of cementitious materials, the fundamentals of concrete deterioration from carbonation-induced corrosion, chloride-induced corrosion, sulphate attack, alkali–aggregate reaction, frost, etc. However, in view of the serious and insidious nature of the corrosion of steel in concrete repair and repair failures, it is surprising that progress in the repair industry has been so slow, which is probably attributable to some combination of the following:

- Concrete repair is a very complex system exposed to the exterior and interior environments and their interaction (Fig. 1).
- The fundamental guidance for addressing corrosion problems does not exist. The mechanism of passivation and corrosion of steel in a complex repair environment is poorly understood. The whole area concerning "additional protection" of reinforcement in repair is currently highly speculative.
- Corrosion of steel embedded in cement-based materials is an extremely complex phenomenon involving environmental, metallurgical, interfacial, and continuum considerations. Most of the research in this area is being done by the civil engineering departments of universities where few workers have adequate knowledge of the subject.
- The industry and government agencies have been lax in support of research leading to a resolution to problems. Real progress cannot be made on the basis of "graduate students working for limited periods". It is necessary to initiate programs which include a balanced practical approach and are adequately funded.
- A utopian dream exists that the problems can be resolved by using "high performance" materials, corrosion inhibitors, protective coatings, etc., or belt and suspender systems. This caused many workers in the field to ignore the basics in the technology of concrete and other cement-based materials.
- Significant knowledge to design durable repairs already exists in a relatively "quite refined state", as stated by Mather [1]. But the manner in which this knowledge is used is primitive.

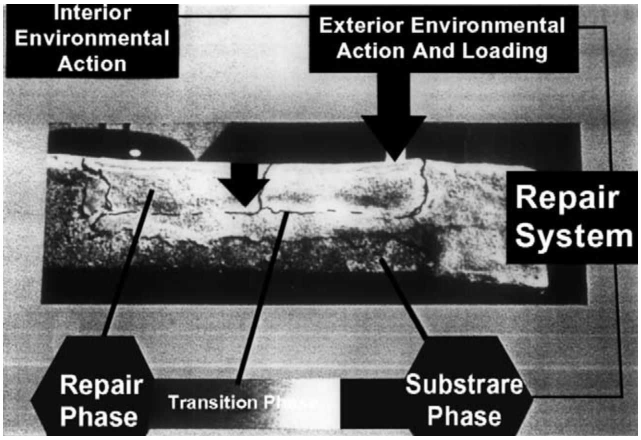

Fig. 1. Concrete repair system and its loading.

Several research studies in the repair field have been concerned with the improvement of properties of repair materials and their dimensional behaviour relative to the existing substrate. But these activities will lead to improvements in repair durability only if the issues of electrochemical compatibility are also addressed. Removal of deteriorated concrete and its replacement with a repair material, even the best one, may result in accelerated rebar corrosion due to macrocell formation.

The subject of this paper is also devoted to several confusing issues and attempts to establish the facts concerning the protection of reinforcement from premature corrosion in concrete repair, particularly that offered by corrosion inhibitors.

How can we expect repaired concrete structures to be durable if the testing methods, design and specification of corrosion protection methods, are relying on an inadequate assumption that electrochemistry in a repair system is similar to that occurring in "new construction?" There are significant differences between new construction and repair jobs; there are often different factors leading to corrosion of reinforcement in new an repaired concrete structures and, therefore, in the methods of protection.

It is not the intent of this paper to criticize existing methods and materials for additional protection of reinforcement in repairs, or to discuss in depth the merits or demerits of one protection system against another. The author can offer no panacea, or at least express a reasonably objective view of the right and wrong way to protect reinforcement in repaired structures. Much to our regret, this is not so. The problem is too complex because the existing knowledge is not sufficient to offer a panacea.

