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16. Abstract
This report is a literature review of alternative reinforcement materials for concrete. The time period covered is the last 12 years and the review is restricted to metallic reinforcement materials which may or may not be coated. The materials include epoxy coated steels, galvanized steel, corrosion resistant steels, dual-phase steels, and stainless steels. Also included are steels coated with types of coatings (other than epoxy) and steels which use various types of paints for corrosion protection.

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Corrosion Performance of Polymer-Coated, Metal-Clad, and Other Rebars as Reinforcements in Concrete: Literature Review

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Research Project 7-4904
Feasibility of Hot-Dipped (Zinc) Galvanizing and Other Coatings for the Protection of Reinforcing Steel

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in cooperation with the
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Disclaimers

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1. Literature Review of Alternative Metallic Reinforcement for Concrete

1.1 Introduction

One of the most important aspects of an investigation is the literature review that precedes and accompanies it. This allows the researchers to be aware of the most up-to-date information regarding that subject. A very thorough literature review of work associated with epoxy-coated reinforcement (ECR) was carried out during Project 1265.

More than 140 related articles were included in the dissertations of Kahhaleh (Kahhaleh 1994) and Vaca (Vaca 1998) and the final reports for that project. Since that time, studies associated with alternative reinforcement materials have increased tremendously.

Some of the types of materials were summarized in a state-of-the art review about a year ago (Wheat and Deshpande 2001). The paper was included in a previous semiannual report for Project 4904, but is included in Appendix A for completeness.

Most of the articles for the metallic alternatives can be grouped into the following categories: epoxy, galvanized steel, corrosion resistant steel, dual-phase steels, stainless steels, and other systems of interest. Some of the articles are briefly described below.

1.1.1 Epoxy

- "Corrosion Protection Properties of Epoxy Coating on Reinforcement Steel in Concrete—Three Years of Field Exposure" (Sederholm 1996).

  A study was done to determine the effect of the size of coating damage. The outdoor tests involved continuous electrochemical measurements on simulated corrosion cells of epoxy-coated steel rods in chloride-containing concrete and the exposure of steel rods (repaired in different ways) in chloride-containing concrete.

- "Low Frequency Electrochemical Impedance for Measuring Corrosion of Epoxy-Coated Reinforcing Steel in Concrete" (Sagues and Zayed 1991).

  The investigation involved modeling partially disbanded epoxy-coated reinforcing steel in concrete.

1.1.2 Galvanized Steel

- "Corrosion Resistance of Galvanized Steel in Concrete" (Thangavel et al. 1995).

  The performance of electrogalvanized steel in concrete under immersed conditions (seawater and potable water) and under weathering condition (indoor and outdoor) was assessed by monitoring the potential during a period of two–three years.

1.2 Various Steel and Steel Claddings

1.2.1 Corrosion Resistant Steels

- "Effect of Aggressive Chloride Environment on Corrosion Resistant Reinforcing Steels Embedded in Concrete" (Banerjee et al. 1997).

  High corrosion resistant (HCR) reinforcement bars, developed through a thermomechanical treatment, were evaluated in aggressive chloride environments in concrete through short-term accelerated tests and long-term field exposure tests.

- "Mechanism of Reinforcement Corrosion in Concrete Structures and its Prevention by Using Corrosion Resistant Rebars — A New Product of Tata Steel" (Singh, Jha, and Chattejee 1995).

  The most suitable composition for a new variety of reinforcing steel bars, given the brand name TISCON-CRS, was extensively tested for its compatibility in the laboratory. Field tests were also carried out in marine and industrial environments to evaluate its performance.

- "Development of Corrosion Resistant Steel Bars for Prestressed Concrete in Saline Environments" (Shiraga et al. 1992).

  The effects of Ni, Cr, Mo, Cu, and W alloying additions in boron steel (NC32B) were examined to develop steel bars with good corrosion resistance for prestressed concrete in saline environments.

1.2.2 Dual-Phase Steels

- "The Application of Dual-Phase Steels for Corrosion Resistant Reinforcement of Concrete" (Thomas 1996).

  Work conducted at the University of California-Berkeley demonstrated the excellent mechanical properties and superior corrosion resistance of dual-phase steels that make the alloys particularly advantageous for use as bar, rod, and wire reinforcement in concrete structures.

1.2.3 Stainless Steels

- "Effect of Chemical Composition on Corrosion Behaviour of Stainless Steels In Chloride-Contaminated and Carbonated Concrete" (Bertolini et al. 1999).

The paper deals with the corrosion resistance of stainless steels in chloride-contaminated and carbonated concrete. The stainless steels studied were 304L, 316L, 430, and 410.

- "Experiences on Stainless Steel Behaviour in Reinforced Concrete" (Bertolini et al. 1998).

  The paper describes the behavior of stainless steel coupled with carbon steel in order to study the corrosion behavior of reinforced concrete structures in which stainless steels are used only for partial substitution of carbon steel. The effect of galvanic coupling between stainless steel and active carbon steel in chloride-contaminated concrete was studied.

- "Practical and Economical Aspects of Application of Stainless Steel as Reinforcement in Concrete" (Klinghoffer et al. 1999).

  The behavior of stainless steel in connection with carbon steel was evaluated in order to study the consequences of galvanic coupling for corrosion of reinforced concrete structures in which stainless steel bars are used for limited parts of the reinforcement.

- "Application of Austenitic and Duplex Stainless Steels for Concrete Reinforcement for Improved Corrosion Resistance" (Anon 1998).

  The behavior of two duplex Italian stainless steel grades, together with different austenitic Italian stainless steel grades were compared with a commercial unalloyed Italian steel commonly used for concrete reinforcement in civil buildings.

- "Corrosion Behavior of Welded Stainless Reinforcing Steel in Concrete" (Nurnberger, Beul, and Onuseit 1995).

  Electrochemical investigations and field tests were carried out on reinforced concrete elements containing stainless steel in welded applications.

- "Corrosion Behaviour of a Duplex Stainless Stainless Steel in Chloride-Contaminated Concrete" (Pastore and Pedeferri 1991).

  Electrochemical tests were carried out to study the corrosion behavior of a 23Cr4Ni duplex stainless steel, as well as 304 and 316 stainless steels in chloride-contaminated concrete with up to 3% chlorides by weight of cement.

1.3 Other Systems of Interest

- "Coatings for Corrosion Protection of Steel Used in Reinforced Concrete" (Sanjuro et al. 1992).

Silicon and silicon-titanium protective coatings were deposited on steel rebars using a novel chemical vapor deposition technique. Selected coated samples were tested for corrosion resistance by chemical and electrochemical techniques.

- "Zinc-Silicate Thermal Spray Coatings: Properties, Processes and Applications" (Krepski 1992).

  A zinc-silicate composite thermal spray coating was examined in simulated concrete pore solution.

- "Using Electroless Nickel to Coat Reinforcing Steel in Chloride-Contaminated Concrete" (Sanchez et al. 1998).

  Steel rebars were coated in an electroless Ni bath for various times and subjected to different heat treatments. The Ni-coated bars were embedded in concrete samples with NaCl concentrations at 0, 0.10, 0.15, and 0.20% based on concrete weight.

A more detailed summary of articles of specific interest to Project 4904 is given in Chapter 2. That chapter begins with a summary of articles that give descriptions of techniques used to study the corrosion of steel in concrete.

2. Literature Review of Corrosion of Steel in Concrete (Compendex 1990–March 2000)

2.1 Literature Review on Corrosion Evaluation and Testing

In this chapter, literature review on various corrosion measuring techniques will be discussed. Some of them include AC impedance response, multi-electrode electrical resistivity array, polarization resistance technique, acoustic emission (AE) technique, galvanostatic transient methods. A brief summary of this literature review is presented in Chapter 5.

"A Study of Comparison of Methods for Measuring the Electrochemical Corrosion of Steel in Concrete" (Hassanein et al. 1999)

A study was conducted on different methods to measure corrosion. A brief summary is as follows:

- The use of various electrochemical techniques is accessed theoretically and experimentally to obtain information on the corrosion state of steel in concrete. The transient response produced by potentiostatic, galvanostatic, and coulostatic perturbations together with the AC impedance response may all be analyzed to give information on the interfacial capacitance and polarization resistance describing the steel-concrete interface.

- Except for the coulostatically induced transient, these responses also contain information on the electrolyte resistance. Because of the slow transient behavior of steel in concrete, the measurement of AC impedance data in the frequency-domain may require a long measurement period. Nearly complete galvanostatic and coulostatic transients also may require long measurement periods.

- However, in the case of the coulostatically induced transient, the duration of the perturbation is very small. Thus, any perturbation-induced changes in the corrosion state of the steel are limited. Potentiostatic transients are generally recorded in the shortest time period (typically 30 seconds), the perturbation again being applied while the transient is recorded; unlike the other methods, this measurement period is relatively insensitive to the corrosion rate. In theory, the data obtained by all the transient methods may be converted from the time domain into the frequency domain to give the impedance spectrum. Coulostatically induced transients offer the most advantages in this respect.

"Study of Nondestructive Measurement of Corrosion State of Reinforcing Steel in Concrete" (Monteiro et al. 1998)

Monteiro et al. studied non destructive measurement of corrosion in 1998. A brief summary is as follows:

- This paper presents a new nondestructive method that uses a multi-electrode electrical resistivity array to measure the complex impedance along the surface of a concrete structure to determine the position of the reinforcing bars and their corrosion state.

- A laboratory demonstration of this method was conducted on a concrete block with four embedded steel reinforcing rods, each with a different surface preparation to simulate a variety of conditions: corroded, clean, coated bar, and gold-plated. The gold-plated bar was intended to represent a condition of complete chemical inertness and the painted bar was intended to represent the condition that should, in principle, offer only capacitive coupling to the concrete.

- The surface spectral resistivity method was successful to locate the bars and distinguish between the different surface impedances of the bars; it can thus be concluded that the method can be a useful tool in assessing corroded reinforcement in concrete structures (Monteiro et al. 1998).

"Review of Field and Laboratory Experience with Electrochemical Methods for Assessing Corrosion of Steel in Concrete" (Videm 1997)

Videm reviewed electrochemical methods of assessing corrosion. The observations are noted below:

- The electrochemical techniques discussed are: potential mapping with reference electrodes at the surface, corrosion potential monitoring with reference electrodes embedded in the concrete, potentiodynamic scans, potentiostatic polarization, galvanostatic pulse technique, AC impedance spectroscopy, and monitoring of electrochemical noise.

- Laboratory experiments were carried out in alkaline solutions, in mortar slabs with and without chloride additions, and at an 840-m-long (2756-ft-long), 16-year-old bridge at the coast of northern Norway. A very complex electrochemistry of iron in alkaline media takes place because of the very low volume of pore water in contact with the steel. Due to the low volume, even very small impressed polarization currents alter the composition of the environment adjacent to the steel. This complicates the interpretation of the electrochemical tests, leading to a series of disadvantages.

- It was concluded that the standard electrochemical techniques for determination of the corrosion rate in aqueous solutions do not function well for steel in concrete, at least not for routine applications (Videm 1997).

"Study of Electrochemical Noise Technique for the Prediction of Corrosion Rate of Steel in Concrete" (Katwan et al. 1996)

Katwan et al. studied electrochemical noise technique. A brief summary is as follows:

- A research program was undertaken to examine the limitations and applicability of the Electrochemical Noise Technique (ECN) for the determination of corrosion rates of steel reinforcement. The measurements were made on full-scale reinforced concrete beams under cyclic and static loading and exposed to a corrosive environment.

- Results from short-and long-term tests suggest, rather surprisingly, that for a given test condition, equal accuracy in predicting the corrosion rate can be obtained from the standard deviation of the potential noise and the electrode potential. There are indications, however, that valuable qualitative information about the state of corrosion may be obtained by means of potential trace (Katwan 1996).

“An Estimation of Steel Corrosion Rate in Reinforced Concrete Using Equivalent Circuit Fittings of Impedance Spectra” (Gu and Beaudoin 1998)

Gu and BeaudoinBeaudoin researched impedance spectra in 1998, and the following observations were made:

- Three equivalent circuit models were utilized to fit the alternating current (AC) impedance spectra obtained from the 5-year-old, “lollipop-like” reinforced concrete samples. The RC parameters obtained from two of the equivalent circuit fittings were compared. The differences in polarization resistance and double layer capacitance were evaluated. The variation in the values of these elements was found to be up to 70%.

- These two parameters also were determined from the fitting of the low-frequency portion of the corresponding impedance spectrum for the third equivalent circuit, and the differences were within 40%. The other RC parameters and their relationship with Rp also were discussed.

- Finally, the corrosion rates of the samples, determined from both the AC impedance and linear polarization methods, were compared and the differences in this study were found to be about 100% (Gu and Beaudoin 1998).

“The Use of Acoustic Emission Technique for Detection of Reinforcing Steel Corrosion in Concrete” (Li et al. 1998)

Li et al. studied the application of acoustic emission technique for determination of steel in concrete. The following observations were made:

- The feasibility of using acoustic emission (AE) technique in rebar corrosion detection is studied. The correlation between the characteristics of the acoustic emission events and the behavior of the rebar corrosion in HCl solution is examined. The possibility of the corrosion detection of rebar inside concrete is investigated using an accelerated corrosion experimental method (Li 1998).

"Review of Potentiostatic Transients Applied to the Corrosion of Steel in Concrete" (Glass et al. 1997)

Glass et al. reviewed potentiostatic transients applied to corrosion and made the following observations:

- Potentiostatically induced current transients obtained on a range of reinforced concrete specimens were studied to give approximate values of the polarization resistance and interfacial capacitance. The polarization resistance was compared with the values obtained using more conventional DC methods of analysis. Though it was consistently lower, it was within the error normally attributed to the polarization resistance method of corrosion rate determination.

- The interfacial capacitance values determined increased from passive steel to active steel. This has a dominant effect on the time required for potentiostatically induced current transients to reach a steady state with a longer time being required by actively corroding steel.

- By contrast, the potential decay time constants describing galvanostatically or coulostatically induced potential transients decrease with an increase in corrosion rate. Values less than 25 s for active specimens and greater than 40 s for passive specimens were determined in this work (Glass et al.1997).

"Analysis on Modeling the Time-Dependent Response to External Polarization of a Corrosion Macrocell on Steel in Concrete" (Kranc and Sagues 1997)

Kranc and Sagues analyzed time-dependant response to external polarization in 1997. A brief summary is as follows:

- A numerical prediction of the time-domain response to external excitation of a system with macroscopic but unevenly distributed corrosion is presented. Model development for a corrosion macrocell on a steel bar in concrete subjected to a potential-step excitation is used as an illustration of the computational approach. The electrolyte is assumed to be purely resistive, while the metal-steel interface is subject to nonlinear polarization boundary conditions, including Butler-Volmer kinetics for the cathodic and anodic reactions (Kranc and Sagues 1997).

- A purely capacitive charge storage mechanism is assumed for the metal-electrolyte interface. The polarization of the cathodic reaction is subject to non-uniform mass transport through the electrolyte. The performance of the model is demonstrated in a simulated polarization experiment. Applications of the model for determining the capabilities of electrochemical test techniques for steel in concrete are examined.

"Analysis of Galvanostatic Transient Methods Used to Monitor the Corrosion Rate of Steel in Concrete" (Glass et al. 1992).

Glass et al. analyzed galvanostatic transient methods to study their application in corrosion of steel in concrete. The following conclusions were made:

- The sensitivity of the time constants describing galvanostatically induced potential-time transients to corrosion rate changes was examined on steel embedded in concrete. The shape of the transients changed with changes in corrosion rate. However, the decay was not an exponential function, which would be expected if it were determined by activation-controlled reactions.

- The time constants resulting from an assumed exponential decay were insensitive to corrosion rate changes. However, a proposed empirical function, which fitted the transients more accurately, produced time constants that were inversely proportional to the corrosion rate of active steel. Generally, potential-time transients are expected to be insensitive to specimen area and this may prove to be an advantage when monitoring the corrosion rate of an unknown or variable steel area (Glass et al. 1992).

"A Study of Relationships between Anodic Polarization and Corrosion of Steel in Concrete" (Baweja et al. 1993)

Baweja et al. studied anodic polarization and its application to corrosion. The results are as follows:

- There is as yet no method of assessment that would enable the rapid and accurate prediction of the extent of corrosion of reinforcing steel in concrete on site. Half-cell potential techniques commonly used in situ give only probabilistic information on corrosion activity.

- Research effort is thus needed to assess more accurately the corrosion characteristics of steel in concrete with an ultimate view of site application. Long-term investigations on chloride-induced corrosion of steel reinforcement have been conducted on a series of concrete slab specimens to establish relationships between electrochemically induced corrosion of steel reinforcement.

- Potentiodynamic anodic polarization procedures were used to monitor corrosion of steel reinforcement in concrete slab specimens over a period of 4 years. A statistically significant relationship between the area under the corrosion current-time relationship and the weight loss of steel reinforcement was established. Assessments of corrosion rates of steel in the concretes studied were thus verified. Reinforcement corrosion was found to be localized under the high chloride conditions occurring mainly in an area adjacent to the chloride source (Baweja et al. 1993).

"Field Measurement of the Corrosion Rate of Steel in Concrete Using a Microprocessor-Controlled Unit" (Broomfield 1996)

Broomfield studied a microprocessor-controlled unit for field measurement of corrosion rate. A brief summary is as follows:

- This is the principle of corrosion rate measurement by the linear polarization resistance method: the equipment measures the half-cell potential, applies a small current, and measures the change in potential.

- The corrosion rate is proportional to the applied current divided by the potential shift (Broomfield 1996). Using the technique in the field on reinforced concrete structures is complicated because the area of measurement must be defined and readings fluctuate with the weather conditions.

- This paper describes the use of a corrosion rate device in Europe and the USA on bridges, buildings, and other structures. Its application for measuring the effectiveness of chloride removal and other rehabilitation techniques is discussed.

"Evaluation of Corrosion of Steel in Concrete Structures by Magnetic-Based NDE Techniques" (Ghorbanpoor et al. 1996)

Ghorbanpoor et al. studied NDE techniques for evaluation of corrosion in steel. A brief summary is as follows:

- Corrosion damage of steel in concrete structures is a major concern. NDE techniques based on variations in induced magnetic fields due to loss of steel have been shown to be an effective tool. This paper includes results from laboratory investigation, field tests, and numerical analysis based on this concept.

- Test specimens included reinforcing bars and prestressing cables with simulated flaws as well as flaws from real corrosion. Variations in the magnetic field were recorded as electrical signals that were characterized to aid in the detection of corrosion and evaluation of the condition of steel in concrete.

