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**DEGRADATION OF NORMAL PORTLAND AND
SLAG CEMENT CONCRETE UNDER LOAD,
DUE TO REINFORCEMENT CORROSION**

**DÉGRADATION DU BÉTON NORMAL PORTLAND ET À CIMENT
À LAITIER SOUS CHARGE, DUE À LA CORROSION DES ARMATURES**

K.E. PHILIPOSE, J.J. BEAUDOIN, and R.F. FELDMAN

Presented at the 4th CANMET International Conference in Istanbul, Turkey, 1992 May 3-8.

Chalk River Laboratories

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DÉGRADATION DU BÉTON NORMAL PORTLAND ET À CIMENT À LAITIER
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par

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RÉSUMÉ

La corrosion des armatures est l'un des mécanismes importants de dégradation des éléments de béton armé. La majorité des études publiées de corrosion de l'armature d'acier du béton intéressent des échantillons non chargés. Toutefois, le béton de construction subit une déformation importante au voisinage des armatures d'acier qui résistent aux charges (contraintes) de traction - ce qui produit un système (réseau) de microfissures.

Dans ce rapport, on présente les premiers résultats d'une étude effectuée pour déterminer l'effet de la charge appliquée et de la microfissuration sur la vitesse de pénétration de l'ion de chlorure et de corrosion de l'acier dans le béton. On a soumis à une charge des échantillons de poutres en béton à un seul support pour produire une déformation maximale d'environ 600 $\mu\epsilon$ sur la face de traction. On a surveillé la pénétration de l'ion de chlorure sur des carottes prélevées de poutres chargées, à l'aide de techniques d'analyse XDE. Parmi les variables étudiées, il y a deux types de béton, deux épaisseurs d'enrobage de l'acier, trois niveaux de charge appliquée, des ronds d'acier à béton soudés et non soudés et l'exposition des faces de traction et compression de poutres à la solution de chlorure. Un mélange à béton a comporté du ciment Portland de type 10, l'autre mélange a comporté 75% de laitier de haut fourneau, 22% de ciment de type 50 et 3% de fumée de silice.

On a établi que la vitesse de pénétration de l'ion de chlorure dans le béton armé, d'où le temps qu'il faut à l'ion de chlorure pour parvenir à l'armature d'acier, est fonction de la charge appliquée et de la qualité du béton. On examine la dépendance des descripteurs (identificateurs) de processus de corrosion -- formation de la couche passive, temps d'amorçage et temps de propagation -- vis-à-vis du niveau de charge appliquée.

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ABSTRACT

The corrosion of reinforcement is one of the major degradation mechanisms of reinforced concrete elements. The majority of studies published on concrete-steel corrosion have been conducted on unstressed specimens. Structural concrete, however, is subjected to substantial strain near the steel reinforcing bars that resist tensile loads, which results in a system of microcracks.

This report presents the initial results of an investigation to determine the effect of applied load and microcracking on the rate of ingress of chloride ion and corrosion of steel in concrete. Simply-supported concrete beam specimens were loaded to give a maximum strain of about 600 $\mu\epsilon$ on the tension face. Chloride ion ingress on cores taken from loaded specimens was monitored using energy-dispersive X-ray analysis techniques. Corrosion current and rate measurements using linear polarization electrochemical techniques were also obtained on the same loaded specimens. Variables investigated included two concrete types, two steel cover-depths, three applied load levels, bonded and unbonded rebars and the exposure of tension and compression beam faces to chloride solution. One concrete mixture was made with type 10 Portland cement, the other with 75% blast-furnace slag, 22% type 50 cement and 3% silica fume.

The rate of chloride ion ingress into reinforced concrete, and hence the time for chloride ion to reach the reinforcing steel, is shown to be dependent on applied load and the concrete quality. The dependence of corrosion process descriptors--passive layer formation, initiation period and propagation period--on the level of applied load is discussed.

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1. INTRODUCTION

The premature deterioration of some parts of concrete structures, such as highway bridge decks after only a few years of service, can be attributed to the corrosion of reinforcing steel. The pH environment of concrete is alkaline enough to afford natural protection of the reinforcing steel. This protective layer around the steel can be breached when chlorides from de-icing salts or salts added to concrete mix come into contact with the reinforcing bars. As the concentration of chloride ions adjacent to the reinforcing steel increases with time, the protective layer is depassivated and corrosion of the steel is initiated. The reinforcement corrodes and an increase in volume takes place due to the formation of rust. The increase in volume exerts internal forces on the concrete, which results in deterioration caused by cracking and spalling.

The rate of corrosion is usually very slow and thus long-term experiments are required to study it. However, it is well understood that, for corrosion to start, sufficient oxygen must be available, and chloride ions must come in contact with the reinforcing steel. Hence the diffusion rate of chlorides and oxygen through the concrete covering the steel reinforcing bars and the depth of concrete cover are two important parameters. When service loads are applied to a reinforced element, mechanical strains are induced in the reinforcing bars. As the bars elongate, the concrete around the bars experiences microcracking, as the modulus of elasticity of concrete is only one tenth that of steel. These microcracks can provide channels in concrete for the penetration of chloride ions. Although the diffusion rate is influenced by the concrete's permeability, the degree of microcracking of the concrete can also be an important parameter that influences reinforcement corrosion.