The consequence and probability of repair failure due to the premature corrosion of the reinforcing steel is not necessarily a single simplistic solution as may be appropriate for newly constructed structures. Our success in the repair field may depend on our ability to resolve the controversies, to differentiate sense from nonsense. The nonsense will be abundant, no matter what we do: this field, due to the lack of proper education, is presently well positioned to import a lot of misconceptions; any field where education and research are inadequate is going to have great trouble getting rid of the prevailing misconceptions.

The author realizes that some statements will not be shared by many since it hits at the crux of the controversy. But in this case, much more than a hair, perhaps, divides concepts from misconcepts.

2. A glimpse of corrosion problem

According to published data, steel reinforcement in concrete and in concrete-like materials is, in general, well protected from corrosion by the alkaline nature of the cementitious matrix surrounding it. In general, this is true, it is protected, and it is not supposed to corrode. But such concrete "in general" may only exist as "labcrete", in a small specimen. In the real world, reinforcing and prestressing steels are subject to corrosion due to carbonation and chloride ion attack.

Steel reinforcement in concrete does not corrode because the surface of the steel in the alkaline environment is passivated; steel in concrete corrodes when its surface is depassivated during the manufacturing of the structure, or becomes active during service (Fig. 2). Corrosion is the electrochemical reaction, and the important factor affecting a corrosion cell is the difference in potentials of the metal. The driving force for current and corrosion is the potential development. Since the structure of steel and the contact layer of concrete are both heterogenous, the requirement for potential difference between the separate portions of the metal surface (the electrochemical inhomogeneity) is always satisfied.

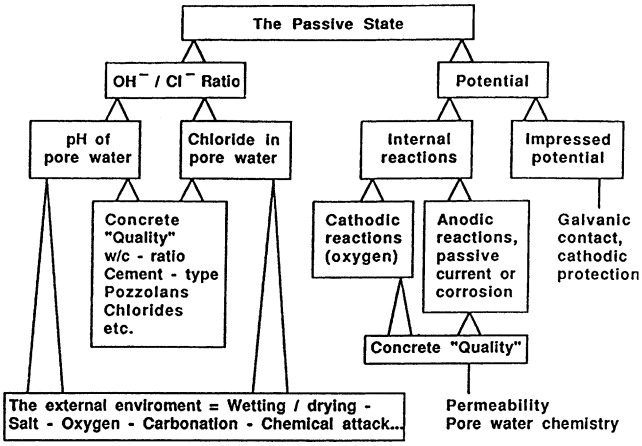

Fig. 2. A schematic overview of factors, which have an influence on the maintenance of the passive state of steel in concrete.

Concrete is a permeable material, where aggressive agents diffuse (micropermeability) through it and reach the reinforcing steel, causing its depassivation and corrosion, when water and oxygen are available. Corrosion by this mode however, is a relatively lengthy process. Concrete is a brittle material and always contains microcracks. When these microcracks combine in a network with macrocracks, the prevailing transport mechanism is not diffusion, it is the permeation of water and aggressive agents via water through the cracks to the reinforcement (macropermeability). Why enter through the closed door, when an open door is nearby (Fig. 3)?

High permeability of concrete and other cement-based materials affected by cracking is truly responsible for the lack of durability. For corrosion to occur, it is necessary that both the passivating film on the steel is destroyed and that there exists a differential electrochemical potential within the steel–concrete system. The natural protection of steel by the high alkalinity of cement matrix is disturbed due to the following reasons:

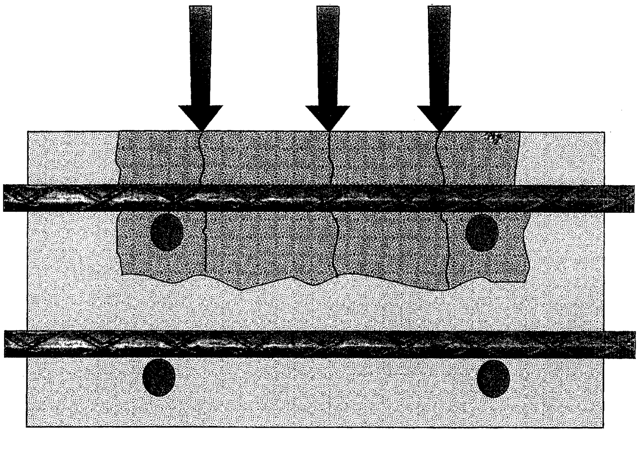

Fig. 3. Macropermeability in concrete repair.