- It was found that the amplitude of the signals could be related to the extent of the corrosion (Ghorbanpoor 1996). Loss of cross sectional area in bars and cables of approximately 3% could be detected by the technique. The results of a finite element analysis yielded a good agreement with those from the experiment. The technique offers significant capabilities for field assessment of the condition of steel in concrete structures.

“Analysis of Corrosion Monitoring of Steel Rebars in Concrete Structures by AC Impedance Method” (Yokota et al. 1996)

Yokota et al. used the AC impedance method to monitor corrosion in 1996. The following observations were made:

- Corrosion monitoring by AC impedance has been investigated to evaluate on-site corrosion rates of concrete reinforcing steel bars and to estimate the service life of concrete structures.

- A new corrosion monitoring method has been developed to measure the corrosion rates of rebars in only a short time. It takes only a few minutes to obtain a corrosion rate for rebars by measuring impedance at two frequencies.

- Further, a portable monitoring apparatus has been successfully made for the purpose of on-site measurements of corrosion rates of rebars. This apparatus was applied to rebars in real concrete structures. Corrosion rates estimated by this apparatus had an almost linear correlation with measured corrosion rates. These results proved that this newly developed method and apparatus are able to evaluate on-site corrosion rates of rebars in real concrete structures (Yokota et al. 1996).

“Comparison of Corrosion Rate–Measuring Devices” (Sehgal et al. 1992)

Sehgal et al. compared several corrosion rate–measuring devices and made the following conclusions:

- The principles of the various corrosion rate–measuring instruments (3LP, Nippon Steel Company, and GECOR devices) are presented. The corrosion rate determined by these devices is compared with that obtained by standard electrochemical and nonelectrochemical corrosion rate–measuring methods (Sehgal 1992).

- For corroding steel coupons in acid, similarities were found between the electrochemical and nonelectrochemical rate–determining systems, but for passive specimens, the systems produced different results. A linear relationship was observed between the results obtained by the Nippon device and impedance spectroscopy for small mortar specimens irrespective of the test solution, exposure to solution, or test cycle. The significance of this relationship is discussed. Testing of large concrete specimens shows that, for passive steel-in-concrete systems, all devices were incapable of confining the signal distribution from the counter electrode to the rebar area directly below the counter electrode when the size of the working electrode far exceeded that of the counter electrode.

- The reason may be either the inherent difficulty in confining signal distribution in a passive steel-in-concrete system or the small size of the counter electrode used.

- However, for an active system, the confinement resulted in calculated Rp values that are much closer to the actual average rate.

"Reference Half Cells for Monitoring Corrosion Condition of Steel in Concrete" (Ali 1990)

Ali studied reference half cells to monitor corrosion of steel in concrete. Some conclusions are as follows:

- Use of half-cell potentials for monitoring corrosion condition of steel in concrete structures is a well-established technique. Once any external sign of corrosion appears on the concrete, a fairly major repair is necessary. Thus, any method of nondestructively ascertaining the probability that reinforcement is corroding at an early stage as possible is of a great use to engineers (Ali 1990).

- The half-cell technique is a useful tool in this respect. When used with other test methods, it allows for a more complete picture of damaged structures. Moreover, commissioning a particular cathodic protection (CP) criterion for protecting steel-in-concrete structures relies on the half-cell potential technique.

- Thus, the importance of corrosion detection and corrosion inhibition (CP) necessitates the selection of suitable half cells. Commercially available reference half cells are a copper–copper sulfate half cell, a silver–silver chloride half cell, a less-used zinc–zinc chloride half cell, and a saturated calomel half cell.

"Determination of the Corrosion Rate of Steel in Concrete Using Polarization Resistance Test" (Rozental 1989)

Rozental studied polarization resistance test to study corrosion of steel in concrete. A brief summary is as follows:

- The corrosion rate of steel in concrete specimens was studied. Concrete specimens with two steel rods with lead soldered to their ends were used. After preparation, the specimens were held for 28 days in a normal storage chamber and then immersed in a 3 M NaCl solution. The specimens were held in a chamber with a relative humidity of 70–85% at room temperature, with polarization curves being recorded.

- The results of the study agreed with the corrosion rates obtained by other methods (Rozental 1989).

2.2 Literature Review of Coatings, Claddings, and Various Other Steels as Reinforcements in Concrete

In this section, literature reviews on coatings and claddings are described in brief. A summary of this literature review is presented in Chapter 5. Some of the coatings, claddings and other systems considered here are epoxy, galvanized, PVC, copper, stainless steel, dual-phase steel, recycled steel, silicon and silicon-titanium coatings, cross-linking polymer coatings, and others.

2.2.1 Literature Review of Epoxy-Coated Reinforcing Steel

"Estimating the Service Life of Epoxy-Coated Reinforcing Steel" (Weyers et al. 1998)

Weyers et al. researched epoxy coatings on steel. A short description is as follows:

- In this study, corrosion protection performance of fusion-bonded, epoxy-coated reinforcing steel (FBECR) was evaluated in chloride-doped simulated concrete pore water solutions and field structures. Results indicate that a different corrosion protection failure mode exists in the field than in short-term laboratory studies.

- In laboratory studies, the chloride is right at the bar surface area, and the degree or corrosion protection is a function of the quality of the coating.

- In contrast, in field structures, the epoxy coating disbonds from the steel in moist-wet concrete. The rate of epoxy disbondment and the chloride concentration at the bar depth determine if the chloride corrosion threshold limit is reached before or after the epoxy disbonds.

- If the coating is disbonded when the chlorides reach the corrosion threshold limit, corrosion takes place under the coating in an acidic environment and the corrosion protection of FBECR is nil. In Virginia, FBECR may provide protection for about 5% of the bridge decks and thus FBECR is not a cost-effective corrosion protection system for Virginia bridges (Weyers et al. 1998).

"A Study on Extending Building Life with Fusion-Bonded Epoxy" (Poon and Tasker 1998)

Poon and Tasker studied fusion-bonded epoxy coatings. They made the following conclusion:

- The application of fusion-bonded epoxy coatings (FBEC) bolsters the life of a building by preventing corrosion, and it decreases the amount of maintenance a building requires. FBEC has been successfully used in Hong Kong for several years. Both the Hong Kong S.A.R. government specification for buildings and for civil engineering approve its use as an effective anticorrosion system.

"An Overview of Corrosion Resistant Epoxy-Coated Reinforcing Steel" (Mathey et al. 1994)

Mathey et al. researched epoxy coatings on reinforcing steel.

- This paper describes research conducted in the 1970s to evaluate and develop criteria for nonmetallic coatings to protect steel reinforcing bars embedded in concrete bridge decks from the corrosive action of chlorides.

- The objectives of the research, the technical challenges faced, the conduct of the research, and how the results were implemented for improvement of structural engineering practice are discussed in depth. Also, reasons for the successful transition from research to field application are explored (Mathey et al. 1994).

"Study of Various Factors Affecting Cathodic Disbondment of Epoxy Coatings for Steel Reinforcing Bars" (McHattie et al. 1996)

McHattie et al. studied cathodic disbondment of epoxy coatings. A brief summary is as follows:

- According to this paper, fusion-bonded epoxy coatings have been used successfully for more than 20 years to prevent corrosion of concrete-reinforcing steel. Recent attention in the epoxy-coated rebar (ECR) industry has focused on service in hot/wet environments. New specifications mandate quality control programs that include cathodic-disbondment testing.

- Many systems are available to meet the new industry requirements, including chromate and nonchromate surface treatments, coatings for prefabricated rebar, and developmental coatings that combine bendability and good adhesion retention. Beyond the choice of a coating system, various factors play a role in the cathodic-disbondment resistance of ECR.

- The application temperature, thickness of the coating, steel surface preparation, and contamination are vital factors. If a surface treatment is used, the weight of treatment applied is important. Finally, the test conditions of time, temperature, and pH have a dramatic impact on the cathodic-disbondment test results for a given system and even on the relative test performance of different systems (McHattie 1996).

"A Summary of the North American Experience Epoxy-Coated Reinforcing Steel" (Manning 1996)

Manning studied epoxy coatings in 1996. A brief summary is as follows:

- Manning combines a brief history of epoxy-coated reinforcing steel in North America with a summary of investigations of its corrosion performance. Epoxy-coated reinforcement was developed in the early 1970s. After demonstration projects in the mid-1970s, the market, largely in the transportation sector, expanded rapidly and epoxy coating became the preferred method of corrosion protection in highway bridges.

- The first evidence of unsatisfactory field performance emerged in 1986 in bridges in the Florida Keys. Isolated examples of corrosion of coated reinforcement were reported from about 1990 onwards, though many field investigations reported good performance as well. Laboratory studies were equally controversial, some predicting good performance and others predicting only a short extension of service life.

- According to this study (Manning 1996), some improvements have been made in increasing the adhesion of coatings and decreasing the number of defects, but the effect on the service life of epoxy-coated reinforcement is uncertain because the necessary and sufficient conditions for effective, long-term field performance have not been defined.

"States Sticking to Epoxy in Rebar Corrosion Debate" (Anon 1994)

A brief outline is as follows:

- During this research, the controversy over how well epoxy coatings protect rebar from corrosion in wet, salty environments had stirred confusion among transportation agencies.

- According to the paper, the Federal Highway Administration has encouraged the use of epoxies for 20 years, but FHWA and many state agencies now are reevaluating their use of the material. Georgia, for example, has stopped using epoxy coating to protect rebar in coastal substructures, and the New York State Thruway Authority has switched to galvanized rebar (Anon 1994).

"A Focus on Improving the Performance of Epoxy-Coated Rebar" (Lampton et al. 1996)

Lampton et al. studied epoxy coatings. A brief description is as follows:

- Prior to this study, certain field experiences involving less-than-expected performance of fusion-bonded, epoxy-coated steel reinforcing bar (ECR) in concrete had led to considerable debate on the long-term effectiveness of the technology. Research precipitated by this controversy has once again ascertained the importance of discontinuities in the epoxy barrier coating and the coating's adhesion to the steel.

- This paper examines parameters affecting the latter of these two performance determiners — what can be done in the epoxy powder coating formulation area and steel surface preparation to improve the long-term adhesion of the epoxy coating to the steel (Lampton et al. 1996).

"A Study of Macrocell Corrosion Testing of Bent Epoxy-Coated Bars in Chloride Solution" (Kahhaleh et al. 1994)

Kahhaleh et al. studied macrocell corrosion testing of bent epoxy-coated rebars. A summary is as follows:

- An investigation was carried out to assess the current U.S. specification limits on acceptable damage to fusion-bonded, epoxy-coated bent bars expressed as percentage pinholes/damage (about 1 to 2%). In an accelerated macrocell corrosion test (caused by alternate wetting and drying cycles), concrete prisms containing coated or uncoated bent bars were exposed to chlorides and observed for two years.

- Data on macrocell corrosion currents, supported by observations from autopsied specimens, indicate that heavily damaged epoxy-coated bent bars (around 10%)

were prone to considerable corrosion activity. The coating bond strength to steel was considerably reduced and underfilm corrosion was progressive.

- Patching damaged areas was not fully effective. The corroded sites, including blisters on the coating surface, were generally found facing voids in the surrounding concrete. Curiously, bars with smaller diameter performed much better than bars with larger diameter bars (Kahhaleh 1994). The report concluded that current U.S. specification limits on allowable damage to coating need to be made more stringent.

2.2.2 Literature Review of Galvanized Reinforcing Steel

"Study on Chloride-Ion Induced Corrosion of Galvanized and Black Steel Reinforcement in High-Performance Concrete" (Gowripalan and Mohamed 1998)

Gowripalan and Mohamed studied chloride-ion induced corrosion of galvanized and black steel. A brief summary is as follows:

- This research deals with the experimental investigation on the effectiveness of the use of high-performance concrete (HPC) and galvanized steel in reducing reinforcement corrosion. Two normal–strength concrete (NSC) mixtures with 28-day compressive strengths of 30 and 40 MPa and two high–strength concrete (HSC) mixtures with compressive strengths of 50 and 80 MPa were used for this study.

- The rapid chloride ion penetration test was used to study the ion penetration and the results were compared with those of long-term immersion tests in 4% NaCl solution over a period of 1 year.

- Half-cell potential measurements were used to monitor the initiation of corrosion. The pH values of HPC pastes and mortars were monitored for 90 days to study the effect of silica fume on the pH of concrete and corrosion initiation.

- The results showed that HPC reduced chloride ion penetration significantly. Silica fume at a 10% replacement level reduced the pH of concrete from 14.0 to 12.8 over a period of 90 days (Gowripalan and Mohamed 1998).

"Study of Corrosion Protection of Steel with Hot-Dip Galvanizing" (Subramanian 1996)

Subramanian studied corrosion protection of hot-dip galvanized steel. A brief summary is as follows:

- The author highlights the problem of corrosion of reinforcing steel in concrete structures and stresses the need for providing coating to the rebars. In particular, the latest information on important technical findings pertaining to hot-dip galvanizing are discussed, including the data on the latest research and development work of India's Associated Cement Companies (Subramanian 1996).

"Study of the Corrosion Resistance of Galvanized Steel in Concrete" (Thangavel et al. 1995)

Thangavel et al. studied corrosion protection of galvanized steel. A brief summary is as follows:

- This study assesses the performance of electrogalvanized steel in concrete under immersed conditions (seawater and potable water), as well as under weathering conditions (indoor and outdoor), by monitoring the potential during a period of 2 to 3 years.

- It is shown that under immersed conditions, zinc undergoes rapid dissolution. It performs better in atmospheric exposure. Whether the zinc is immersed in solution or exposed to the atmosphere, the extent of corrosion increases with the chloride content in concrete (Thangavel et al.1995).

2.2.3 Literature Review of Various Steels and Steel Claddings

"Study Involving Corrosion Susceptibility of Dual-Phase Steel in Concrete" (Trejo et al. 1994)

Trejo et al. studied corrosion susceptibility of dual-phase steel. A brief summary is as follows:

- This paper presents preliminary results on the mechanical and corrosion properties of a Fe-2Si-0.1C-0.1Nb dual-phase ferrite martensite (DFM) steel embedded in concrete. According to this paper, previous research has shown that these steels can attain higher tensile strengths, higher energy absorption, more ductility, better fatigue toughness, weldability, and better corrosion resistance than conventional reinforcement steels.

- This investigation concludes that Fe-2Si-0.1C-0.1 Nb DFM steels containing 18% martensite volume, when embedded in small concrete beams and subjected to an accelerated corrosive environment, are more resistant to corrosion than standard billet reinforcement.

- Thus, they may offer considerable potential as a new economical steel for concrete reinforcement (Trejo et al. 1994).

"Study Involving Application of Dual-Phase Steels for Corrosion Resistant Reinforcement of Concrete" (Thomas 1996)

Thomas studied dual-phase steels and stated the following:

- Dual-phase steels are low carbon content alloys processed to yield microstructures that consist of a mixture of ferrite and martensite. The processing, microstructures, and mechanical properties of dual-phase steels have been studied for several years.

- Dual-phase steels have excellent mechanical properties and superior corrosion resistance that make these alloys particularly advantageous for use as bar, rod, and wire reinforcement in concrete structures (Thomas 1996).

"Research of Corrosion Protection of Reinforced Concrete Members by Using Recycled Steel" (Someh et al. 1996)

Someh et al. studied the use of recycled steel as reinforcement in concrete. A brief summary is as follows:

- There were two objects of focus in this research. The first was the recycling idea of reusing waste steels and the second was to protect corrosion of reinforcing concrete using a natural method.

- The study investigated retarding or inhibiting corrosion of reinforced concrete by reusing steel shavings or steel cans as steel fibers around embedded steel bars as a sacrificial anode.

- The investigation was carried out in a transparent gel. Reinforced concrete specimens indicated that steel fibers from steel cans or steel shavings can become a sacrificial anode to prevent corrosion of steel bars. Additionally, exposed reinforced concrete specimens under severe conditions proved the role of above materials in corrosion prevention, especially for steel cans. Anticorrosion behavior also was observed for embedded steel bars (Someh 1996).

"Study of Corrosion-Resisting Steels in Chloride-Bearing Concrete" (Rasheeduzzafar et al. 1992)

Rasheeduzzafar et al. studied corrosion-resisting steels in chloride-bearing concrete and made the following observations:

- This research evaluates bare mild, galvanized, epoxy-coated, and stainless-clad reinforcing steels in a 7-year exposure site program for corrosion-resistance performance in chloride-bearing concretes. Reinforcing material and chloride content of concrete were the variables. Bars were cast in prismatic specimens of 0.45 water-cement ratio, good-quality concrete containing three levels of chloride: 4, 8, and 32 lb/yd3 (2.4, 4.8, and 19.2 kg/m3, corresponding to 0.6, 1.2, and 4.8% by weight of cement).

- The specimens were exposed to the environment of eastern Saudi Arabia on a site at King Fahd University of Petroleum and Minerals, Dhahran.

- The results indicate that mild steel bars had suffered severe rust-related damage for all three chloride levels with significant loss of section and rib degradation for 8-lb and 32-lb chloride-bearing concretes.

- For galvanized reinforcing steel in equivalent chloride-bearing concrete compared to bare mild steel, there was a decay in the onset of cracking, a reduction in metal loss, and an amelioration in the incidence and severity of concrete failure condition. However, in both 8-lb and 32-lb chloride concretes, there was severe corrosion accompanied by concrete cracking.

- The results show that the use of galvanized steel in concretes with high levels of chloride delays concrete failure by only a finite period of time. Epoxy-coated bars performed exceedingly well as corrosion-resistant steel in 4-lb and 8-lb chloride concretes, as no corrosion and concrete cracking were observed.

- However, for the 32-lb chloride concrete, significant corrosion was observed on the substrate steel below the coating.

- This led to a systematic breakdown of the coating and cracking of concrete. These results indicate that epoxy barrier coatings may have a finite tolerance limit for chlorides. Among corrosion-resisting steels, the best durability performance is exhibited by the stainless-clad reinforcing bars. After 7 years of embedment in 32-lb chloride concrete, no sign of corrosion was observed on any of the bars tested (Rasheeduzzafar et al. 1992).

"Study of Stainless Steel Reinforcing as Corrosion Protection" (McDonald et al. 1995)

McDonald et al. studied stainless steel as corrosion protection in concrete in 1995. A brief description is as follows:

- This paper reviews the work conducted by several researchers in Europe. The review discusses the use of solid stainless steel and stainless steel–clad reinforcing bars for the construction of corrosion-resistant reinforced concrete structures.

- Results of laboratory and field tests from these researchers, as well as the costs associated with the use of such bars, are reviewed (McDonald et al. 1995).