- Neutralization, a reduction of pH below 10 due to the chemical reaction between the products of hydration of cement and carbon dioxide which diffuses from the atmosphere (carbonation). Carbonation by diffusion is a very lengthy process: approximately 1 mm of concrete cover carbonates in a year. Cracks in the concrete, on the other hand, allow carbon dioxide easy permeation through the concrete cover, and carbonation occurs rapidly.
- The presence of chloride ions at the reinforcement level. Chloride ions may penetrate into the concrete due to one of three processes: diffusion due to a concentration gradient, absorption from salt solutions form, and/or by flow of the solution through the cracks.

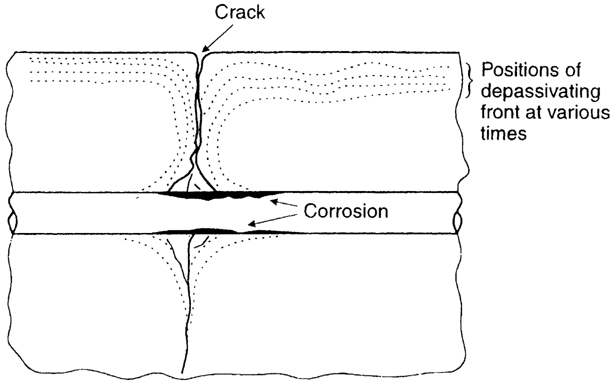

Fig. 4. Schematic description of the advance of depassivating front in a region of crack [3].

The differential electrochemical potential may develop due to the dissimilarities in the chemical environment of steel, such as the result of nonuniformed carbonation, the variation in the rate of penetration of chlorides, moisture, oxygen, etc. Reinforcing steel in the variety of a crack starts to corrode from a localized depassivation of steel because of the weakened steel–cement-matrix contact and disturbed steel passivating film. Steel depassivates from reduced alkalinity at the surface of the reinforcement, or from accumulation of aggressive ions, chlorides, in particular.

Acid gasses and aggressive ions penetrate the cracked material much easier than they do in crack-free concrete. The active coefficient of carbon dioxide diffusion (penetration) in a concrete crack 0.20 mm (0.008 in.) wide is about three orders of magnitude higher than in average quality crack-free concrete. The same holds true for the transport of aggressive ions, the rate of substance transfer by capillary suction is even greater. According to previous data reinforcement in a crack wider than 0.1 mm (0.004 in.) initially corrodes more rapidly than the unprotected steel, both in the air and with the cyclic wetting and drying [2]. A high initial rate of steel corrosion in the cracked concrete versus the unprotected steel, apart from the effect of microcells, can be accounted for by a much longer preservation of moisture on the steel surface in the crack than on the open steel surface. Chlorides also penetrate faster through cracks towards the reinforcement. Cracks often have a high chloride concentration at the root of the crack near the reinforcing steel (Fig. 4) [3]. As soon as corrosion starts, the rate of corrosion is controlled by the conductivity of the concrete, the difference in potential or voltage between the anodic and cathodic areas, and the rate at which oxygen reaches the cathode. The width and the direction of cracks are not of critical importance, but the amount of cracks per unit of area is critical.

Repairs are more prone to cracking and, therefore, to corrosion than newly constructed concrete structures. When freshly placed and hardened repair material is exposed to ambient temperature and humidity, it experiences drying shrinkage strain. The type and magnitude of this strain will depend on the characteristics of the repair material, temperature and the humidity of the environment, the geometry of the repair, the degree of the restraint, and the temperatures of the repair material and substrate. The repair material would crack when the induced tensile stress exceeds its tensile strength. This cracking often occurs and destroys the repair's watertightness, increases its permeability to aggressive agents from the exterior enviornment, and intensifies the transport of substances inside the system.

Transport of substances through and in the repair system is a very complex process, consisting of a combination of liquid flow through macro and microcrack systems, capillary transport, diffusion, and osmotic effects. The exact contribution of each process needs to be quantified in each particular situation. The effects of such variables as location of the repair in the structure, chemical environment in the composite repair system, amount and distribution of cracks in both phases, temperature, moisture, and stresses need to be considered.

It appears that adequate attention to the specifics of concrete repair—its significant differences with new construction—is not paid by those who commission and perform repairs. The three primary issues related to premature corrosion in repaired concrete structures, namely cracking as a result of drying-shrinkage, electrochemical incompatibility, and changes in interior environment caused by repair requires due consideration. Therefore, a brief review of the principles governing the failure of repair from these three causes will be helpful here.

When an existing concrete structure, suffering from corrosion of embedded reinforcement and concrete deterioration, is being repaired, some of the chloride contaminated concrete may be left in place. In this case, there is always a risk that corrosion activity may continue or even accelerate, because the repair phase has a

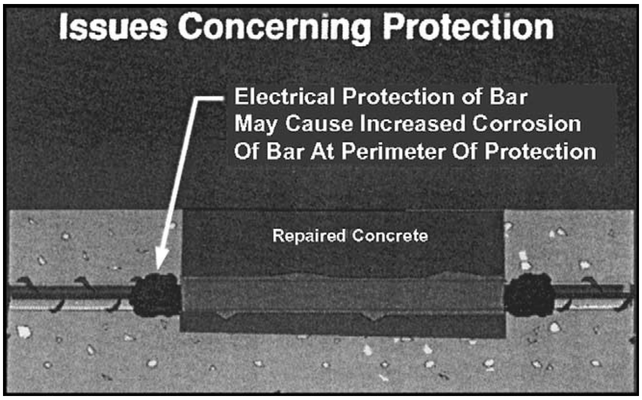

Fig. 5. Corrosion of reinforcement at the repair perimeter (ring effect).

different moisture, oxygen and chloride content than the surrounding concrete, and strong corrosion cells may be established resulting in spalling of the repair itself or, more frequently, of the concrete around the repair (Fig. 5).

It is difficult to predict the effect of a repair on electrochemical activity in a repaired structure because it is a function of the change in potentials, the nature of the repair materials, and the exterior and interior environments. If the steel in the repair area is only partially exposed with a bar that is embedded halfway in existing, chloride-contaminated concrete and halfway in new repair material, strong corrosion cells may develop. The half of the bar in the existing concrete will become anodic and will corrode at a rapid rate, driven by the other half acting as a cathode. Repair phase deterioration and failure may develop this way in less than a year. If concrete is removed completely from around the reinforcement and replaced by a repair material, reactions similar to those mentioned above can accelerate the corrosion of the steel at the perimeter of the repair in the surrounding existing concrete. The risk of corrosion in concrete repair due to electrochemical incompatibility between "old" and "new" portions of the structure is always present.

The durability criteria for concrete repairs differs from that of newly constructed concrete structures [4]. The factors that relate to such durability criteria are not only normal physical and chemical attacks from the exterior environment, but the attack from the interior environment and the changes in the interior environment created by the application of the repair material (Fig. 6).

It is never advisable to design any structure without first having a very clear idea of what environment it is going to be exposed to, and how it is going to behave in this environment. Unfortunately, repair projects are often not designed this way. Very little consideration is given to the interior environment in the repair system and, therefore, little is known about how the repair will behave in this environment. In repair systems, the interior is constantly changing due to the existence of the interior transport mechanism in addition to the exterior transport described earlier. Water with dissolved salts may be transported by temperature and pressure gradients. Dissolved substances can also move by diffusion in water saturated concrete with a stagnant water phase if there is a concentration gradient. Finally, ions will migrate in an electric field, and this is what provides electrical conductivity in a repair system.