2.3 Literature Review of Other Systems of Interest

"A Study of Various Coatings for Corrosion Protection of Steel Used in Reinforced Concrete" (Sanjurjo 1992)

Sanjurjo studied various coatings for corrosion protection of steel. A brief summary is as follows:

- In this research, silicon and silicon-titanium protective coatings were deposited on steel rebars, wires, and fibers using a novel chemical vapor deposition technique that combines the low cost of pack metallization with the advantages of subhalide chemistry and with the high heat and mass transfer of a fluidized bed reactor.

- The steel samples were immersed in a bed of silicon or silicon-titanium particles fluidized by an argon–0.1% HCl mixture and kept at temperatures ranging from 400 to 750°C (752 to 1382°F). Diffusion coatings were obtained in all cases.

- Various coating rates were obtained at the highest temperatures. Selected coated samples were tested for corrosion resistance by chemical and electrochemical techniques.

- In general, silicon provided some corrosion protection as expected (Sanjurjo 1992). AC impedance measurements in acidic chloride solutions indicated that very thin and very thick silicon coatings were as protective as coatings 1 to 5. The best coatings were obtained when silicon and titanium were codeposited at temperatures around 550°C (1022°C). These coatings increased the corrosion resistance by more than an order of magnitude with respect to the uncoated sample.

"A Study of Coated Steel Reinforcement for Corrosion Protection in Concrete" (Yeomans 1995)

Yeomans studied coated steel reinforcement in 1995 and made the following observations:

- Coated steel reinforcement is widely used in new concrete construction to provide enhanced corrosion protection to the embedded steel. While concrete itself provides natural corrosion protection to steel, this effect may be lost as a result of degradation of the concrete mass or the penetration of aggressive species from the environment through the cover concrete to the reinforcement.

- Coating of the reinforcement reduces the risk of corrosive attack in concrete. Two coating systems namely fusion-bonded epoxy coatings and hot-dip galvanized coatings, are widely applied to steel for this purpose.

- An overview is presented of the characteristics and use of epoxy-coated steel and galvanized steel reinforcement in concrete. The nature of the protection afforded by these coating systems is explained together with their methods of application and relevant codes and standards. A discussion and comparison of typical characteristics of the two system is given. The results of recent research comparing both the accelerated corrosion behavior and the bond and slip performance of black steel, epoxy-coated steel, and galvanized steel reinforcement in concrete is presented (Yeomans 1995).

"Waterborne Corrosion Protective Coatings for Steel and Concrete Based on Polymers Cross-Linking with Active and Reactive Pigments: An Overview" (Tippl 1989)

Tippl studied waterborne corrosion protective coatings. A short description of the research is as follows:

- The author has developed a polymer system that crosslinks with itself. Test results were compared with waterborne protective coatings.

- The second step of these developments was to find reactive pigments that are crosslinking with the system.

- Similar systems are used for concrete protection. The required parameters for successful protection of concrete were discussed (Tippl 1989).

“Testing the Performance of Copper-Clad Reinforcing Bars” (McDonald et al. 1996)

McDonald et al. studied copper-clad rebars. A short description is as follows:

- Several long-term laboratory tests have been conducted showing that copper-clad bars may be a viable option for corrosion protection. This paper discusses the performance of copper-clad bars in concrete in relation to black bars (McDonald, 1996).

“Performance Study of Black, Galvanized, and Epoxy-Coated Reinforcing Steels in Chloride-Contaminated Concrete” (Yeomans 1994)

Yeomans studied black, galvanized, and epoxy-coated rebars in concrete. A brief summary is as follows:

- The corrosion performance of black steel, galvanized steel, and epoxy-coated steel in concrete was investigated in this paper. Samples were exposed to cyclic salt water wetting and drying or to a continuous salt fog.

- Corrosion assessments included half-cell potential monitoring, chloride (Cl-) analysis, and metal loss determinations. Galvanized steel resisted Cl- levels in concrete approximately 2.5 times that which caused corrosion of black steel.

- Zinc (Zn) provided sacrificial protection for a period approximately 4 to 5 times that for the initiation of corrosion of black steel in equivalent conditions. At the cut ends of galvanized bars, the Zn locally protected the exposed steel to a distance of approximately 8 mm (0.315 in.). Epoxy coating imparted excellent overall corrosion protection.

- However, at points of damage to the coating and at the unrepaired cut ends of bars, localized corrosion on the exposed steel occurred over the same interval and to a similar extent as for uncoated steel (Yeomans 1994). In many instances, corrosion proceeded along the bar under the epoxy coating with subsequent detachment of the coating. Repairs to cut ends of epoxy-coated bars did not delay corrosion of the steel substrate substantially.

“A Detailed Study of Epoxy-Phenolic IPN Coating for Concrete and Reinforcing Steel” (Aggarwal et al. 1995)

Aggarwal et al. studied epoxy-phenolic interpenetrating polymer network (IPN) coatings. A brief summary is as follows:

- The coatings based on an epoxy-phenolic IPN system for the protection of concrete structures and reinforcing steel bars have been developed. Properties of the developed coating systems along with their corrosion protection efficacy are discussed in this article.

- It is observed that the developed IPN coating provides excellent protection to concrete structures. The reinforcing steel bars coated with modified IPN have much more life in comparison to uncoated steel bars (Aggarwal 1995). The cost of coating the steel bars with a modified IPN system would be in the range of 15 to 20%.

"Influence of Protective Coatings on Steel-Concrete Bond" (Thangavel et al. 1995)

Thangavel et al. studied the influence of protective coatings on the steel-concrete bond. A brief description is as follows:

- Generally, coatings are recommended to prevent rebar corrosion in concrete structures. It is imperative that these coatings, apart from having corrosion-resistant properties, must be able to develop the necessary bond strength at the rebar-concrete interface for the reliable performance of reinforced concrete structures.

- In this study, the bond behavior of coated bars with two coating thicknesses is assessed and compared.

- From the studies, it is observed that, while the coated steel rebars improved the bond strength when compared with plain mild steel rebars, the galvanizing and epoxy coating reduced the bond strength at higher thicknesses of coatings.

- On the other hand, in the case of inhibited cement slurry coated rebar, the bond strength improves at higher thicknesses of coatings.

"Experiments to Slow Down Corrosion Damage in Concrete: The Use of Organic-Coated, Ceramic-Clad, Metallic-Clad, and Solid Metallic Reinforcing Bars" (McDonald et al. 1996)

McDonald et al. conducted experiments to study corrosion performance of organic-coated, ceramic-clad, metallic-coated, and solid metallic rebars in 1996. A brief summary is as follows:

- The Federal Highway Administration initiated a program to develop corrosion-resistant reinforcing steels with a 75-to 100-year design life for concrete structures using organic, inorganic, ceramic, metallic, and solid metallic bars. A series of tests was conducted, showing that the materials tested in this project were effective in slowing corrosion damage (McDonald 1996).

"Influence of Galvanizing and PVC-Coating of Reinforcing Steels and of Inhibitors on Steel Corrosion in Cracked Concrete" (Nuernberger and Beul 1991).

Nuernberger and Beul studied PVC coatings. A brief summary is as follows:

- Cracked concrete beams of different concrete qualities with carbonized cracks were exposed in artificial seawater, under frost and deicing salt conditions, and in an industrial climate. The reinforcement was composed of black steel, galvanized steel, and PVC-coated steel. For the purpose of additional protection, the concrete was partly mixed with an inhibitor Ca(NO2)2.

- It was found that the inhibitor protects satisfactorily only in the case of the higher concrete quality and not to a high crack width. A protective effect of galvanizing is found in lower chloride contents (< 1.5% relative to cement) and smaller crack widths. The chosen PVC-coating failed because of chemical instability in the alkaline medium concrete (Nuernberger and Beul 1991).

3. Literature Review of Alternative Metallic Reinforcement for Concrete

(Metadex and Compendex 2000–March 2002)

Chapter 2 included a summary of some of the key research associated with the corrosion of steel in concrete in general and alternative reinforcement materials from 1990–March 2000 found in the Compendex search. This chapter will describe some of the work that has taken place since that time. A complete listing from the Metadex search (2000–March 2002) can be found in Appendix B. The work can still be divided into similar categories and much of it is a continuation of work that was initiated during the previous decade. Articles from two other categories have been added, namely articles that have to do with the effect of surface condition and manufacturing process on the corrosion of steel in concrete. The titles of some of the relevant articles are given below.

3.1 Epoxy-Coated Steel

- "Accelerated Testing of Plain and Epoxy-Coated Reinforcement in Simulated Seawater and Chloride Solutions" (Erdogu, Bremner, and Kondratova 2001) *Cement and Concrete Research*, v 31, n 5, May 2001, pp 713–718.

3.2 Galvanized Reinforcing Steel

- "Studies on Corrosion Resistance of Galvanized Reinforcement Bars in Simulated Concrete Solutions" (Saravanan et al. 2001) *Transactions of the Institute of Metal Finishing*, v 79, n 4, July 2001, pp 146–150.

- "Porous Structure of the ITZ (Interfacial Transition Zone) Around Galvanized and Ordinary Steel Reinforcements" (Belaid, Arliguie, and Francois, 2001) *Cement and Concrete Research*, v 31, n 11, Nov. 2001, pp 1561–1566.

"Effect of Bar Properties on Bond Strength of Galvanized Reinforcement" (Belaid, Arliguie, and Francois 2001) *Journal of Materials in Civil Engineering*, v 13, n 6, Nov./Dec. 2001, pp 454–458.

3.3 Various Steels and Steel Claddings

3.3.1 Alloy Steels

- "New Atmospheric-Resistant, Low-Alloyed Steels and Surface Treatment for Construction" (Miyuki 2001) *Zairyo to Kankyo/Corrosion Engineering*, v 50, n 5, May 2001, pp 199–202.

3.3.2 Stainless Steels

- “Service Life of RC Structures in Corrosive Environment: A Comparison of Carbon Steel and SS Bars” (Mani and Srinivasan 2001) *Indian Concrete Journal*, v 75, n 7, July 2001, pp 456–460.

- “Stainless Steel Reinforcement” (Knudsen and Skovsgaard 2001) *Concrete Engineering International,* v 13, n 3, Autumn 2001, pp 59–62.

- “Laboratory and Field Experience on the Use of Stainless Steel to Improve Durability of Reinforced Concrete” (Bertolini and Pedeferi 2002) *Corrosion Review*, v 20, n 1–2, 2002, pp 129–152.

- “Galvanic Coupling Between Carbon Steel and Austenitic Stainless Steel in Alkaline Media” (Abreu et al. 2002) *Electrochemica Acta*, v 47, n 13–14, May 25, 2002, pp 2271–2279.

- “Chloride Threshold Levels in Clad 316L and Solid 316N Stainless Steel Rebar” (M.F. Hurley and J.R. Scully 2002) Paper 02224, Corrosion 2002, National Association of Corrosion Engineers, 2002.

- “Effect of Crack Width and Bar Types on Corrosion of Steel in Concrete” (Hisada et al. 2001) *Journal of Materials in Civil Engineering*, v 13, n 3, May/June 2001, pp 194–201.

- “Inspecting a Half-Century Concrete Pier Made with Stainless Steel Reinforcement in Mexico” (Castro-Borges et al. 2002) Paper 02207, Corrosion 2002, National Association of Corrosion Engineers, 2002.

- “Practical and Economic Aspects of Application of Austenitic Stainless Steel, AISI 316, as Reinforcement in Concrete” (Klinghoffer et al.) Conf. titled Corrosion of Reinforcement in Concrete: Corrosion Mechanism and Corrosion Protection, Aachen, Germany, 1999, European Federation of Corrosion Publications, v 31, pp 121–133, 2000.

- “Oxygen Reduction on Mild Steel and Stainless Steel in Alkaline Solutions” (Jaggi, Elsener, and Bohni) Conf. titled Corrosion of Reinforcement in Concrete: Corrosion Mechanism and Corrosion Protection, Aachen, Germany, 1999, European Federation of Corrosion Publications, v 31, pp 3–12, 2000.

- “Corrosion Behavior of Stainless Steels in Chloride-Contaminated and Carbonated Concrete” (Bertolini et al.) *International Journal for Restoration of Buildings and Monuments*, v 6, n 3, 2000, pp 273–292.

3.4 Some Other Systems of Interest

- "Electroless Nickel Coating for Reinforcing Steel in Chloride-Contaminated Concrete" (Sanchez et al. 2001) *Corrosion Review*, v 19, n 2, 2001, pp 105–118.

- "Effect of Coatings Applied on Rebars in Concrete" (Morris, Vazquez, and De Sanchez 2000) *Journal of Materials Science*, v 35, n 8, 2000, pp 1885–1890.

- "An Introduction to Glass-Reinforced Coatings" (Byrd 2001) *Journal of Protective Coatings and Linings*, v 18, n 11, Nov. 2001, pp 30–37.

- "Effect of Prior Damage on the Performance of Cement-Based Coatings on Rebar: Macrocell Corrosion Studies" (Vedalakshmi et al. 2000) *Cement and Concrete Composites*, v 22, n 6, Dec. 2000, pp 417–421.

- "Effect of Waterproofing Coatings on Steel Reinforcement Corrosion and Physical Properties of Concrete" (Al-Dulaijan et al. 2002) *Cement and Concrete Composites*, v 24, n 1, Feb. 2002, pp 127–137.

- "Water-Disperse Paints (WDP) for Corrosion Protection of Steel and Reinforced Concrete Structures" (Lobkovskij and Luk'yanenko 2002) *Stroitel'nye Materialy*, v 10, Oct. 2000, pp 32–33.

- "Measuring Adhesion of Coatings to Concrete and Steel" (Cunningham and Steele 2000) Paper 00008, Corrosion 2000, National Association of Corrosion Engineers.

3.5 Surface Condition

3.5.1 Pre-Rusted

- "Corrosion of Pre-Rusted Steel in Concrete" (Novak, Chang, and Ayyad 1997) EUROCORR 1997, v I, Trondheim, Norway, Sept. 22–25, 1997, Norwegian University of Science and Technology, Congress Department, Gloshaugen, Trondheim, N-7034, Norway, 1997, pp 511–516.

- "Corrosion of Steel Rebars in Concrete" (Novak, Dong, and Joska 1996) *Koroze a Ochrana Materialu*, 40, (1), 1996, pp 2–7.

- "Influence of Pre-Rusting on Steel Corrosion in Concrete" (Novak, Mala, and Joska 2001) *Cement and Concrete Research*, v 31, n 4, April 2001, pp 589–593.

- "Effect of Degree of Corrosion on the Properties of Reinforcing Steel Bars" (Almusallam 2001) *Construction and Building Materials*, v 15, n 8, Dec. 2001, pp 361–368.

- “Investigation of Scale and Rust on Steel Activation in Model Concrete Pore Solution” (Novak, Mala, and Kouril) EUROCORR 2002, The European Corrosion Congress, Lake Garda, Italy, Sept. 30–Oct. 4, 2001, *Associazione Italiana diMetallurgia*, Piazzale Rodolfo Morandi 2, Milano, I-200121, Italy, 2001.

3.6 Manufacturing Process

- “Effect of Steel Manufacturing Process and Atmospheric Corrosion on the Corrosion-Resistance of Steel Bars in Concrete” (Al-Zahrani et al. 2002) *Cement and Concrete Composites*, v 24, n 1, Feb. 2002, pp 151–158.

4. Experiences of the States

Introduction

In December 2001, a letter was sent to the Department of Transportation in each state requesting information about any research projects or experiences with alternative reinforcement materials. The District of Columbia and twelve states responded (Private Communication, 2002). The states were Alaska, Delaware, Georgia, Hawaii, Illinois, Kansas, Louisiana, North Dakota, Oregon, Pennsylvania, South Dakota, and Washington. Some of the responses are described below.

The District of Columbia, Georgia, and Hawaii

The District of Columbia, Georgia, and Hawaii indicated that epoxy-coated reinforcement was generally the only type of alternative reinforcement being used. This is consistent with many other states as well.

Alaska

The Alaska DOT will soon begin a project to examine the behavior of a number of alternative reinforcement materials and will compare the behavior to that of uncoated or black steel. Their matrix of materials will include ECR, 316L, clad rebar, and MMFX microcomposite steel. The MMFX steel has come out of the development of the dual-phase steels (Thomas; Trejo). Alaska will be using an existing dock facility and will hang separate beams in the submerged, tidal, and splash zones. The beams will be arranged vertically with lead wires brought up to a test station in which potential and current flow can be measured.

Delaware

Delaware is planning a project that will use stainless clad rebar. It is anticipated that it will use experimental bridge funding.

Hawaii

The Hawaii DOT has used ECR in some harbor facilities. One of the sites that was constructed in 1988 showed no traces of corrosion after the coating was peeled from steel removed from cores.

Illinois

The Illinois DOT has had experience with galvanized bars in the foundations and decking of an all-galvanized metal bridge. The bars experienced degradation of the zinc coating by complete absence of the eta phase (pure zinc). When subjected to bending, the zinc coating spalled off, leaving only the hard and very brittle gamma phase, which is expected to provide little galvanic protection.

Illinois has also had experience with copper-clad and stainless-clad bars. While the copper-clad bars were successful, the manufacturer has gone bankrupt. The stainless-clad bars were tubes filled with rail-steel scrap cuttings and then sintered at high temperatures to fuse them. The bars exhibited limited ductility and failed the bend test.

Kansas

The Kansas DOT is actively involved in a project on alternative reinforcement materials that is headed by Dr. David Darwin at the University of Kansas. In addition, they are funding construction of bridges with various types of alternative reinforcement and a field investigation of their performance over a 10-year period.

Louisiana

Louisiana has used ECR for about 15 years, particularly for bridges that could be subjected to salting during winter months. More recently, they have looked into stainless-clad rebars after overcoming some initial problems with bending.

They are currently conducting laboratory testing of the corrosion resistant steel MMFX.

Michigan

The Michigan DOT has worked on stainless, stainless clad, aramid fiber, ECR, and MMFX II. Most projects are still ongoing.

North Dakota

The North Dakota DOT generally uses ECR; however, they constructed a bridge using stainless-clad rebar in the summer of 2001.

Oregon

The Oregon DOT has been quite innovative and has several stainless and stainless-clad bridges. In their correspondence, they also indicated that North Carolina, Montana, Missouri, and Ontario, Canada, had involvement with stainless or stainless-clad bridges as well.

Pennsylvania

The Pennsylvania DOT has been using ECR since 1974. In addition, galvanized rebars were used in approximately 273 bridge decks from 1973 to 1982. In 1982, an in-depth study of 4 galvanized bridges decks and a review of 51 others indicated that there were no major distresses on the bridges decks that could be related back to corrosion of the galvanized rebar.