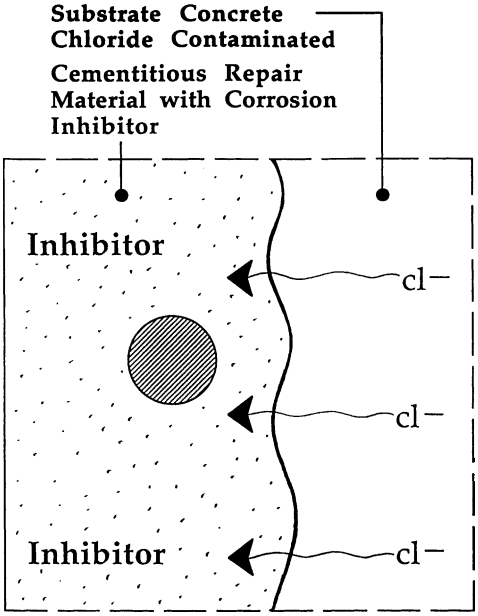

Fig. 6. Penetration of Cl$^-$ from existing substrate into repair with added corrosion inhibitor.

With a complex composite system such as a concrete repair, aggressive exterior and interior environments, and their interaction, become a major factor in initiating a progressively cumulative damage attack. Progression of reinforcement corrosion and concrete deterioration becomes an overall synergistic process, a complex combination of a variety of individual mechanisms, the exact role, effect and contribution of each is not clearly understood. Variability in almost everything is typical for repair systems. Occasionally these variables cancel each other, but usually, as a rule, they are likely to be cumulative. It is appropriate to note the first law of concrete repair corrosion, "If the repair can get in the wrong environment, it will".

The effects of interior and exterior environments and their combination on the corrosion process is foremost among the most important and less known area. A better understanding in this area may lead to better solutions to corrosion problems. The interactions of repair with existing structure, with existing environment, with loading conditions, also needs considerable study as this represents the real world conditions to which repaired structures are exposed.

3. A glimpse of corrosion protection

When a new concrete structure is to serve in a severe environment, it is always debatable whether one can rely on the quality of the concrete alone to protect the embedded steel in it from corrosion, or, if the steel would need additional protection of one kind or another.

In severe environments, a wide range of aggressive agents can penetrate concrete and initiate a damage process in a very short time of exposure. A sensible solution for long-term durability, where the risk of chloride-induced corrosion exists, is to adopt a global design strategy (belts and suspenders) in which the concrete is designed and protected to develop its high quality through low permeability cover, whilst the steel is additionally protected to counteract the possible poor field practices lack of quality control.

Based on some of the positive experience learned from newly constructed structures, the material manufacturers offer a tiered choice of corrosion protective systems for concrete repair with varying degrees of cost. The systems include the use of various protective coatings, cathodic protection, corrosion-inhibiting admixtures, etc. In some cases, combinations of protection systems have been recommended. Several theoretical justifications have been proposed for different protective systems, but all contain elements of speculation and not one of them has demonstrated effectiveness beyond a doubt. Current protection theories are usually resolved into one of three mechanisms or their combinations:

1. Electrochemical barrier between reinforcement and cementititous material to minimize reactive sites (barrier coatings).
2. Cathodic protection in the form of sacrifical anode.
3. Chemical stabilization of the steel surface.

Since their introduction in the repair field, the performance of barrier coatings for reinforcing steel in a corrosive environment has been questioned. One of the major concerns is the effect of partial coating of an electrically continuous rebar. Another concern is the effect of discontinuities such as pinholes, damages, or holidays. Proponents of the method make blanket statements that barrier coatings must be defect-free. Whether or not these statements could be particularly applied to reinforcement in concrete repair is debatable. Because of the problems with barrier coatings, and more recently the appearance of evidence supporting these concerns, serious consideration has been given to other options. One of the options used is rebar protective coating combining two components: barrier coating with inhibitor and barrier coating with zinc as a sacrificial anode [5].