In another report on ECR and galvanized rebar in 1988, it was concluded that both galvanized and ECR were generally in excellent condition despite high chloride contents in surrounding cement concrete. The report noted, however, that in every galvanized rebar bridge deck evaluated in detail, the remaining coating thickness was comprised almost solely of zinc-iron alloy layers. The free zinc outer layer had been expended.

The Pennsylvania DOT placed stainless-clad bars in a bridge deck built in 1976 and initiated a study on the performance and applicability of solid stainless steel rebars and stainless-clad rebars in 1999.

In 2001, the Department experimentally placed MMFX microcomposite steel bars in a bridge deck and parapets of a single-span structure.

South Dakota

South Dakota routinely uses ECR. They conducted a research project to investigate stainless-clad rebar and chose not to use it. They also investigated MMFX rebar and chose not to use it.

Washington

The Washington DOT routinely uses ECR in their bridge decks. In the summer of 2001, they constructed a concrete pavement section with stainless-clad bars.

5. Summary

As can be seen from this literature review, the subject of alternative reinforcement materials for concrete is a very intense and exciting one. Many materials are being investigated and many test procedures are being utilized. The electrochemical methods that seem to have the most application in the field are polarization resistance and possible AC impedance (or Electrochemical Impedance Spectroscopy).

It is evident that the quality of the concrete plays a major role in the behavior of any type of reinforcement because the concrete is the first defense against corrosion.

ECR, probably the most-used alternative reinforcement material, is particularly susceptible to defects. However, efforts are being made to make the coating more robust. On the other hand, stainless steel has superior inherent corrosion resistance, which is reflected in its performance and its cost. Concerns still remain regarding galvanic corrosion with more active carbon steels even though studies suggest that the concerns in field applications may be unwarranted.

This literature review has shown that there are many viable alternative materials that can possess corrosion behavior in reinforced concrete that is between that of black steel and stainless steel. Because test results vary significantly depending on the test conditions, choices must be made based on the results of many tests, especially those that are more representative of the potential field conditions. Much work is going on to try to develop test procedures that will be able to predict field behavior within a relatively short period of time.

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Appendix A:
Alternative Reinforcement Materials for Concrete—
A State of the Art Review

Paper
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CORROSION2001

ALTERNATIVE REINFORCEMENT MATERIALS FOR CONCRETE-A STATE OF THE ART REVIEW

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ABSTRACT

Many materials have been developed and/or utilized over the last thirty years to respond to the problem of corrosion of steel in concrete. Results of some of the most recent work will be described as well as some of the challenges that still remain.

INTRODUCTION

As steel reinforcement in concrete corrodes, the results can be observed in staining, cracking, and spalling. In addition, the concrete structure is left vulnerable to repeated intrusion of aggressive species. For many years, the problem was addressed primarily by changing the concrete (incorporating additives that led to a decrease in concrete permeability) or changing the surface of the steel. The former could be done with better consolidation, use of admixtures such as fly ash or silica fume, etc. and the latter could be done by adding corrosion inhibitors.

In the past 25 years or so, attention has also focused on a search for more corrosion resistant materials that can be used as reinforcement. A study of more than 40 coatings indicated that epoxy-coated reinforcement (ECR) could provide improved corrosion resistance (1). Subsequent research performed by FHWA seemed to confirm those findings (2). As a result of this and other studies, epoxy-coated reinforcement was used on many structures beginning in the early 1970s.

One of the first investigations to indicate that there could be some problems with ECR took place in the 1980s (3). In his study, it was pointed out that initial or subsequent damage to the ECR could severely diminish its effectiveness. Similar findings were observed by Lee, McIntyre and Hartt (4). These findings were demonstrated quite dramatically in substructures in the Florida Keys.

Since that time, ECR, has been studied by many investigators (5-8). In addition, a conference was held to bring together laboratory investigators as well as practitioners (9). State DOTs were invited and encouraged to share their experiences. The findings were inconclusive. Many states had praise for ECR, while a few states had experienced problems with delamination and early deterioration.

One of the most comprehensive studies of alternative materials was conducted to develop cost effective "new breeds" of organic, inorganic, ceramic, and metallic coatings as well as metallic alloys that could be utilized on or as reinforcement in portland cement concrete (10). More than 33 types of bars were subjected to screening tests in solutions which were used to simulate concrete and salt-contaminated concrete. Most of these solutions were alkaline in nature and usually contained potassium hydroxide, sodium hydroxide, calcium hydroxide or combinations of the above with and without the addition of salt.

Subsequently twelve different bar types were tested in concrete; black bars, three bendable and three nonbendable epoxies, Type 304 and 316 stainless steel, copper-clad, galvanized, and zinc alloy clad bar. In the concrete tests, the bars used were straight and bent, damaged and undamaged, and the concrete was cracked and uncracked. Measurements of macrocell voltages, half-cell potentials, electrical impedance spectroscopy, linear polarization, and mat-to-mat resistances were used in conjunction with visual observations to determine the effectiveness of each system.

The research supported the continued use of epoxy-coated reinforcement, however, it was emphasized that for best performance epoxy-coated bars should be used for both top and bottom mats of a slab. It was also concluded that Type 316 stainless steel reinforcement bars should be considered in extremely corrosive situations such as marine substructures or other cases where costs associated with repair and road closure might be very high.

It should be pointed out that some of the differences in corrosion behavior observed by different investigators are due to experimental differences, such as water/cement, quality of concrete, amount of cover, type of cement and aggregate, age of concrete before exposure, age of concrete before testing, method of testing, etc. Therefore, the reader is encouraged to exercise caution when comparing results from different investigations, since all of the above factors can influence the outcome.

COATED REINFORCEMENT

Many of these materials in the above investigation continue to be tested either alone or in comparison with other materials; in laboratory and field applications. For example, the corrosion protection performance of epoxy-coated reinforcing steel was evaluated in 18 concrete bridge decks in Virginia in 1997 (11). The decks were 2 to 20 years old at the time of the investigation. The ECR inspection consisted of visual examination and damage evaluation, coating thickness and adhesion determination as well as the condition of the steel underneath the epoxy coating. The investigator concluded that the coating had debonded from the reinforcing steel before chloride arrival. The investigator felt that the visible signs of a possibility of corrosion underneath the coating suggested that ECR would not provide any or little additional service life for concrete bridge decks in comparison to black steel.

A study in another state also involved an extensive field and laboratory investigation of concrete bridge decks (12). One hundred and twenty three concrete bridge decks containing epoxy-coated reinforcement, uncoated reinforcement, and various other corrosion protection systems were included in a field investigation. In general, corrosion of the epoxy coated reinforcement was discovered in areas of cracking and shallow cover. In addition, holiday testing indicated that in some instances as many as 31 holidays per meter were created after casting. This number was reduced by improving concrete practice, but shows a potential source of problems. The results of sixteen specimens subjected to cycles of exposure in the laboratory evaluation indicated that if the mat to mat resistance was greater than 5000 ohms, then over the 48-week period, no corrosion activity was observed. The investigator concluded that a high mat to mat resistance could be obtained by the use of epoxy-coated reinforcement with limited damage to the coating.

In another study which described the history and use of ECR, improvements in adhesion as well as efforts to reduce defects were described (13). It was mentioned that the effect of these improvements on service life is still uncertain because the conditions which allow for effective long-term field performance are not completely defined.

In an investigation which compared epoxy-coated and galvanized steel with black steel, differences in the mechanisms of corrosion in each system were described. In particular, research comparing the accelerated corrosion behavior of the three systems was presented (14). Concrete cylinders with either black steel, hot dip galvanized steel or fusion bonded epoxy coated steel bars were exposed to a cyclic wetting and drying in 3.5% salt solution and continuous salt fog. It was concluded that epoxy coating provided excellent corrosion protection if the coating remained intact. Holidays and points of minor damage continued to be a problem. Galvanized reinforcement could tolerate chloride levels at least 2.5 times higher than those causing corrosion in black steel under equivalent conditions and could delay the onset of corrosion on the order of 4-5 times that for the corrosion of black steel. It was also concluded that duplex coatings, a combination of either a paint or a fusion bonded powder over galvanizing, could extend the life of the base steel for longer than the sum of the lives of the coatings alone.

In a study of three coatings that are representative of those commonly used during the repair of concrete affected by corrosion in the coastal regions of Argentina, an epoxy rust conversion coating, a zinc rich epoxy, and a sprayed zinc coating were evaluated (15). Two exposure conditions were investigated; immersed in a saline solution (wet) and exposed to an indoor atmosphere (dry). The rebar corrosion potential, the corrosion rate, and the electrical resistance between bars were measured during approximately 800 days. All coatings provided satisfactory performance in the dry condition, while the performance in the wet condition depended on the particular formulation. The rust conversion coating increased the corrosion rate of the reinforcing steel and thus was not recommended. Bars coated with epoxy zinc-rich and sprayed zinc exhibited corrosion potential values typical of zinc in the active state and the investigators interpreted this to mean that the coatings provided a sacrificial type of cathodic protection to the bar.

To address some of the deficiencies in epoxy-coated bars, many alternative coatings have been researched (16). For example, waterborne corrosion protective coatings for steel and concrete based on polymer cross-linking with active and reactive pigments were reported. Test results were compared with usual waterborne protective coatings and the idea of modifying these coatings for concrete applications was proposed. Work is also ongoing on modifications to epoxy formulations that will make the coatings more resistant to damage (17). Other coatings such as nylon (18) and PVC (19) have also been proposed and are currently being investigated (20).

MODIFIED CARBON STEELS AS REINFORCEMENT

Dual-phase steels are low carbon content alloys which are processed to yield microstructures consisting of a mixture of ferrite and martensite. Compared with conventionally processed plain carbon steels, these alloys are reported to have high strength, good ductility, excellent cold formability, and excellent corrosion resistance (21-22). Based on currents measured during macrocell tests, their developers believe their improved corrosion resistance could eliminate the need for protective coatings with considerable cost savings.

High corrosion resistant (HCR) reinforcement bars, developed by Steel Authority of India Limited through thermomechanical treatment are reported to have superior corrosion resistance compared to conventional cold twisted and deformed bars (23). These bars have lower carbon and manganese contents than typical cold twisted rebars and small additions of Cu, Cr, and Ni to improve corrosion resistance. The corrosion behavior of these bars was investigated in aggressive chloride environments in concrete through short-term accelerated tests and long-term field exposure tests. Galvanostatic tests conducted with admixted chloride and a synthetic sea water environment under short duration tests showed superior resistance of the HCR bars. Long duration (583 days) field tests in marine conditions also revealed much lower corrosion rates for the HCR bars.

STAINLESS STEELS AS REINFORCEMENT

The development of duplex stainless steels (DSS) has also resulted in reinforcement bars that may provide enhanced corrosion protection in concrete. Duplex stainless steels with a high content of N have several advantages (24). The Ni-free DSSs in which nickel is completely replaced by nitrogen offer higher strength, improved weldability, and improved corrosion resistance. While they are not cheap, they could find applications where high strength and corrosion resistance are required.

While it is clear that stainless steels possess enhanced corrosion protection, concern is often raised about galvanic corrosion associated with stainless steel/black steel connections in concrete. These effects have been described and some investigations such as Seibert (25) have indicated that the currents are quite high, while others have suggested that they are either not as high as might be expected or that they can be substantially minimized (26). In Seibert's study, both uncoupled 316 stainless steels and duplex stainless steel (M33) showed excellent corrosion resistance in chloride contaminated mortar cylinders as well as in simulated concrete pore solutions with chloride concentrations up to 20%. Overall, however, coupling of stainless steel and black steel reinforcement was not recommended.

FIBER REINFORCED PLASTICS AS REINFORCEMENT

The severe corrosion problems that can be associated with metallic materials in concrete have caused some researchers to investigate non-metallic materials. In particular, fiber reinforced plastic (FRP) reinforcement materials of composites where the fiber is either glass, carbon, or a hybrid have become very popular (27-28). If correctly applied, these composites are expected to result in significant benefits related to cost and durability (29). Advantages include high strength and stiffness to weight ratios, controllable thermal expansion and damping characteristics, electromagnetic neutrality, and resistance to corrosion and chemical attack.

In a study of deterioration mechanisms of steel and FRP reinforcement in aggressive environments, steel and galvanized steel in concrete with and without silica fume additions as well as glass (FRP) and aramid (FRP) in acidic and alkaline solutions were studied (30). The use of galvanized steel only appeared to offer better protection than silica fume concrete alone with ordinary steel. Scanning electron microscopy (SEM) examination of aramid FRP in an epoxy matrix showed that aramid fibers and matrix could be leached out after immersion in 0.05 M sulfuric acid for 460 days. It also showed that the matrix absorbed water by diffusion. Aramid (FRP) rods made of epoxy matrix were relatively durable in an alkaline environment but not in acids or water. Aramid FRP made of vinly ester had higher absorption rates as much as 10 times those made with epoxy resin matrix. While the behavior of FRP reinforcement in alkaline environments is of primary concern for applications in concrete, questions about exposure to other environments during various stages of preparation or prior to casting in concrete have resulted in interest in the behavior in acidic and other aqueous environments as well.

All of this is a reminder that while the issue of corrosion may be addressed with the use of FRPs, another set of concerns is raised, namely, moisture absorption, mechanical properties, bond strength, design criteria, long-term durability, etc. This latter matter was addressed in a study of the time dependent behavior of reinforced concrete members with carbon fiber reinforced plastics (CFRP) under sustained load (31). In this investigation, concrete beams and columns were instrumented and monitored to observe the change in the behavior due to the creep and shrinkage of concrete. An analytical method was developed to predict the long term behavior of the CFRP reinforced concrete members. Other issues are compression properties (32) the bond behavior and design recommendations if FRP rebars are used in concrete (33) and of course, durability (34). Nevertheless, FRP reinforcement is being used in a number of applications (35) and laboratory and especially field testing will ultimately answer many of the questions that have been raised. The McKinleyville Bridge in West Virginia is the first vehicular bridge in this country whose concrete deck is reinforced with FRP rebars. It was load tested and is continuing to be monitored (36).

CONCLUSIONS

The search for alternatives to black reinforcing steel has unleashed interest in all types of materials. Some of these are ordinary steels which can be coated with a variety of organic or metallic coatings, carbon steels whose microstructures can be changed by small elemental additions and heat treatment, inherently corrosion resistant alloys like austenitic or ferritic stainless steels, and nonmetallic materials like composites. All of this has resulted in many options for concrete reinforcement, and no doubt some of these materials will perform better in some situations than others. The use of laboratory tests will be helpful in understanding many of the variables, but actual field performance, which is influenced by so many combinations of factors, will provide the ultimate test.

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ACKNOWLEDGMENTS

This literature search was prompted by a need to know the state of the art in alternative materials before beginning an investigation into alternative metallic reinforcement for concrete. The authors are grateful to the Texas Department of Transportation, the Federal Highway Administration, and the other member of the research team, Jonathon Seddelmeyer, David W. Fowler, and James O. Jirsa for their assistance.

01652/8

Appendix B:
Welcome to DialogClassic Web

Welcome to DialogClassic Web(tm)

```
 Dialog level 02.05.06D
Last logoff:  20jun02 12:14:27
Logon file415 20jun02 15:49:38

File 415:DIALOG Bluesheets(TM)  2002/Jun 17
       (c) 2002 The Dialog Corporation

      Set  Items  Description
      ---  -----  -----------
Cost is in DialUnits
?
B 32
       20jun02 15:49:48 User016167 Session D1441.1
            $0.00    0.078 DialUnits File415
     $0.00  Estimated cost File415
     $0.03  INTERNET
     $0.03  Estimated cost this search
     $0.03  Estimated total session cost   0.078 DialUnits

File  32:METADEX(R)  1966-2002/Aug B1
       (c) 2002 Cambridge Scientific Abs
*File  32: See Help Codes32 for a list of the Alloy Class Codes(CC=)
and Alloy Class Names(CN=) used in Metadex.

      Set  Items  Description
      ---  -----  -----------
?
S CORROSION?/TI AND STEEL?/TI AND CONCRETE?/TI
           64170  CORROSION?/TI
          197599  STEEL?/TI
            4249  CONCRETE?/TI
      S1     560  CORROSION?/TI AND STEEL?/TI AND CONCRETE?/TI
?
S S1 AND PY=2000:2002
             560  S1
           85508  PY=2000 : PY=2002
      S2      54  S1 AND PY=2000:2002
?
T 2/7/1-54
```

2/7/1
DIALOG(R)File 32:METADEX(R)

1302764 MA Number: 200208-35-2105
Cathodic Protection of Steel in Concrete.
Stockert, L ; Hofmann, M ; Hummer, J
Fachhochschule Wurzburg-Schweinfurt
Conference: EUROCORR 2001: The European Corrosion Congress, Lake Garda, Italy, 30 Sept.-4 Oct. 2001
Publ: Associazione Italiana diMetallurgia, Piazzale Rodolfo Morandi 2, Milano, I-200121, Italy, 2001
EUROCORR 2001 Congress Proceedings Pp 7
ISSN: 88-85298-41-9
Country of Publication: Italy
Journal Announcement: 0208
Document Type: Conference Paper
Language: ENGLISH
Abstract: Corrosion of steel in concrete is one of the critical problems in civil engineering. Cathodic protection of steel in concrete is a reliable technique for dealing with corrosion problems in reinforced concrete structures. With the help of an automated test device various protection systems are compared and atmospheric influences like temperature, rainfall and humidity on the electrochemical potential of the

steel reinforcement are studied. These influences may result in considerable potential shifts both to negative or positive directions, dependent on the protection system. These shifts have to be considered when the performance of cathodic protection systems is controlled by instant-off measurements. Numerical Data; Graphs. 8 ref.

2/7/2
DIALOG(R)File 32:METADEX(R)

1302760 MA Number: 200208-35-2101
Corrosion Protection of Steel Rebar in Concrete using Migrating Corrosion Inhibitors,.
Bavarian, B ; Reiner, L
California State University (Northridge)
Conference: EUROCORR 2001: The European Corrosion Congress, Lake Garda, Italy, 30 Sept.-4 Oct. 2001
Publ: Associazione Italiana diMetallurgia, Piazzale Rodolfo Morandi 2, Milano, I-200121, Italy, 2001
EUROCORR 2001 Congress Proceedings Pp 10
ISSN: 88-85298-41-9
Country of Publication: Italy
Journal Announcement: 0208
Document Type: Conference Paper
Language: ENGLISH
Abstract: The effectiveness of two commercially available migrating corrosion inhibitors (MCI) for steel rebar in concrete was investigated. Ten concrete specimens with varying densities were prepared with reinforcement placed at 1 inch (2.5 cm) concrete coverage. Corrosion inhibitors were applied to the surfaces of the concrete after 28 days of curing. Specimens were immersed in a 3.5% sodium chloride solution. Using DC Electrochemical and Electrochemical Impedance Spectroscopy, the specimens were evaluated to determine changes in their corrosion potential and resistance polarization (Rp) over 378 days period. These MCI products have exhibited promising corrosion inhibiting properties by maintaining a high resistance polarization (low corrosion rate) for the rebar in concrete. The MCI products proved to be more effective in the low-density concrete samples. XPS analysis demonstrated the presence of inhibitor on the steel rebar surface, indicating that the MCI did migrate through the concrete layer to the rebar for corrosion protection. The XPS depth profiling showed presence of a 100 nm layer of an amine-rich compound on the rebar surface, which justify increase in the Rp values and corrosion protection on the steel rebars in the MCI treated concrete samples. Numerical Data; Graphs. 14 ref.

2/7/3
DIALOG(R)File 32:METADEX(R)

1302757 MA Number: 200208-35-2098
Corrosion inhibitors for steel in concrete - an EFC state of the art report.
Elsener, B
Universita di Cagliari
Conference: EUROCORR 2001: The European Corrosion Congress, Lake Garda, Italy, 30 Sept.-4 Oct. 2001
Publ: Associazione Italiana diMetallurgia, Piazzale Rodolfo Morandi 2, Milano, I-200121, Italy, 2001
EUROCORR 2001 Congress Proceedings Pp 10
ISSN: 88-85298-41-9
Country of Publication: Italy
Journal Announcement: 0208

Document Type: Conference Paper
Language: ENGLISH
Abstract: Corrosion of reinforcing steel represents the most widespread form of deterioration of concrete structures resulting in significant costs for repair and replacement worldwide. Despite the huge demand, a simple, cheap and reliable technique that either protects the steel in concrete from corrosion or at least lowers its corrosion rate is still lacking. The concrete repair industry has developed novel techniques that are claimed to prevent the steel from corrosion and/or to restore the protective character of the cover concrete by introducing corrosion inhibitors into the carbonated or chloride contaminated concrete. The author has prepared a State of the Art Report for the Working Party 11 "Corrosion of Steel in Concrete" of the European Federation of Corrosion on this topic, including more then 150 references. In this paper a short review on literature results regarding the performance of the most frequently used inhibitors for steel in concrete in laboratory and in field tests is given, in particular two inorganic inhibitors, calcium nitrite (DCI) and MFP, and several organic inhibitors, the "migrating inhibitors" (MCI or SIKA) and an organic corrosion-inhibiting admixture (OCI) are adressed. The problem of transport of inhibitors into concrete is discussed. A critical review of corrosion inhibitors to be used on reinforced concrete structures regarding concentration dependence, durability and measurement and control of the inhibitor action is given. Numerical Data; Graphs. 30 ref.

2/7/4
DIALOG(R)File 32:METADEX(R)

1302754 MA Number: 200208-35-2095
Influence of stray currents on corrosion of steel in concrete.
Bertolini, L ; Carsana, M ; Pedeferri, P
Politecnico di Milano
Conference: EUROCORR 2001: The European Corrosion Congress, Lake Garda, Italy, 30 Sept.-4 Oct. 2001
Publ: Associazione Italiana diMetallurgia, Piazzale Rodolfo Morandi 2, Milano, I-200121, Italy, 2001
EUROCORR 2001 Congress Proceedings Pp 11
ISSN: 88-85298-41-9
Country of Publication: Italy
Journal Announcement: 0208
Document Type: Conference Paper
Language: ENGLISH
Abstract: The effects of stray current on corrosion of steel in concrete have been studied. Both the mechanisms of corrosion initiation on reinforcement initially passive and the effects of the stray current on reinforcement already corroding have been investigated. Tests were carried out on specimens of cement paste and concrete with steel inserts subjected to the circulation of DC and AC current. The influence of several factors was studied, such as: the type of current (AC or DC), the current density, the presence of interruptions in the circulation of current, the chloride content in the concrete. The mechanism of initiation of corrosion was also investigated by measuring changes in pH and chloride content induced by the stray current in the cement paste in the vicinity of the steel surface. Results showed that DC current can induce corrosion initiation on the reinforcement in the anodic zone only after it has circulated for a certain time. The aggressiveness of stray current was influenced by current density, the presence of chloride and interruptions in the current. AC current proved to be much less dangerous than DC, although it can influence the corrosion rate of steel in chloride contaminated concrete and stimulate macrocouples. Numerical Data; Graphs. 7 ref.

2/7/5
DIALOG(R)File 32:METADEX(R)

1302752 MA Number: 200208-35-2093
Macrocell corrosion of steel in concrete - experiments and numerical modelling.
Jaggi, S ; Bohni, H ; Elsener, B
Eidgenossische Technische Hochschule Honggerberg
Conference: EUROCORR 2001: The European Corrosion Congress, Lake Garda, Italy, 30 Sept.-4 Oct. 2001
Publ: Associazione Italiana diMetallurgia, Piazzale Rodolfo Morandi 2, Milano, I-200121, Italy, 2001
EUROCORR 2001 Congress Proceedings Pp 11
ISSN: 88-85298-41-9
Country of Publication: Italy
Journal Announcement: 0208
Document Type: Conference Paper
Language: ENGLISH
Abstract: Macrocell corrosion with a local anode and a large cathode frequently occurs in chloride induced corrosion of rebars in concrete and is responsible for very high local corrosion attacks and reduction in cross section of the rebars found e.g. in bridge decks or substructures. In model macrocells in mortar and in concrete the influence of resistivity, temperature and geometrical arrangement (area ratio between cathode and anode, location of cathode) on macrocell current and its distribution on the cathode has been studied. The cathodic oxygen reduction reaction and the anodic dissolution of the steel in pitting conditions have been studied separately and used as input data for the numerical modelling of the macrocell with the same geometrical anode / cathode arrangements as the mortar experiments. A very good agreement between modelling and experiments was found for the total macrocell current, its distribution and its temperature dependance. This numerical approach allows to perform parameter studies very rapidly and to design experiments with macrocells in concrete in a rational way. Numerical Data; Graphs. 24 ref.

2/7/6
DIALOG(R)File 32:METADEX(R)

1302751 MA Number: 200208-35-2092
Influence of scale and rust on steel activation in model concrete pore solution.
Novak, P ; Mala, R ; Kouril, M
University of Chemistry and Technology (Prague)
Conference: EUROCORR 2001: The European Corrosion Congress, Lake Garda, Italy, 30 Sept.-4 Oct. 2001
Publ: Associazione Italiana diMetallurgia, Piazzale Rodolfo Morandi 2, Milano, I-200121, Italy, 2001
EUROCORR 2001 Congress Proceedings Pp 5
ISSN: 88-85298-41-9
Country of Publication: Italy
Journal Announcement: 0208
Document Type: Conference Paper
Language: ENGLISH
Abstract: Corrosion behavior of carbon steel (0.2 %C) was observed in model pore solution of concrete with chloride content ranging <0.01 to 50 g/l. Short-term exposure tests were carried out in solutions with oxygen of 1 or 8 mg/l and pH 12.5 or 13.3, respectively. The aim was to determine, on the basis of polarization resistance measurements, the critical chloride concentration, at which the steel surface becomes activated. The measurements were performed on three types of steel surfaces - bare, scaled and pre-rusted. Compared with the bare surface, a layer of scale on the steel surface increases the critical chloride concentration 3 to 6 times. Steel activation in alkaline solution with balanced concentration of oxygen proceeds at chloride concentration >1 g/l. Lower oxygen concentration leads

to an increase in critical Cl exp - concentration in the case of bare and scaled surfaces. No significant shift of the critical chloride concentration with pH change was found, and the results prove that the critical ratio of concentration Cl exp - /OH exp - has no practical importance for the evaluation of corrosion aggressivity of concrete toward steel. In the region of low chloride concentrations, the pre-rusted surface showed the lowest corrosion resistance of all the tested types of surfaces, and the results proved the negative effect of the rust layer formed by atmospheric exposure. Numerical Data. 9 ref.

2/7/7
DIALOG(R)File 32:METADEX(R)

1302585 MA Number: 200208-35-1926
New types of corrosion inhibitors for protection of steel in concrete.
Pepenar, I
INERC
Romania, 2001
UPB Buletin Stiintific, Series B: Chemistry and Materials Science 63, (3), 149-156 2001
ISSN: 1454-2331
Country of Publication: Romania
Journal Announcement: 0208
Document Type: Article
Language: ENGLISH
Abstract: Corrosion inhibitors are chemical substances that prevent or retard corrosion of steel in concrete, in the presence of aggressive agents, increasing thus the durability of new and existing reinforced concrete structures. They may be added in the fresh concrete, in paints for the reinforcement, in repair mortars or may be applied at the concrete surface. The paper presents a research on the protection of steel in concrete by means of traditional corrosion inhibitors (anodic) and of the new types of migrating inhibitors based on ammo-alcohols (MCI, SIKA) and monofluorophosphate (MFP) A critical evaluation of the corrosion inhibitors to be used on reinforced concrete structures, regarding concentration dependence, durability, measurement and control of inhibitor action, are also presented. Graphs. 5 ref.

2/7/8
DIALOG(R)File 32:METADEX(R)

1299316 MA Number: 200207-35-1791
Prevention of steel corrosion in concrete exposed to seawater with submerged sacrificial anodes.
Bertolini, L ; Gastaldi, M ; Pedeferri, M ; Redaelli, E
Politecnico di Milano
USA, 2002
Corrosion Science 44, (7), 1497-1513 July 2002
ISSN: 0010-938X
Country of Publication: USA
Journal Announcement: 0207
Document Type: Article
Language: ENGLISH
Abstract: This paper presents the results of a study of the effectiveness of submerged sacrificial anodes in preventing the onset of pitting corrosion in the emerged part of marine piles. Experimental tests were carried out on reinforced concrete columns with steel embedded both in chloride free concrete and chloride contaminated concrete in order to compare the effects of sacrificial anodes on passive steel and on corroding steel. Results have shown, at least under the present testing conditions, that sacrificial anodes may be more effective in preventing corrosion

initiation (i.e. in providing cathodic prevention) than in controlling ongoing pitting corrosion (i.e. in guaranteeing cathodic protection). Monitoring criteria for this type of prevention are also discussed. Graphs. 22 ref.

2/7/9
DIALOG(R)File 32:METADEX(R)

1296818 MA Number: 200206-62-0984
Inspecting a half-century concrete pier made with stainless steel reinforcement in Mexico.
Castro-Borges, P ; Troconis-Rincon, O ; Moreno, E I ; Torres-Acosta, A A ; Martinez-Madrid, M ; Knudsen, A
Instituto Politecnico Nacional (Mexico)
Conference: Corrosion/2002, Denver, CO, USA, 7-11 Apr. 2002
Publ: NACE International, P.O. Box 218340, Houston, TX 77218, USA, 2002
Corrosion/2002 Pp 11
Country of Publication: USA
Report No.: 02207
Journal Announcement: 0206
Document Type: Conference Paper
Language: ENGLISH
Abstract: A 60-year old reinforced concrete pier, constructed with stainless steel reinforcing bars (rebars), and exposed to a tropical marine environment, has shown good performance during its service life. Visual inspection has shown no deterioration symptoms on sub- and super-structures, while recent marine structures (adjacent or close to this pier), constructed in the past three decades, have been deteriorated significantly due to severe corrosion of the embedded carbon steel presenting a lot of concrete delamination. A preliminary study has been performed in order to find the reasons why this pier as performed satisfactory in more than 60 years. The paper describes the tests performed to the pier, which included chloride content and concrete resistivity as well as electrochemical measurements to the stainless steel rebar. Brief discussion about durability issues on this pier, based on the obtained results, is given in this paper. Numerical Data; Graphs. 13 ref.

2/7/10
DIALOG(R)File 32:METADEX(R)

1295570 MA Number: 200206-35-1428
Cathodic protection of steel reinforced concrete structures using a galvanic zinc hydrogel system.
Dykstra, B G ; Wehling, J E ; Piazza, J L
3M
Conference: Corrosion/2002, Denver, CO, USA, 7-11 Apr. 2002
Publ: NACE International, P.O. Box 218340, Houston, TX 77218, USA, 2002
Corrosion/2002 Pp 13
Country of Publication: USA
Report No.: 02269
Journal Announcement: 0206
Document Type: Conference Paper
Language: ENGLISH
Abstract: There are over 500,000 condominium units along the Florida coastline, most of which have experienced significant corrosion of their steel reinforcements due primarily to chloride intrusion from the ocean salt spray. Some of the condominium associations in Florida have in the past five years recognized that cathodic protection is the only

rehabilitation method that will truly prevent the corrosion of the reinforcing steel and the resultant concrete spalling and delamination. The installations of a galvanic zinc-hydrogel system will be described in detail, and monitoring data will be presented for at least six months of active service. The system consists of a 10-mil zinc foil bonded to an ionically conductive hydrogel adhesive, which is applied directly to the surface of the steel-reinforced concrete. A copper wire connects the zinc anode to multiple steel rebars. The performance is monitored by measuring the current flow in the wire, by measuring the amount of zinc consumed or, more generally, by taking depolarization readings at regular intervals. All of these measurements are an indication of the performance of the galvanic system and the corrosion of the steel rebars that is being prevented. Numerical Data. 10 ref.

2/7/11
DIALOG(R)File 32:METADEX(R)

1295564 MA Number: 200206-35-1422
Steel Activation in Concrete Following Interruption of Long Term Cathodic Polarization.
Presuel, F J ; Sagues, A A ; Kranc, S C
University of South Florida
Conference: Corrosion/2002, Denver, CO, USA, 7-11 Apr. 2002
Publ: NACE International, P.O. Box 218340, Houston, TX 77218, USA, 2002
Corrosion/2002 Pp 14
Country of Publication: USA
Report No.: 02259
Journal Announcement: 0206
Document Type: Conference Paper
Language: ENGLISH
Abstract: A set of partially immersed reinforced concrete columns with mature corrosion patterns was used to demonstrate that corrosion macrocell currents provided "cathodic prevention" to parts of the steel assembly that remained passive even though exposed to high chloride (approx4.7% of the cement weight) concrete. Depassivation of that steel was observed upon macrocell decoupling. Graphs. 34 ref.

2/7/12
DIALOG(R)File 32:METADEX(R)

1295560 MA Number: 200206-35-1418
An Update on the Long Term Use of Cathodic Protection of Steel Reinforced Concrete Marine Structures.
Kessler, R J ; Powers, R G ; Lasa, I R
Florida Department of Transportation
Conference: Corrosion/2002, Denver, CO, USA, 7-11 Apr. 2002
Publ: NACE International, P.O. Box 218340, Houston, TX 77218, USA, 2002
Corrosion/2002 Pp 14
Country of Publication: USA
Report No.: 02254
Journal Announcement: 0206
Document Type: Conference Paper
Language: ENGLISH
Abstract: Cathodic protection has become the preferred method for mitigating corrosion of steel reinforcement in concrete in Florida's marine bridge substructures. Over the past twenty years, the Florida Department of Transportation (FDOT) has installed a variety of cathodic protection systems including both impressed current systems and sacrificial anode

systems. An overview of the installation and long term performance is presented for cathodic protection systems comprised of: 1) conductive rubber anodes, 2) titanium mesh anodes cast into structural concrete, 3) titanium mesh anodes cast into grouted pile jackets, 4) sacrificial zinc mesh anodes cast into grouted pile jackets and, 5) sprayed zinc anodes. Additionally, an overview is presented on FDOT experience with the use of remote monitoring systems and alternate power supplies such as solar power and battery power. Graphs. 4 ref.

2/7/13
DIALOG(R)File 32:METADEX(R)

1295314 MA Number: 200206-35-1172
Corrosion of reinforced steel bars embedded in concrete: a study of electrochemical and surface analysis.
Bartolo-Perez, P ; Pena, J L ; Salas, F H ; Wheat, H G ; Hernandez-Duque, G
CINVESTAV
Israel, 2000
Corrosion Reviews 18, (2-3), 255-266 2000
ISSN: 0048-7538
Country of Publication: Israel
Journal Announcement: 0206
Document Type: Article
Language: ENGLISH
Abstract: We present a study of corrosion of reinforced steel bars embedded in concrete. We carried out both electrochemical analysis /E sub corr , polarization resistance (R sub p), and electrochemical impedance spectroscopy (EIS)/ and surface analysis by AES, XPS, SEM, and EDAX. We found that 1/R sub P >28 mu S/cm exp 2 , which gives I sub corr > 0.73 mu A/cm exp 2 , indicating that severe corrosion was occurring. After a 20-week exposure, the Nyquist plot of the electrochemical impedance Z(j omega) showed two capacitive arcs and rests of a third one, the corresponding time constants RC being related to the double layer, the interfacial thin film, and the concrete matrix, respectively. The interfacial thin film resistance (R sub f) and the double-layer resistance (R sub ct) are found to be about 220 Omega and 320 Omega , respectively. Departure from the capacitive semi-circles is observed, indicating the presence of diffusion-driven corrosion. Analysis of AES allowed us to determine the concentration of corrosion products on the surface and in the near surface region. Migration of S, C, and Ca to the surface was observed. Graphs; Spectra; Photomicrographs. 20 ref.

2/7/14
DIALOG(R)File 32:METADEX(R)

1290387 MA Number: 200204-35-0788
Nonexponential transients resulting from application of the interruption technique to assess corrosion rate of steel in concrete.
Feliu, V ; Cobo, A ; Gonzalez, J A ; Feliu, S
Universidad de Castilla
USA, 2002
Corrosion 58, (1), 72-81 Jan. 2002
ISSN: 0010-9312
Country of Publication: USA
Journal Announcement: 0204
Document Type: Article
Language: ENGLISH
Abstract: A numerical method was developed to model the voltage response after a direct current (DC) interruption through an equivalent circuit

representing a steel/concrete system. Based on computer simulation and experimental observations, the paper discusses the applicability of classical procedures of analysis of the voltage decay curves in order to assess the corrosion status of reinforcing steel. It is shown that the accuracy of these determinations may be strongly dependent on the nonexponential behavior of the response, and it may therefore be significantly affected by the duration of the current pulse applied and the portion of the decay curve used in the analysis. Apparently, more elaborate methods of analyzing voltage decay curves are necessary. Graphs; Numerical Data. 19 ref.