The most serious concern regarding protective systems in concrete repairs is that only a portion of the electrically continuous rebar is being treated. By doing this, we are contributing to the already existing "non-uniformity" in repair system, thereby increasing the risk of corrosion activity in the repaired structure?

4. Corrosion inhibitors

A corrosion inhibiting admixture in concrete is a chemical compound which when added in small concentrations to concrete effectively checks, decreases, or prevents reaction of steel with the surrounding environment. Corrosion inhibiting admixtures, depending on how they affect the corrosion process, can be grouped into three broad classes: (a) anodic, (b) cathodic and (c) mixed, depending on whether they interface with the corrosion reaction preferentially at the anodic or cathodic sites, or whether both are involved.

Anodic inhibitors are materials which function as inhibitors due to their ability to accept electrons. They exert their action by stifling the reaction at the anode. Most of the admixtures in this group are effective only when present in sufficiently high concentrations. The concentration required is often determined by the level of chloride to which the steel will be exposed. When sufficient quantities are used, corrosion occurs, and the intensity is localized, causing severe pitting.

Cathodic inhibitors act either by slowing the cathodic reaction or by selectively precipitating cathodic sites. Materials in this group are strong proton acceptors and their action in contrast to anodic inhibitors is usually indirect.

Mixed inhibitors may simultaneously affect both anodic and cathodic processes. A mixed inhibitor is usually more desirable because its effect is all encompassing, covering corrosion resulting from chloride attack as well as that due to microcells on the metal surface. Since microcell corrosion is characterized by microscopic distances separating anodic and cathodic areas, it is impossible to locate either the anodic or cathodic sites on the reinforcement.

Although many inhibitors of steel corrosion in concrete have been suggested, only a few have been seriously studied for effectiveness and influence on concrete properties. In 1957, Moskvin and Alexeev [6] investigated the corrosion-inhibiting ability of strong oxidizing agents (barium nitrite, sodium nitrite, potassium nitrite, potassium chromate, and potassium dichromate) on steel in normal and porous concrete. These inhibitors, added in amounts varying from 0.5% to 3% from the weight of cement, were found to improve corrosion protection, with sodium nitrite offering the best protection from chloride induced corrosion. Further testing of sodium salts in concrete indicated an increased risk of alkali–aggregate reaction and unsightly efflorescence [7]. Sodium and potassium salts of chromates and benzoates have been shown to reduce the corrosion rate; however, they significantly decrease the compressive strengths of the concrete and mortar to which they were added [8].

In the 1960s, calcium nitrite became available for use as an anodic type of corrosion inhibitor. It had been proposed that calcium nitrite inhibits corrosion by reacting with ferrous ions to form a film of ferric oxide, Fe_2O_3, around the anode according to the following [9]:

$$2Fe^{++} + 2OH + 2NO_2 \rightarrow 2NO + Fe_2O_3 + H_2O$$

One of the serious drawbacks in the use of anodic inhibitors is that the admixtures are effective in maintaining passivity only if present in sufficiently high concentrations. It is speculated that if inadequate quantities are used or if the ratio of the inhibitor to the chloride level is small corrosion becomes intensely localized and the attack is significant [10].

It is generally agreed that calcium nitrite corrosion-inhibiting effect is degenerative in nature. The unbound nitrite ions diminish in concentration as they stabilize the passivation layer of the steel reinforcement. Due to the relatively small amounts in concrete, the admixture tends to be dispersed in the mass rather then at concrete/steel interface.

Another important problem to consider is concrete cracking. Any corrosion attack is most likely to develop as a consequence of cracks or other defects in the concrete, due to a more rapid transport of moisture and aggressive ions in the defect. If the corrosion inhibitor is water soluble, it is likely to be leached away from the defect area, just as the alkali hydroxides are normally leached away from concrete over time. Thus the protective agent may be lost when the aggressive ions reach the embedded reinforcing steel.