2/7/15
DIALOG(R)File 32:METADEX(R)

1285311 MA Number: 200203-35-0527
Corrosion of reinforcing steel evaluated by means of concrete resistivity measurements.
Morris, W ; Vico, A ; Vazquez, M ; De Sanchez, S R
Universidad Nacional de Mar del Plata
USA, 2002
Corrosion Science 44, (1), 81-99 Jan. 2002
ISSN: 0010-938X
Country of Publication: USA
Journal Announcement: 0203
Document Type: Article
Language: ENGLISH
Abstract: The corrosion behaviour of reinforcing steel bars (rebars) in four different concrete mix designs commonly used at coastal cities in Argentina is studied. The investigation has two basic objectives: to evaluate the influence of certain local variables that affect the rebar corrosion process, among which the common practice of using sea sand as a fine aggregate, exposure conditions and typical mix designs are the most important, and to establish a rebar corrosion evaluation criterion based on measurements of concrete electrical resistivity. Two exposure conditions were investigated: seashore environment and partially immersed in a saline solution. Two water to cements and various chloride ions additions were selected for the study. Electrochemical parameters characteristic of the corrosion process were evaluated together with mechanical, chemical and physical properties of the concrete mixes. Rebars in contact with a good quality concrete (f sub c approx = 30 MPa) exposed for 1000 days to the seashore environment remained in the passive state, even when its surface chloride concentration reached 0.75% with respect to cement content. This behaviour was even better than that observed on a standard-quality uncontaminated concrete (f sub c approx = 20 MPa). When immersed in a saline solution, all rebar segments presented an active behaviour (E sub corr < -0.35 V vs. copper sulphate electrode and i sub corr > 0.2 mu A cm exp -2), although the CR depended primarily on the concrete quality and the initial chloride concentration. Graphs. 39 ref.

2/7/16
DIALOG(R)File 32:METADEX(R)

1283579 MA Number: 200202-35-0371
Corrosion Inhibitors for Steel in Concrete. State of the Art Report.
Elsener, B
Institute of Materials (UK)
UK, 2001
European Federation of Corrosion Publications 35, 1-68 2001
ISSN: 1354-5116
Country of Publication: UK
Journal Announcement: 0202

Document Type: Article
Language: ENGLISH

Abstract: In general, reinforced concrete has proved to be successful in terms of both structural performance and durability because the concrete provides chemical and physical corrosion protection of the rebars. The alkaline pore solution passivates the steel and the concrete cover prevents or at least retards the ingress of corrosion-promoting substances. However, there are instances of premature failure of reinforced concrete components due to corrosion of the reinforcement. The two factors provoking corrosion are the ingress of chloride ions from deicing salts or sea water or the reaction of the alkaline pore solution with carbon dioxide from the atmosphere, a process known as carbonation. As a result of the corrosion reaction the cross section of the rebars is reduced and rust is formed. This process can cause cracking or spalling of the concrete and dangerous loss of structural stability. In this state of the art report a literature survey on inhibitors for steel in concrete, covering laboratory results, field experience and long term performance, is given. The literature results available are commented upon and critically evaluated with respect to the inhibitor performance and durability. The problem of testing different inhibitors for steel in concrete is addressed and - as far as available - results from field tests with inhibitors are presented. Graphs. 157 ref.

2/7/17
DIALOG(R)File 32:METADEX(R)

1281476 MA Number: 200202-22-0146
Possibility of improvement of potentiodynamic method for monitoring corrosion rate of steel reinforcement in concrete.

Zivica, V
Institute of Structures & Architecture (Slovak Republic)

India, 2001
Bulletin of Materials Science (India) 24, (5), 555-558 Oct. 2001
ISSN: 0250-4707
Country of Publication: India
Journal Announcement: 0202
Document Type: Article
Language: ENGLISH

Abstract: Quantitative data on corroding steel reinforcement in reinforced concrete structures are undoubtedly very useful for evaluation of their service life and timely repairs. The method of electrode potential measurement is a convenient and simple test for this purpose, but it provides no quantitative data on corrosion rate and only information regarding active or passive state of steel reinforcement can be obtained. We show here the possibility of obtaining quantitative data on degree of corrosion of steel reinforcement by a potentiodynamic method. The developed method is based on experimentally estimated mathematical relation between the results of potentiodynamic method and degree of corrosion of steel reinforcement. It is possible to calculate the degree of corrosion of steel reinforcement using this mathematical relation and the measured values of current density by the potentiodynamic method. Numerical Data; Graphs. 14 ref.

2/7/18
DIALOG(R)File 32:METADEX(R)

1278758 MA Number: 200201-35-0055
Multistep genetic algorithm for detecting corrosion of reinforcing steels in concrete.

Ridha, M ; Amaya, K ; Aoki, S

Tokyo Institute of Technology
Publ: National Association of Corrosion Engineers, P.O. Box 218340, Houston, TX 77084, USA, 2001
Corrosion 57, (9), 794-801 Sept. 2001
ISSN: 0010-9312
Country of Publication: USA
Journal Announcement: 0201
Document Type: Article
Language: ENGLISH
Abstract: In this article, a multistep genetic algorithm is developed to overcome some difficulties of the inverse analysis method for accurately detecting a corrosion profile on the steel matrices from a small number of potential data, which are measured on the surface of the concrete structure. In this method, the corrosion profile, which represents the number, locations, and shapes of plural corrosion areas on the steel matrices, is modeled into a binary string instead of a set of unknown parameters. The binary string is defined by discretizing the steel matrices into a suitable number of segments using a certain resolution. Each segment is represented by one binary bit. The fitness value is inversely proportional to the cost function, which is a function of the difference between the calculated and measured potentials at some locations on the surface of the concrete structure. The calculated values of potential are obtained by solving Laplace's equation using the boundary element method (BEM). In general, when a large area of examination is discretized using a required resolution, a very long binary string is needed to encode all of the segments. Hence, a long calculation time is required for carrying out the standard genetic algorithm. An example of numerical simulation was used to demonstrate the effectiveness of the proposed method. Graphs. 18 ref.

2/7/19
DIALOG(R)File 32:METADEX(R)

1278742 MA Number: 200201-35-0039
Effect of placement and compaction on carbonation of concrete and corrosion of steel at cold joint.
Sawamoto, T ; Tsuji, M ; Kimachi, Y
Science University of Tokyo
Publ: Society of Materials Science, Japan, One Yoshida Izumidano-cho Sakyo-ku, Kyoto, Japan, 2001
Journal of the Society of Materials Science, Japan 50, (8), 865-872 Aug. 2001
ISSN: 0514-5163
Country of Publication: Japan
Journal Announcement: 0201
Document Type: Article
Language: JAPANESE
Abstract: It is important to place concrete continuously for construction being joint-less. However, in case placing is discontinued for some reasons, some defects such as cold joints should remain. At the first stage in this study, effects of placing conditions on continuity of concrete were investigated. The flexural and compressive strength at joint between placing layers was almost the same as that of joint-less concrete when upper layer concrete was placed over lower layer immediately after the lower layer being revibrated and softened to wet until the initial setting. This result was the same as what is recommended in J.S.C.E. Specification 1974. This principle was deleted from the Specification 1986 onward, because ready mixed concrete had been common and continuously placed by concrete pump. At the next stage, effects of placing time interval on carbonation and corrosion were evaluated by some accelerated tests on specimens compacted without revibration before placing upper layer concrete. This study shows that the longer the placing time interval, the faster the carbonation velocity factor becomes and the earlier the corrosion starts. When the placing time interval is required by some

accidents, lower layer concrete should be revibrated in order not to make any defects; otherwise it would be necessary that carbonation velocity and margin of cover concrete depth recommended in the Specification January 2000 should be increased. On the other hand, some type of monitoring specimen would be necessary to maintain the durability of RC structures as there are uncertainties, such as effective use of recycled aggregate, new type of cement such as eco-cement, and change of environment due to industrialization of neighboring countries. It is also clarified that a specimen which is tested in this accelerated test can probably indicate environmental conditions when the specimen is applied to monitor. Graphs. 11 ref.

2/7/20
DIALOG(R)File 32:METADEX(R)

1278741 MA Number: 200201-35-0038
Corrosion cell formation pattern and rate of steel corrosion induced by carbonation in concrete with defects.
Osuki, N ; Miyazato, S -I ; Kimura, H
Tokyo Institute of Technology
Publ: Society of Materials Science, Japan, One Yoshida Izumidano-cho Sakyo-ku, Kyoto, Japan, 2001
Journal of the Society of Materials Science, Japan 50, (8), 857-864 Aug. 2001
ISSN: 0514-5163
Country of Publication: Japan
Journal Announcement: 0201
Document Type: Article
Language: JAPANESE
Abstract: The objective of this study was to analyze comprehensively the corrosion cell formation pattern (macro-cell and micro-cell) and the corrosion rate induced by carbonation in concrete with joints or cracks. First, mortar tests were performed using specimens with model defects that simulated cold joints or bending cracks. Herein three important factors that caused steel corrosion were investigated in detail. These factors were: 1) carbonized location, 2) supply of water and oxygen, and 3) water-cement ratio of mortar. Next, concrete tests were performed using specimens with cold joints and bending cracks. The results obtained in this study were as follows: a) 27 cases of which the carbonized location, supply of water and oxygen, and the water-cement ratio of mortar differed were experimented. As results, the corrosion cell formation pattern and the corrosion rate were comprehensively analyzed based on unified conditions. b) In the case of carbonation-induced corrosion with defects, macro-cell corrosion would be formed regardless of the water-cement ratio. Also, the corrosion rate decreased with the decreasing of water-cement ratio. c) The result b) was confirmed not only in mortar tests but also in concrete tests. d) According to above results, it could be said that the low water cement ratio was excellent in the durability for the steel corrosion, when concrete with defects received the influence of carbonation. Numerical Data ; Graphs. 9 ref.

2/7/21
DIALOG(R)File 32:METADEX(R)

1277045 MA Number: 200112-35-3083
Macrocell and microcell corrosion of steel reinforcement in the concrete crack zone.
Chang, Z T ; Cherry, B ; Marosszeky, M
University of New South Wales
Conference: Corrosion & Prevention-2000, Auckland, New Zealand, 19-22

Nov. 2000
Publ: Australasian Corrosion Association, Australasian Corrosion Centre, P.O. Box 250, Clayton, Victoria 3168, Australia, 2001
Pp9
ISSN: 1442-0139
Country of Publication: Australia
Report No.: Paper 029
Journal Announcement: 0112
Document Type: Conference Paper
Language: ENGLISH
Abstract: While cracks in concrete structures impair the protection afforded by concrete cover to steel reinforcement in the crack zone, the influence of crack width on the corrosion rate of reinforcement over the long term is a subject of controversy. A comprehensive experimental program to investigate the corrosion rate of steel reinforcement in concrete crack zones is currently in progress at the Building Research Centre, UNSW. The main objectives of the study include the influences of crack width on the corrosion rate of reinforcement in concrete specimens submerged in seawater, the contributions of micro-cell and macro-cell mechanisms on the total corrosion rate and the effects of cathode to anode ratios. The current paper presents the results of a preliminary investigation with a reinforced concrete specimen immersed in a 3% NaCl solution. The specimen contains two steel rebars, a short rebar intersecting a crack and another rebar embedded in sound concrete. The rebars could be connected to simulate a continuous bar. The electrical potential of both rebars was monitored over time. The microcell corrosion rate was assessed with a polarisation resistance technique while the macrocell effect was evaluated from the galvanic current measured with a Zero-Resistance Ammeter (ZRA). Graphs. 14 ref.

2/7/22
DIALOG(R)File 32:METADEX(R)

1268845 MA Number: 200110-35-2562
Use of galvanostatic pulse measurements on active reinforcing steel in concrete to assess corrosion rates.
Law, D W ; Millard, S G ; Bungey, J H
Heriot-Watt University
UK, 2001
British Corrosion Journal 36, (1), 75-80 2001
ISSN: 0007-0599
Country of Publication: UK
Journal Announcement: 0110
Document Type: Article
Language: ENGLISH
Abstract: This paper reports the results of galvanostatic pulse transient response experiments to determine the corrosion parameters associated with actively corroding reinforcing steel in concrete. Galvanostatic pulse measurements have been conducted on a number of short 100 mm sections of steel reinforcing bar embedded in chloride contaminated concrete. The duration of the applied galvanostatic pulse was 90 s and the lateral distance of the point of measurement from the bar varied from zero to 400 mm. All of the bars monitored were conditioned so that they were actively corroding at different rates. Analysis of the galvanostatic pulse transient response has enabled the separate components that make up the measured transients to be isolated and evaluated. These components display a range of resistivities and capacitances, dependent on the corrosion condition of the reinforcing steel, which may be attributed to the corrosion process, to effects within the concrete cover, or to film effects on the surface of the concrete. Significant variations in corrosion rates have been observed dependent on the assignment of the separate components to either corrosion or to other processes. The data indicate that it is not feasible to assign the component based solely on the capacitance. An inappropriate selection

of measurement time or equilibrium time may result in part of the resistance associated with the corrosion process being left out or an additional resistance not controlling the rate of corrosion being included. Numerical Data; Graphs. 15 ref.

2/7/23
DIALOG(R)File 32:METADEX(R)

1265427 MA Number: 200109-35-2355
Detailed modeling of corrosion macrocells on steel reinforcing in concrete.
Kranc, S C ; Sagues, A A
University of South Florida
USA, 2001
Corrosion Science 43, (7), 1355-1372 July 2001
ISSN: 0010-938X
Country of Publication: USA
Journal Announcement: 0109
Document Type: Article
Language: ENGLISH
Abstract: Numerical modeling of the distribution corrosion of steel reinforcing bars (rebars) in concrete structures is complicated by the spatial distribution of the rebars in the volume of concrete, by nonlinear boundary conditions associated with the polarization of the corrosion reactions at the steel surface, and by mass transfer processes of the reactants in the bulk of the concrete. A computational method for solving the governing equations has been developed from finite difference representations and a solution procedure that retains the nonlinear character of the boundary conditions. A strategy was successfully devised to compute the local potential and current density at the rebar surface with a minimum of computational effort. Both the problem of free corrosion and cathodic potential are discussed for the example of a square slab, reinforced with a double mat of crossing rebars. Graphs. 25 ref.

2/7/24
DIALOG(R)File 32:METADEX(R)

1265350 MA Number: 200109-35-2278
Corrosion inhibitors for steel in reinforced concrete.
Martins, M ; De Macedo, L F R ; Filgueiras, M R T
Universidade do Estado do Rio de Janeiro
Conference: 55 Congresso Anual Associacao Brasileria de Metalurgia e Materiais, Rio de Janeiro, Brazil, 24-28 July 2000
Publ: Associacao Brasileira de Metalurgia e Materiais, Rua Antonio Comparato, 218, Cx. Postal 42081, Sao Paulo, CEP 04605, Brazil, 2000
Anais do 55 Congresso Anual da Associacao Brasileira e Materiais 453-462 2000
Country of Publication: Brazil
Journal Announcement: 0109
Document Type: Conference Paper
Language: PORTUGUESE
Abstract: The mixture of granular components combined to the water, forms an aggregate, which associated to metallic armors, constitutes the structure of reinforced concrete. With the cure process, the necessary rigidity is established, so that the armed concrete functions as a structural material, as well as the formation of calcium hydroxide, starting from the reaction of the calcium oxide present in the mixture that confers to the concrete the basic character. Among the pathologies to what the structures of reinforced concrete, are subjected the carbonation of the concrete and the erosion of the armors, are the more critics, compromising between integrity and capacity support. The inherent porosity of the

concrete allows the diffusion of carbonic gas and water through their pores and consequently the reaction with hydroxide of calcium forming calcium carbonate. In this process, the passivated iron layer is penetrated allowing the formation of oxides with larger volume creating several internal tensions generating displacements of the concrete. This work was directed to analyze the parameters that are related to the beginning of this corrosion process and the organic addictive behavior, which are possible to be incorporated to the mixture, in such way that the corrosion process can be significantly inhibited.

2/7/25
DIALOG(R)File 32:METADEX(R)

1262170 MA Number: 200108-35-2056
Cathodic corrosion protection of steel reinforced concrete structures with a new conductive composite paint system.
Schwarz, W
Swiss Federal Institute of Technology
Switzerland, 2000
International Journal for Restoration of Buildings and Monuments 6, (6), 597-618 2000
ISSN: 0947-4498
Country of Publication: Switzerland
Journal Announcement: 0108
Document Type: Article
Language: ENGLISH
Abstract: Corrosion of steel in concrete is one of the critical problems in civil engineering with regard to the durability of reinforced concrete structures. Cathodic protection (CP) of the steel rebars in concrete structures evolved during the past 25 years as a reliable method to extend the lifetime of reinforced concrete structures. During the CP operation, proportional to the applied protection current, acids are generated at the anode/concrete interface. This effect limits durability and performance of various CP-systems. This contribution describes a newly developed conductive composite paint for use as anode material, characterized by high durability at high current densities and easy applicability, and its practical application for the corrosion protection of a parking deck in Oslo. Graphs. 19 ref.

2/7/26
DIALOG(R)File 32:METADEX(R)

1256777 MA Number: 200106-31-2687
Hydrogen damage of high tensile steel in concrete.
Abdel-Karim, R ; El-Raghy, S M ; Waheed, A F ; Swellam, M H
Cairo University
Conference: Chemistry and Electrochemistry of Corrosion and Stress Corrosion Cracking: A Symposium Honoring the Contributions of R.W. Staehle as held at the 2001 TMS Annual Meeting, New Orleans, LA, USA, 11-15 Feb. 2001
Publ: Minerals, Metals and Materials Society/AIME, 184 Thorn Hill Road, Warrendale, PA 15086-7528, USA, 2001
Chemistry and Electrochemistry of Corrosion and Stress Corrosion Cracking: A Symposium Honoring the Contributions of R.W. Staehle 649-662 2001
ISSN: 0-87339-478-X
Country of Publication: USA
Journal Announcement: 0106
Document Type: Conference Paper
Language: ENGLISH
Abstract: Tempered Martensitic high tensile steel bars of different

diameters used in prestressed concrete were tested for susceptibility for hydrogen damage. Bare and embedded bars in concrete were cathodically charged in chloride solutions of different pH. The as received tensile strength was in the range of 2000 MPa. A drop in strength and ductility due to hydrogen attack was found to be dependent on many factors including electrolyte, type of concrete and bar diameter reflected on the microstructure. The maximum drop in both tensile strength and in ductility was observed at pH 7.5 more than in acidic or basic solutions. High-grade concrete (HGC) with silica fume slightly reduced the hdyrogen damage caused by the same impressed current density. Bars with 4-mm diameters were more susceptible to hydrogen embrittlement than those of 5-mm or 6-mm diameter. Further heat treatment effects were investigated and proved the least affected microstructure was the tempered martensite. Numerical Data; Photomicrographs; Graphs. 11 ref.

2/7/27
DIALOG(R)File 32:METADEX(R)

1255566 MA Number: 200106-35-1743
The effectiveness of penetrating inhibitors for steel corrosion in concrete.
Dhouibi, L ; Triki, E ; Raharinaivo, A
Ecole Nationale d'Ingenieurs de Tunis
Conference: 9th European Symposium on Corrosion Inhibitors. Vol. 1, Ferrara, Italy, 4-8 Sept. 2000
Publ: University of Ferrara Corrosion Study Centre, Via L. Borsari, 46, 1-44100 Ferrara, Italy, 2000
9th European Symposium on Corrosion Inhibitors. Vol. 1 347-362 Sept. 2000
Country of Publication: Italy
Journal Announcement: 0106
Document Type: Conference Paper
Language: ENGLISH
Abstract: This paper concerns the effectiveness of four inhibitors against steel corrosion in concrete. The experiment was carried with two Portland cements. For each cement, two concrete proportions were used: cement content 400 kg.m exp -3 or 250 kg.m exp -3 with water-cement ratio equal 0.4 or 0.6, respectively. Steel rods were placed in concrete specimens, 6.5 mm in diameter, 120 mm high. After a curing for 28 days, specimens were immersed successively in two solutions. The first one was 0.5 M sodium chloride which is able to induce metal corrosion. This immersion lasted three months. The second solution was distilled water added with inhibitors, which were: sodium nitrite, calcium nitrate or sodium phosphate (0.2 M) or alkanolamine (11.5 ml.L exp -1). In this case the test period was one year. Before and after immersion in the second solution, specimens were taken out of this solution. So, the condition of reinforcing steel was assessed by using electrochemical AC impedance spectroscopy (EIS). The results indicated that: - after three months immersion in the first (salty) solution, in concrete made with higher content (400 kg.m exp -3) chloride penetration was low and steel remained passivated. However, for lower concrete density, chloride depassivated steel and induced its corrosion. After an immersion during one year in the second solution, inhibitors penetrated into concrete and they were able to inhibit steel corrosion. Numerical Data; Graphs. 16 ref.

2/7/28
DIALOG(R)File 32:METADEX(R)

1253672 MA Number: 200105-35-1259
Corrosion behavior of steel bars embedded in fly ash concrete

deteriorated by chlorides and carbonation.
Aihara, J ; Ishihara, M
Japan Atomic Energy Research Institute
Japan, 2000
Journal of the Society of Materials Science, Japan 49, (10), 1115-1120 Oct. 2000
ISSN: 0514-5163
Country of Publication: Japan
Journal Announcement: 0105
Document Type: Article
Language: JAPANESE
Abstract: An analytical study on thermal diffusivity for anisotropic materials using a laser flash method was carried out to clarify the applicability of the method which has been established for an isotropic materials. A measurement error for anisotropic materials caused by the laser pulse intensity distribution was estimated analtyically using a finite element calculation code. In this paper the analytical result on the measurement error of the anisotropic materials was presented and the applicability of the laser flash method to the anisotropic material was discussed. Numerical Data; Graphs. 4 ref.

2/7/29
DIALOG(R)File 32:METADEX(R)

1253666 MA Number: 200105-35-1253
Study on the macro-cell corrosion of steel in concrete containing chloride.
Yan, P ; You, Y
Tsinghua University
China, 2000
Cailiao Kexue yu Gongcheng (Materials Science and Engineering) (China) 18, 46-48, 11 Apr.-June 2000
ISSN: 1004-793X
Country of Publication: China
Journal Announcement: 0105
Document Type: Article
Language: CHINESE
Abstract: The relationship of the corrosion rate of steel and the resistance of concrete was studied to characterize the macro-cell corrosion of reinforcement in the concrete containing chloride. A changeable resistance was linked in series between the anion and cathode of the macro-cell to simulate the change of the concrete resistance. The results show that the corrosion potential of reinforcement is mainly determined by the anion reaction while the corrosion rate is controlled by the cathode reaction. There is a superior influence of the concrete resistance upon the corrosion rate of reinforcement. Graphs. 3 ref.

2/7/30
DIALOG(R)File 32:METADEX(R)

1252183 MA Number: 200105-35-1167
Competitive role of inhibitive and aggressive ions in the corrosion of steel in concrete.
Muralidharan, S ; Saraswathy, V ; Thangavel, K ; Srinivasan, S
Central Electrochemical Research Institute (India)
Netherlands, 2000
Journal of Applied Electrochemistry 30, (11), 1255-1259 Nov. 2000
ISSN: 0021-891X
Country of Publication: Netherlands
Journal Announcement: 0105

Document Type: Article
Language: ENGLISH
Abstract: The effect of various inhibitive ions (hydroxide, citrate, stannate) for the corrosion of steel in concrete was studied by weight loss measurements, chronopotential studies, anodic polarization technique and compressive strength tests. The salient features of the investigation were: in 100% OPC and in OPC+fly ash (3:1 ratio) extracts the passivity of steel was readily destroyed even by the presence of 10 000 ppm of chloride. However in 100% OPC and also in OPC+fly ash (3:1 ratio) extracts containing inhibitive and complexing agents like hydroxide, citrate and stannate, the passivity of steel was maintained even in the presence of 30 000 ppm of chloride. The addition of inhibitive ions like hydroxide, citrate and stannate not only decreased the corrosion rate of steel in simulated concrete environments but also increased the compressive strength of mortars. Citrates, stannates and CaO are effective inhibitors of the corrosion of steel in concrete. Numerical Data; Graphs. 22 ref.

2/7/31
DIALOG(R)File 32:METADEX(R)

1251403 MA Number: 200104-61-0537
Practical and economic aspects of application of austenitic stainless steel, AISI 316, as reinforcement in concrete.
Klinghoffer, O ; Frolund, T ; Kofoed, B ; Knudsen, A ; Jensen, F M ; Skovsgaard, T
FORCE Institute
Conference: Corrosion of Reinforcement in Concrete: Corrosion Mechanisms and Corrosion Protection, Aachen, Germany, 1999
UK, 2000
European Federation of Corrosion Publications 31, 121-133 2000
ISSN: 1354-5116
Country of Publication: UK
Report No.: Book No. 746
Journal Announcement: 0104
Document Type: Conference Paper
Language: ENGLISH
Abstract: Reinforced concrete used for housing and industrial construction is often damaged due to corrosion of the reinforcement. The total cost in the EC for repair of damages caused by corrosion may be estimated from the cost in the UK on highways alone to be approx50M ECU per year. A way to lengthen the lifetime fo structure is to use corrosion resistant reinforcing materials, e.g. stainless steel. The intelligent use of stainless steel, which means combining with traditional carbon steel in locations exposed to very corrosive environments, can be a very cost-effective option when considering different rehabilitation methods. However, most civil engineers have an unfounded fear of using stainless steel and carbon steel together in the same concrete structure. For this reason, the behavior of the austenitic stainless steel, AISI 316, in connection with carbn steel has been evaluated in order to study the consequences of galvanic coupling for corrosion reinforced concrete structures. The experimental study includes results from different concrete samples, in which AISI 316, stainless steel, has been combined with carbon steel in the proportions that are foreseen for on-site applications. These results include measurements of the macrocouple current between stainless steel and carbon steel during exposure to accelerated ingress of chloride. Additionally, measurements of electrochemical potentials and corrosion rate of the macrocouple were made. The obtained results show that galvanic coupling with stainless steel results in an enhanced corrosion rate of the active carbon steel in a chloride-contaminated solution. A Life Cycle Cost calculation, based on practical cases of repaired bridge columns, has confirmed that the intelligent use of stainless steel in cobmination with carbon steel is very cost-effective. Graphs. 16 ref.

2/7/32
DIALOG(R)File 32:METADEX(R)

1250480 MA Number: 200104-35-1154
Water-disperse paints (WDP) for corrosion protection of steel and reinforced concrete structures.
Lobkovskij, V P ; Luk'yanenko, N A
Russia, 2000
Stroitel'nye Materialy 10, 32-33 Oct. 2000
ISSN: 0585-430X
Country of Publication: Russia
Journal Announcement: 0104
Document Type: Article
Language: RUSSIAN
Abstract: The aim of the paper is to describe the WDP developed for corrosion protection of steel and reinforced concrete structures. The presented WDP have the following advantages: total absence of toxic and combustible substances and therefore their ecological value; fire- and explosion-safety of WDP production and application; low temperature of coating solidification; wasteless process and low prices. The paper contains recommendations for using the concrete kinds of WDP for corrosion protection of different versions of metal and reinforced concrete structures. 2 ref.

2/7/33
DIALOG(R)File 32:METADEX(R)

1250470 MA Number: 200104-35-1144
Layer zinc anodes in cathodic protection of steel reinforcement.
Bohdanowicz, W
Technical University of Gdansk
Conference: Corrosion of Reinforcement in Concrete: Corrosion Mechanisms and Corrosion Protection, Aachen, Germany, 1999
UK, 2000
European Federation of Corrosion Publications 31, 101-107 2000
ISSN: 1354-5116
Country of Publication: UK
Report No.: Book No. 746
Journal Announcement: 0104
Document Type: Conference Paper
Language: ENGLISH
Abstract: The continuing increase in the number of reinforced concrete structures being built, their cost and strategic importance, require that good attention is given to their durability. In the case of reinforced concrete road structures, contaminated with chlorides during winter from de-icing salts, cathodic protection provides a modern method of corrosion protection. Inert anodes as used in impressed current schemes in industrialised countries may pose a threat to concrete durability due to acidification of the environment close to the anode. This work presents the preliminary examination results of the cathodic polarisation of concrete reinforcement either by the use of an external, layer-like zinc anode as a galvanic (sacrificial) anode or the use impressed current anodes. The results indicate that each solution could be very useful for structures of national highways. Graphs. 9 ref.

2/7/34
DIALOG(R)File 32:METADEX(R)

1250469 MA Number: 200104-35-1143

Sacrificial anodes for cathodic prevention of reinforcing steel around patch repairs applied to chloride-contaminated concrete.

Sergi, G ; Page, C L
Building Research Establishment (UK)

Conference: Corrosion of Reinforcement in Concrete: Corrosion Mechanisms and Corrosion Protection, Aachen, Germany, 1999
UK, 2000
European Federation of Corrosion Publications 31, 93-100 2000
ISSN: 1354-5116
Country of Publication: UK
Report No.: Book No. 746
Journal Announcement: 0104
Document Type: Conference Paper
Language: ENGLISH

Abstract: When steel reinforcement suffers localised corrosion in chloride-contaminated concrete, the most anodic regions of the metal effectively provide cathodic protection to the bars in adjacent cathodic areas. If conventional patch repair is applied to the structure, this form of adventitious cathodic protection is removed and bars which were previously behaving as cathodes in moderately contaminated areas may be transformed to anodes of cells, coupled to cathodic steel in the repaired areas. This paper demonstrates the effectiveness of combining patch repair with embedded sacrifical anodes as a means of providing continuing protection to the surrounding reinforcing bars. The sacrificial anodes designed for this purpose consist of metallic zinc in a specially formulated mortar sturated with lithium hydroxide. The high pH pore electrolyte serves to maintain the activity of the zinc, while the present of lithium ions avoids the risks of alkali-silica reaction that would be incurred if other forms of alkali metal hydroxide were used. Graphs. 4 ref.

2/7/35

DIALOG(R)File 32:METADEX(R)

1250466 MA Number: 200104-35-1140

Organic corrosion inhibitors for steel in concrete.

Elsener, B ; Buchler, M ; Bohni, H
Eidgenossische Technische Hochschule Zurich

Conference: Corrosion of Reinforcement in Concrete: Corrosion Mechanisms and Corrosion Protection, Aachen, Germany, 1999
UK, 2000
European Federation of Corrosion Publications 31, 61-71 2000
ISSN: 1354-5116
Country of Publication: UK
Report No.: Book No. 746
Journal Announcement: 0104
Document Type: Conference Paper
Language: ENGLISH

Abstract: The efficiency of an organic corrosion inhibitor blend in preventing and stopping ongoing chloride-induced corrosion of mild steel has been investigated in saturated. Ca(OH) sub 2 solutions and in ordinary Portland cement (OPC) mortar. The results show that only high concentrations of the inhibitor (approx =10%) allow the inhibition of pit initiation in solution. However, the inhibiting properties can be lost either by evaporation of the volatile constituent of the inhibitor or by the precipitaton of the non-volatile fraction of the inhibitor in presence of calcium ions. The addition of the inhibitor blend to mortar yielded no inhibiting effect except the retardation of the corrosion initiation in the case of chloride-induced corrosion. Once corrosion had started the polarisation resistance values were similar for samples with and without inhibitor. On already corroding steel samples in chloride-containing saturated Ca(OH) sub 2 solutions a slight increase (approx3-4x) of the polarisation resistance was found after adding 10% inhibitor to the

solutions. No significant increase of the polarisation resistance was observed after applying the inhibitor on chloride-containing mortar samples with corroding steel. Field tests on chloride-contaminated structures also showed that virtually no effect of the surface applied organic inhibitor blend on half cell potentials or a reduction of macrocell currents were found. Graphs. 18 ref.

2/7/36
DIALOG(R)File 32:METADEX(R)

1250464 MA Number: 200104-35-1138
Comparison of electrochemical data and mass loss corrosion rate measurements for steel reinforcement in concrete.
Novak, P ; Mala, R
Institute of Chemical Technology (Czech Republic)
Conference: Corrosion of Reinforcement in Concrete: Corrosion Mechanisms and Corrosion Protection, Aachen, Germany, 1999
UK, 2000
European Federation of Corrosion Publications 31, 41-48 2000
ISSN: 1354-5116
Country of Publication: UK
Report No.: Book No. 746
Journal Announcement: 0104
Document Type: Conference Paper
Language: ENGLISH
Abstract: The average corrosion rates of steel reinforcement with different initial surface conditions (nu sub corr) calculated from mass loss after four-year exposure in concrete were evaluated in relation to the average free corrosion potential (E sub corr) and polarisation resistance (R sub p). The corrosion of pre-rusted steel in concrete could not be evaluated reliably based on the E sub corr value. Qualitative correlation of E sub corr and nu sub corr was found only for machined and scaled surfaces. R sub p values were in good qualitative agreement with nu sub corr for all the tested surface conditions. At polarisation resistances >30 Omega m exp 2 , nu sub corr values were <2 mu m/year. Graphs. 12 ref.

2/7/37
DIALOG(R)File 32:METADEX(R)

1250461 MA Number: 200104-35-1135
Oxygen reduction on mild steel and stainless steel in alkaline solutions.
Jaggi, S ; Elsener, B ; Bohni, H
Eidgenossische Technische Hochschule Zurich
Conference: Corrosion of Reinforcement in Concrete: Corrosion Mechanisms and Corrosion Protection, Aachen, Germany, 1999
UK, 2000
European Federation of Corrosion Publications 31, 3-12 2000
ISSN: 1354-5116
Country of Publication: UK
Report No.: Book No. 746
Journal Announcement: 0104
Document Type: Conference Paper
Language: ENGLISH
Abstract: The cathodic polarisation curve of steel in alkaline solutions always shows three regions: (1) oxygen reduction with a Tafel behavior at potentials cathodic to the open circuit potential followed by (2) a diffusion limited current of oxygen reduction at more negative potentials and (3) hydrogen evolution at very negative potentials. The diffusion limited region of the cathodic current density is controlled both by the oxygen concentration in solution and the flow rate whereas in the Tafel region (charage transfer) the temperature and the pretreatment of the

sample determine the intensity of the current density and the slope of the Tafel line. On stainless steels the cathodic reduction currentes are lower then on mild steel. It can be concluded that under usual corrosion conditions for steel in concrete the cathodic oxygen reduction is not diffusion limited but charge transfer controlled. Graphs. 13 ref.

2/7/38
DIALOG(R)File 32:METADEX(R)

1250399 MA Number: 200104-35-1073
Electrochemical methods for evaluating inhibitors of steel corrosion in concrete.
Dhouibi, L ; Triki, E ; Raharinaivo, A ; Trabanelli, G ; Zucchi, F
Ecole Nationale d'Ingenieurs de Tunis
UK, 2000
British Corrosion Journal 35, (2), 145-149 2000
ISSN: 0007-0599
Country of Publication: UK
Journal Announcement: 0104
Document Type: Article
Language: ENGLISH
Abstract: Electrochemical methods were used to evaluate sodium phosphate and sodium nitrite as inhibitors for the corrosion of steel in saturated calcium hydroxide solution containing chloride ions. The studies included immersion, potentiodynamic, potentiostatic, and galvanostatic tests. The results obtained from these methods were in good agreement. They show that sodium nitride is an anodic inhibitor which is not effective if its concentration is lower than that of the chloride ions. Sodium phosphate acts as an anodic inhibitor if its concentration is >0.6 times the chloride concentration. It is totally effective when its concentration equals the chloride concentration. Graphs; Photomicrographs. 5 ref.

2/7/39
DIALOG(R)File 32:METADEX(R)

1245638 MA Number: 200103-35-0771
A study on corrosion rate of reinforcing steel bars in cracked concrete.
Tsukahara, E ; Uomoto, T
Japan Concrete Institute
Japan, 2000
Concrete Research and Technology 11, (1), 75-84 Jan. 2000
ISSN: 1340-4733
Country of Publication: Japan
Journal Announcement: 0103
Document Type: Article
Language: JAPANESE
Abstract: Reinforced concrete is an excellent composite system combining both steel and concrete. However, when a crack is formed in concrete both water and oxygen can easily approach to the surface of steel in concrete, and this causes corrosion of steel reinforcement. The corrosion reduces the performance of reinforced concrete structure. This paper aims to evaluate the corrosion rate of steel in concrete quantitatively, in chloride environment. The results show that corrosion rate of reinforcing steel bar can be predicted numerically by applying different chloride boundary conditions to cracked portion and other surfaces. The effect of temperature is also examined by both experiment and computer simulation. Numerical Data ; Graphs. 11 ref.