A number of proprietary corrosion inhibitors, are currently marketed not only for new construction, but also for repairs of which those based on calcium nitrates are most promising. Incorporated in the concrete mixture, they passivate the steel surface against the action of the chloride ion. Other inhibitors reportedly reduce the sorbitivity of chlorides, even in the presence of cracks.

There is no question that corrosion inhibiting admixtures can be effective in suppressing the rate of corrosion in concrete structures in a variety of situations, when properly used. For this reason, inhibitors are finding their "fit"—not as a panacea for all corrosion problems, but as a way to "buy" time and extend the life of structures [11]. The deterioration of their protective properties with time needs more research. Standards and codes of practice relating to their practical use have to be developed. It must be realized that this is not a structural engineering issue, corrosion and its inhibition are clearly a multidisciplinary field of science and engineering. Knowledge of the chemistry of the environment, the microstructure of the solid, and the distribution of the stresses on or in the solid, etc. are extremely essential.

While these admixtures appear to offer added protection against corrosion in newly constructed concrete structures and lately in concrete repair, there are some concerns and uncertainties related to their use in concrete repairs.

Since the durability requirements of a repair are different and more sever than those of new construction. Corrosion protection in concrete repair systems present special and more complex problems. Reliable information and guidelines on which to base the choice of additional protective strategy, if any, is, at the present time, lacking. For existing structures experiencing corrosion problems, a system approach to the problem is therefore necessary.

In new structures the aggressive attack process can be regarded as a contrast between the exterior environment and the concrete cover to the reinforcement which acts as a defense line for the embedded steel. The attacking agents are always present in exterior environment, and it is up to us to decide whether our protective system is adequate to provide the necessary time before the steel is. If the decision is to strengthen the defense against the corroded extraneous attacking agents, one can use additional protection, including corrosion inhibiting admixtures.

In the case of a repair, the aggressive attack comes from two sides—from exterior and interior environments. In repaired structures with all of the importance of the repair—exterior environment interface, the most critical become repair material—substrate (interior environment) interface.

A complete reliance in concrete repair on corrosion protection practices used in newly constructed structures, including the use of corrosion inhibiting admixtures, may, therefore, become a part of the problem instead of solution to the problem. What happens when corrosion inhibitor is added to the repair material? The local nature of the repair does not address the whole structure's corrosion problem if chlorides or carbonation are widespread. Even if the local repair is adequate with necessary concentration of inhibitor, it can become a clean (noncorroding) cathodic area that stimulates increased corrosion around it. Repair procedures of this type are often characterized by early cracking and spalling in the original concrete adjacent to the "good" repairs.

Another concern is how to maintain the necessary concentration of the inhibitor in the repair phase. It is likely that the inhibitor does not remain in the limited repair area, that it migrates with the water and other ions causing the necessary concentration to be reduced. The porous structure and microcracks in the repair materials and concrete determine their ability to pass moisture under various gradients. The inhibitor solution can also move under a temperature gradient occurring between different parts of the structure. Both moisture and temperature gradients determine the transport of water and other agents, via water, in the repair system. This flow can be significant when the structure is subjected to wetting and drying.

It is also more than likely that chloride ions from chloride contaminated existing concrete (by the transport mechanism described above) will move into the repair phase. In addition, chloride ions from exterior environment will also penetrate into the repair phase. Chloride ions will react with the inhibitor and reduce its critical concentration.

The inhibitor content and its fluctuations within the repair system determines its effectiveness. In the field, the inhibitor content varies in an unforseeable manner. Therefore, it is not possible to make an exact calculation of the effect of inhibiting admixture on the service life of a repaired structure.

After the removal of concrete, reinforcement embedded in it is cleaned from corrosion products and chlorides. However, it is very difficult in practice to remove all corrosion pits, and the possibility exists that the corrosion process will continue.

One method used to “extinguish” chloride pits is to treat the cleaned steel surface with a coating containing an anodic inhibitor. To ensure efficient penetration of the inhibitor the pits should be dried. This can be done, for instance, with a flame beam. However, high temperatures could damage the adjacent concrete.

The key elements for the success of an additional corrosion protection in repair systems is a precise definition of the repair system and its components, a precise definition of the exterior environment, an accurate definition of changes in the interior environment caused by repair, and data from test methods relating laboratory results to field performance.

Existing research and testing methods used for evaluating the effectiveness of protective systems in concrete repair are clearly unsatisfactory. One of the reasons for this is that the tests are related to newly constructed structures and cannot be synthesized into a complete understanding of actual behavior and effects in repair systems. Although reinforcing bars within a repaired structure constitute an electrically continuous system exposed to quite diverse environments, for unknown reasons most of the research studies carried out so far have been done by exposing the entire reinforcement in more or less uniform exposure conditions (Fig. 7). Thus, the effect of the simultaneous existence of diverse exposure conditions with respect to various segments of the reinforcement has not been evaluated. Also, not all parts of the repaired structure are equally vulnerable to corrosion, and corrosion characteristics under actual conditions cannot be clarified by evaluating them individually and/or independently. Laboratory and experimental testing shall be designed to study repair related issues paying more attention to repair location in the existing structure, its geometry, restraint, and nonuniformity. Various loading conditions need to be included in such testing programs.

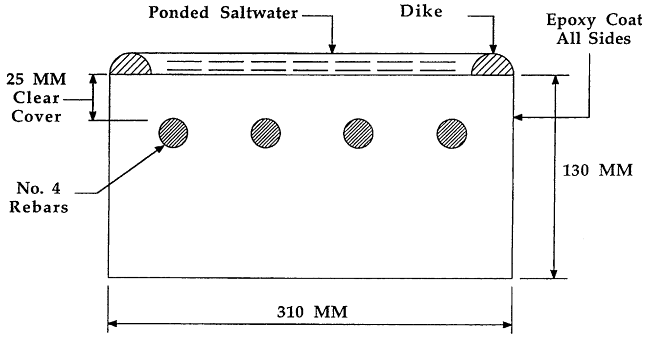

Fig. 7. Corrosion test specimen.

5. Conclusions

(1) Corrosion of embedded reinforcement and its protection in repaired concrete structures is a very complex phenomenon. Many repair failures can be attributed to the lack of complete understanding of the nature and consequences of electrochemical activities in a repair system, and therefore, to an inability to accurately predict the performance of a protective system and service life of a repaired structure.

(2) There are a large number of corrosion protection treatments on the market that claim a variety of properties. Their behavior in protection against corrosion of reinforcement is not well established, and there are no reliable standard test methods to assess their likely performance. Adequate research is required to provide for evaluation of different systems. One needs to know how good the protected repair structure is, and how long it will afford that protection. In order to give confidence in the technology the science should provide the credible basis on which prognosis of performance and longevity can be made.

(3) Overmagnification or poor reproduction of repair systems and exposure conditions, especially interior ones, in laboratory tests, often produce misleading results. How can one expect that the money spent on additional protection of reinforcement in repairs is not wasted, if test methods used to evaluate these protective systems neither reflect the mechanisms of corrosion in repaired structures, nor stimulate the physico-chemical effects that lead to corrosion of steel in a real repaired structure? The research behind some of the currently used test methods is rather narrow.

(4) Investigators of various protection methods are stating that the effectiveness of their methods is always

better in good quality concrete. One can conclude that good quality new concrete and good quality repair are the best protective systems for embedded reinforcing steel from corrosion—this is basics of concrete technology. The protective measures can be taken in addition, but not as substitutes for getting the basics right.

(5) The central theme of this paper revolves not around the truth or falsity of author's views on the several issues; that is irrelevant. What it means is that questions raised are not unsolvable mysteries but simply a proof that we are still in the grouping, study stage. After all as Benjamin Franklin stated, "Well done is better than well said!"

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