2/7/40

DIALOG(R)File 32:METADEX(R)

1245620 MA Number: 200103-35-0753
Corrosion behaviour of stainless steels in chloride contaminated and carbonated concrete.
Bertolini, L ; Gastaldi, M ; Pastore, T ; Pedeferri, M P
Politecnico di Milano
Switzerland, 2000
International Journal for Restoration of Buildings and Monuments 6, (3), 273-292 2000
ISSN: 0947-4498
Country of Publication: Switzerland
Journal Announcement: 0103
Document Type: Article
Language: ENGLISH
Abstract: The paper deals with the corrosion resistance of different stainless steels in chloride contaminated and carbonated concrete. Stainless steel reinforcement has a higher corrosion resistance as compared to the normal carbon steel reinforcement; stainless steels can, however, be subject to localized corrosion if the chloride content in the cong\crete exceeds a certain critical value. This critical value depends on the pH value of the concrete (i.e. carbonated or alkaline concrete), the temperature, the corrosion potential (function of environmental conditions), and the composition and microstructure of the stainless steel. Furthermore, in the rehabilitation of corroding reinforced concrete structures, stainless steel is often used in structures reinforced with normal carbon steel and galvanic coupling can occur. The results of measurements of free corrosion potential, corrosion rate and macrocouple current in reinforced concrete specimens are reported as a function of chloride concentration and humidity. The consequence of coupling with carbon steel reinforcement is also considered. Graphs. 11 ref.

2/7/41
DIALOG(R)File 32:METADEX(R)

1243920 MA Number: 200102-35-0450
Corrosion control of steel-reinforced concrete.
Chung, D D L
State University of New York (Buffalo)
USA, 2000
Journal of Materials Engineering and Performance 9, (5), 585-588 Oct. 2000
ISSN: 1059-9495
Country of Publication: USA
Journal Announcement: 0102
Document Type: Article
Language: ENGLISH
Abstract: The methods and materials for corrosion control of steel-reinforced concrete are reviewed. The methods are steel surface treatment, the use of admixtures in conctrete, surface coating on concrete, and cathodic protection. Numerical Data. 106 ref.

2/7/42
DIALOG(R)File 32:METADEX(R)

1238934 MA Number: 200101-35-0170
Crevice effect on corrosion of steel in simulated concrete pore solutions.
Sagues, A A ; Li, L ; Pickering, H W

University of South Florida
USA, 2000
Corrosion 56, (10), 979-982 Oct. 2000
ISSN: 0010-9312
Country of Publication: USA
Journal Announcement: 0101
Document Type: Article
Language: ENGLISH
Abstract: Effect of a crevice on the breakdown potentials (E sub b) of carbon steel specimens in pH 12.6 saturated calcium hydroxide (Ca[OH] sub 2) solution (SCS) and pH 13.6 simulated concrete pore solution (SPS) with 0.01-1.0 M chloride concentration ([Cl exp -]) was studied with potentiodynamic polarization. The presence of a crevice substantially lowered (by approx0.2 V) the E sub b in SCS when [Cl exp -]>=0.1 M. In SPS, passive film breakdown did not take place up to the oxygen evolution potential (OEP) in the absence of a crevice. However, corrosion developed in the crevice at potentials approx0.5 V below the OEP when a crevice was introduced and [Cl exp -]>=0.1 M. Graphs. 16 ref.

2/7/43
DIALOG(R)File 32:METADEX(R)

1238867 MA Number: 200101-35-0103
Electrical resistance changes as an alternate method for monitoring the corrosion of steel in concrete and mortar.
Cella, P A ; Taylor, S R
University of Virginia
USA, 2000
Corrosion 56, (9), 951-959 Sept. 2000
ISSN: 0010-9312
Country of Publication: USA
Journal Announcement: 0101
Document Type: Article
Language: ENGLISH
Abstract: A very sensitive, unambiguous, and simple procedure was introduced for the assessment of corrosion in concrete. This method consists of making resistance change measurements (RCM) on small diameter (228.6 mu m) 1040 steel (UNS G10400) wires embedded in concrete (or mortar) prisms and correcting the measurements for temperature by use of a noncorroding control wire. Metal loss caused by corrosion lead to a loss in cross-sectional area and, hence, an increase in resistance. Through proper temperature corection, these methods lead to a sensitivity of 1 mu m diameter loss. The wires were heat-treated at 538 deg C for 1 h to attain an oxide chemistry similar to bare rebar, as determined by x-ray photoelectron specroscopy. Although this method was designed for the evaluation of inhibitive admixtures, it was used in the present study to examine supplementary cementitious materials. The rate of steel corrosion in these was assessed by RCM using mortar prisms (25.4x5x5 cm) of the following composition: plain mortar, 50% slag, 25% fly ash, and 6% silica fume. These prisms were ponded with 0.6 M sodium chloride (NaCl) for 140 days and subsequently wet/dry cycled for an additional 140 days. Wires in blocks containing slag, fly ash, and silica fume showed fewer instances of corrision and lower average rates of corrosion than wires in plain mortar. Slag additions were shown to be more effective than fly ash additions at mitigating corrosion, while silica fume was effecive only at deeper cover depths. The RCM method also was compared to electochemical methods: open-circuit potential measurements (half-cell potentials), linear polarization, and electrochemical impedance spectroscopy. In all cases, RCM was more sensitive and definitive on the steel corrosion rates within the mortar. The simplicity and low cost of this approach make it ideally suited as a standard method to assess corrosion prevention methods in concrete. Graphs. 16 ref.

2/7/44
DIALOG(R)File 32:METADEX(R)

1236916 MA Number: 200012-35-3018
Maintenance and rehabilitation considerations for corrosion control of atmospherically exposed existing steel-reinforced concrete structures.
NACE International
Publ: NACE International, P.O. Box 218340, Houston, TX 77218, USA, 2000
NACE International Book of Standards, Volume 1 RP0390-98 2000
ISSN: 1-877914-50-9
Country of Publication: USA
Journal Announcement: 0012
Document Type: Standard
Language: ENGLISH
Abstract: This standard presents corrosion control guidelines that are applicable to existing atmospherically exposed structures made of conventionally reinforced concrete. These guidelines may be used to develop specifications involving repair and rehabilitation of steel-reinforced concrete structures. These guidelines should be used primarily when repair or rehabilitation is being implemented because of deterioration resulting from the corrosion of steel reinforcement. 13 ref.

2/7/45
DIALOG(R)File 32:METADEX(R)

1236906 MA Number: 200012-35-3008
Design considerations for corrosion control of reinforcing steel in concrete.
NACE International
Publ: NACE International, P.O. Box 218340, Houston, TX 77218, USA, 2000
NACE International Book of Standards, Volume 1 RP0187-96 2000
ISSN: 1-877914-50-9
Country of Publication: USA
Journal Announcement: 0012
Document Type: Standard
Language: ENGLISH
Abstract: The purpose of this standard is to given architect-engineers and facility owners design considerations for controlling corrosion of proposed reinforced concrete structures. These considerations include guidelines that provide the architect-engineer with information about the causes of and control methods for the corrosion of reinforcing steel in portland cement concrete structures. 39 ref.

2/7/46
DIALOG(R)File 32:METADEX(R)

1233564 MA Number: 200011-35-2836
Effect of admixtures in concrete on the corrosion resistance of steel reinforced concrete.
Hou, J ; Chung, D D L
State University of New York (Buffalo)
USA, 2000
Corrosion Science 42, (9), 1489-1507 Sept. 2000
ISSN: 0010-938X
Country of Publication: USA
Journal Announcement: 0011

Document Type: Article
Language: ENGLISH

Abstract: The effect of admixtures, namely silica fume, latex, methylcellulose and short carbon fibers (in various combinations), in concrete on the corrosion resistance of steel reinforced concrete was assessed by measuring the corrosion potential and corrosion current density during immersion in Ca(OH) sub 2 and NaCl solutions. Silica fume (15% by weight of cement) was most effective for improving the corrosion resistance, due to decrease of water absorptivity, and not so much due to increase in eletrical resistivity. Latex (20% by weight of cement) improved the corrosion resistance because it decreased the water absorptivity and increased the electrical resistivity. Methylcellulose (04.% by weight of cement) improved corrosion resistance only slightly. Carbon fibers (0.5% by weight of cement) decreased the corrosion resistance due to decrease in electrical resistivity. However, the negative effect could be compensated by adding either silica fume or latex, which reduced the water absorptivity. Graphs. 29 ref.

2/7/47

DIALOG(R)File 32:METADEX(R)

1233518 MA Number: 200011-35-2790

Measurement of steel corrosion in concrete by electrochemical techniques: influence of the redox processes in oxide scales.

Andrade, C ; Bolzoni, F ; Cabeza, M ; Novoa, X R ; Perez, M C
Instituto de Ciencias de las Construccion Eduardo Torroja

Conference: Electrochemical Approach to Selected Corrosion and Corrosion Control Studies, Pavia, Italy, Sept. 1999
UK, 2000
European Federation of Corrosion Publications 28, 332-343 2000
ISSN: 1354-5116
Country of Publication: UK
Report No.: Book No. 733
Journal Announcement: 0011

Document Type: Conference Paper
Language: ENGLISH

Abstract: Alternating and direct current electrochemical measurements were performed on various types of reinforced concrete probes: atmosphere-aged and chloride-contaminated. The samples were selected so that the corrosion potential was equal to ore more positive than -0.3 V vs. SCE. From the a.c. results an interpretation is given of the commonly observed difficulty in reaching the steady state when performing d.c. measurements. The interpretation is based on the redox activity of the oxide layer in this potential range. A Linear Polarisation method is propsoed that allows the measurement of the charge transfer resistance to be associated correctly to the corrosion process. The undesired contributions that need to be eliminated are the bulk concrete resistance and the resistance associated with Fe sub 3 O sub 4Fe sub 2 O sub 3 transformations. Graphs. 30 ref.

2/7/48

DIALOG(R)File 32:METADEX(R)

1231561 MA Number: 200011-35-2655

A predeterminate model of steel bar corrosion ratio considered of concrete carbonation model.

Jin, W -L ; Yan, F ; Zhang, L
Zhejiang University

China, 2000
Zhejiang Daxue Xuebao (Gongxue Ban)/Journal of Zhejiang University

(Engineering Science) 34, (2), 158-163 Mar. 2000
ISSN: 1008-973x
Country of Publication: China
Journal Announcement: 0011
Document Type: Article
Language: CHINESE
Abstract: Abstract Based on the theory of corrosion electrochemistry, a new predeterminate model of steel bar corrosion ratio in concrete under common air condition is established, which considered the effect of Concrete Carbonation Model (CCM) and the variation of steel bars radius. Theoretical analysis shows both that consideration is necessary, meanwhile, the stirrup would be corroded more seriously than the longitudinal steel bar in the same member, so that it is necessary to pay important attention to the problem of shear failure. The relationship between the steel corrosion ratio and parameters in the predeterminate model is also discussed in the paper, and some useful results are obtained. Numerical Data; Graphs. 9 ref.

2/7/49
DIALOG(R)File 32:METADEX(R)

1226275 MA Number: 200009-35-2442
Carbonation of concrete and corrosion of steel bars in existing reinforced concrete structures.
Kitago, Y ; Miyagawa, T
JR West Japan Consultants
Japan, 2000
Journal of the Society of Materials Science, Japan 49, (4), 413-419 Apr. 2000
ISSN: 0514-5163
Country of Publication: Japan
Journal Announcement: 0009
Document Type: Article
Language: JAPANESE
Abstract: In this paper, the cause of corrosion of steel bars in concrete, particularly carbonation of concrete and the effect of repair work are discussed according to comprehensive investigation of existing reinforced concrete structures. A coefficient of carbonation rate (= alpha) which is calculated from the examination exceeds the usual value. Deviations of the coefficient of carbonation rate (= alpha) have a tendency to be smaller in the past few years. A depassivated critical value of the difference between cover and carbonation depth is nearly 10 mm or less. When the difference between those values is 0 mm, the steel bars are perfectly depassivated. When the half cell potential is nearly -120 mV vs Ag/AgCl, the depassivation begins and if the potentials is - 230 mV vs Ag/AgCl, the steel bar is also perfectly depassivated. There is little influences of chloride on the corrosion of steel bars in existing carbonated concrete. The difference between cover and carbonation depth has the most important role in the corrosion of steel bars. Numerical Data; Graphs. 11 ref.

2/7/50
DIALOG(R)File 32:METADEX(R)

1222943 MA Number: 200008-35-2231
Influence of permeability reducing and corrosion inhibiting admixtures in concrete upon initiation of salt induced embedded steel corrosion.
Charvin, S ; Hartt, W H ; Lee, S ; Powers, R G
Florida Atlantic University
Conference: Corrosion 2000, Orlando, FL, USA, 26-31 Mar. 2000

Publ: NACE International, P.O. Box 218340, Houston, TX 77218, USA, 2000
Corrosion 2000 00802.1-00802.27 Mar. 2000
Country of Publication: USA
Journal Announcement: 0008
Document Type: Conference Paper
Language: ENGLISH
Abstract: The research reported herein was performed for the purpose of determining threshold chloride concentrations for high performance concretes under exposure conditions relevant to coastal bridge substructures in Florida. The experiments were based upon a series of reinforced and non-reinforced concrete specimens that contained 20, 35, and 50 percent cement replacement by fly ash, 3, 8, and 15 percent cement replacement by silica fume, and control specimens (no pozzolanic admixture). In addition, the utility of calcium nitrite as a corrosion inhibitor was evaluated based upon slabs that contained 1) 35 percent cement replacement with fly ash and 11.6 l/m exp 3 (4 gal/yd exp 3) calcium nitrite, 8 percent cement replacement with silica fame and 5.8 l/m exp 3 (2 gal/yd exp 3) calcium nitrite, and controls (no pozzalanic admixture with (11.6 l/m exp 3) 4 gal/yd exp 3 calcium nitrite). The specimens, as of this writing, have been exposed to a one week wet - one week dry ponding cycle with natural sea water for approximately 57 months. Numerical Data; Graphs. 23 ref.

2/7/51
DIALOG(R)File 32:METADEX(R)

1222939 MA Number: 200008-35-2227
EIS measurements on cathodically protected steel in concrete.
Talavera, M A ; Perez, T ; Genesca, J ; Castro, P
Universidad Nacional Autonoma de Mexico
Conference: Corrosion 2000, Orlando, FL, USA, 26-31 Mar. 2000
Publ: NACE International, P.O. Box 218340, Houston, TX 77218, USA, 2000
Corrosion 2000 00794.1-00794.9 Mar. 2000
Country of Publication: USA
Journal Announcement: 0008
Document Type: Conference Paper
Language: ENGLISH
Abstract: The use of sacrificial zinc anodes for cathodic protection (CP) of steel in reinforced concrete is a subject of increasing interest in Mexico, specially for their potential applications on highway bridges seriously damaged by chloride contamination. One anode material gaming acceptance is thermally sprayed zinc (TSCP). In this paper, the feasibility of using EIS, as a monitoring tool to determine if the CP level is sufficient to mitigate corrosion was investigated for carbon steel in concrete. As a first approach, this investigation deals with the behavior of the galvanic couple steel/zinc under CP conditions in NaCl solution. The EIS diagrams obtained were compared with those corresponding to laboratory concrete slabs, whose surface was thermal sprayed with Zn. Graphs. 3 ref.

2/7/52
DIALOG(R)File 32:METADEX(R)

1221318 MA Number: 200008-35-2077
Measuring adhesion of coatings to concrete and steel.
Cunningham, T ; Steele, J
Transocean Anti-Corrosion
Conference: Corrosion 2000, Orlando, FL, USA, 26-31 Mar. 2000
Publ: NACE International, P.O. Box 218340, Houston, TX 77218, USA, 2000

Corrosion 2000 00614.1-00614.7 Mar. 2000
Country of Publication: USA
Journal Announcement: 0008
Document Type: Conference Paper
Language: ENGLISH
Abstract: Adhesion of Coatings to both steel and concrete is often used as a measurement of the integrity of the coating system. Different methods of measurement may lead to varying test results. The authors discuss current methods of measuring adhesion on both surfaces and consider the best ways to achieve consistent results. Numerical Data.

2/7/53
DIALOG(R)File 32:METADEX(R)

1214075 MA Number: 200006-35-1453
Corrosion inhibition behaviour of diethylenetriamine/thiourea adduct for steel reinforcements in concrete.
Wang, S ; Lin, W ; Zhang, J ; Fang, Z
Tongji University
China, 2000
Journal of Chinese Society for Corrosion and Protection 20, (1), 15-21 Feb. 2000
ISSN: 1005-4537
Country of Publication: China
Journal Announcement: 0006
Document Type: Article
Language: CHINESE
Abstract: A new polymer DETA-TU (isomolar adduct of diethylenetriamine and thiourea) was first introduced into reinforced concrete to inhibit corrosion of the embedded steel reinforcements. Its inhibition behavior and mechanism were studied with lienar polarization, Tafel polarization, EIS method either in simulated pore solution (SPS) or in real concrete. The results showed that DETA-TU was a mixing type inhibitor. A 1% dosage was sufficient to hinder the corrosion of steel bar in SPS containing 0.1 mol/L NaCl. The salt endurance was increased from 0.02-0.10 mol/L. The results also showed DETA-TU and NaNO sub 2 had a significiant synergistic effect for corrosion inhibition of reinforcing bar, especially at lower NaNO sub 2 concentration. The EIS revealed the double beneficial function of DETA-TU for reinforced concrete, i.e., densifying the concrete pore structure and adsorbing on the surface of the steel reinforcement. YPS analysis showed the inhibition was concentrated at the steel/concrete interface. The concentration gradient of DETA-TU from the steel/concrete interface and bulk concrete was crucial for its inhibition efficiency. Graphs. 8 ref.

2/7/54
DIALOG(R)File 32:METADEX(R)

1210598 MA Number: 200005-35-1263
Overview on electrochemical parameters to assess the corrosion state of steel reinforcement in CAC mortar and concrete.
Sanjuan, M A
Instituto Espanol del Cemento y sus Aplicaciones
USA, 2000
Journal of Materials Science 35, (1), 105-108 1 Jan. 2000
ISSN: 0022-2461
Country of Publication: USA
Journal Announcement: 0005
Document Type: Article
Language: ENGLISH
Abstract: Calcium Aluminate Cement (CAC) can be used successfully in

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mortars and concretes for special applications such as refractory and
sulphate-resistant materials. However, some failures have been reported
when used in reinforced concrete exposed to wet environments in presence of
chloride ions. Chloroaluminates formation in either reinforced CAC mortar
or concrete could be a way to reduce chloride ions in the pore solution of
this material, thereby, decreasing the risk of corrosion. This paper
presents the characteristic values of corrosion rate, corrosion potential
and resistivity and the relationship between them. Assuming a significant
corrosion state at corrosion rate values over 0.1 mu A/cm exp 2 , we can
establish a threshold level for corrosion initiation in reinforced mortar
or concrete of -250 mV and 10 exp 4 Omega cm. Therefore, lesser values
constitute important corrosion rates. Numerical Data; Graphs. 7 ref.
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