Since very little information is available in the literature on the effect of service loads on the degradation of reinforced structures, a research program on the corrosion of steel reinforcement in microcracked concrete beams has been initiated.* The overall objective of this research program is to identify the influence of microcracking on reinforcement corrosion. The effect of different parameters on the degradation of concrete due to reinforcement corrosion will also be investigated.

2. EXPERIMENTAL

2.1 Rationale

An environmental attack model for reinforcement corrosion is shown in Figure 1.

A small amount of reinforcement corrosion takes place during the formation of the passive layer around the steel. When chloride ions diffuse through the concrete cover and depassivate the protective layer, corrosion of the reinforcing bar is accelerated [1]. The time taken for the depassivation of this protective layer is known as the initiation time (see Figure 2). Once this

*The research is funded by the Electric Power Research Institute of the United States, and is part of an overall research program on concrete durability jointly funded and conducted by the National Research Council and ABCL Research.

layer is destroyed, the propagation of corrosion begins. The procedure used in this study included exposing microcracked concrete specimens to a chloride solution and determining the corrosion rate while observing the following:

- diffusion of chloride ions through the concrete cover,
- depassivation of the protective layer around the bars, and
- propagation of steel corrosion.

The diffusion rate of chloride ions was determined by locating the reaction front in the specimens exposed to the salt solution at definite time intervals. The reaction front was considered to be at a depth of penetration where the chloride content of 0.3% by mass of cement was measured. The rate of reinforcement corrosion was measured by the use of polarization-resistance measurements.

2.2 Materials

a) Concrete

Two types of concrete were selected from the concrete types being investigated in a joint AECL/IRC (Institute for Research in Construction) program on concrete durability, with established quality parameters [2,3]. Concrete made of type 10 cement (System 1) served as a control, whereas an improved formulation (System 2) with type 50 cement, blast-furnace slag and silica fume was selected as an example of superior-quality concrete. Table 1 shows the oxide analysis of cements, silica fume and slag. Concrete mixture compositions are given in Table 2. Table 3 gives the porosity and compressive strength development of the two types of concrete system.

b) Reinforcement

Plain, round bars, made of carbon steel with a diameter of 6.5 mm, conforming to AISI 1020, were used in the experiment. The bars were placed in the concrete to obtain the following conditions:

- reinforcement bonded to concrete (cast in place), and
- reinforcement unbonded to concrete (bars placed in pre-formed holes, so that they can be removed for inspection).

c) Concrete Cover

Two concrete cover thicknesses (thickness of concrete from the outside surface to the reinforcement), 12.7 mm and 25.4 mm, were used.

d) Loading of Specimens

Vertical loads were applied centrally on the test beams, which produced maximum strain at the centre and minimum or no strain at supports due to bending. These mechanical strains induced levels of microcracking corresponding to the strain level along the length of the specimen. In the experiment, strains at three locations (centre, quarter points, and support location) were selected for observation.

2.3 Specimen Fabrication

Concrete beams 76 mm wide by 102 mm deep by 305 mm long were manufactured using two types of concrete (see Figure 3). Two different concrete cover thicknesses were incorporated in the test specimens, by locating the reinforcing rods at 12.7 mm and 25.4 mm from the bottom of the moulds. Holes for the steel rods to be inserted later (unbonded condition) were introduced in the beams by casting in rigid plastic tubes in place of the rods and withdrawing them after the concrete was set. The ends of the specimens were sealed to prevent contact with the chloride solution.

2.4 Microcracking

Special stressing assemblies were manufactured to introduce microcracking in the concrete prisms. Each assembly was designed to permit loading to be maintained in the beam specimens during their exposure to chloride solutions (see Figure 3). The load strain diagram (see Figure 4) shows the concrete surface strain from the imposed loads for three concrete specimens. Microcracking of the concrete specimens started when the mechanical strain from the applied load exceeded the strain capacity of the concrete material in tension. Higher loads had to be applied to the System 2 concrete specimens and System 1 specimens with a 12.7 mm cover, compared to System 1 specimens with a 25.4 mm cover, to obtain a nominal surface strain of 600 micrometres per metre.

3. DEPTH OF PENETRATION OF CHLORIDE IONS

Specimens were exposed to a chloride bath with a concentration of 16.7 g of Cl⁻ per litre. Most of the specimens (stressed and unstressed) were immersed in the bath to expose the bottom surface (tension side, in the case of stressed specimens) to the chloride solution. The top surface of some specimens was exposed to study the influence of compressive strains on chloride ingress. The depth of penetration of the ions was measured using electron microprobe analysis on cylinders cored (15 mm diameter x 10 mm deep) from the beam samples. Cores were taken at midpoint, quarter points and end points (support location), and core holes were plugged with fast-setting epoxy.

4. RESULTS

4.1 Chloride Penetration

Figures 5 and 6 show that for both the 12.7 mm and 25.4 mm cover thicknesses, the depth of penetration of chloride ions was substantially higher for System 1 concrete than for System 2. This was expected, because System 2 concrete contains supplementary materials such as blast-furnace slag and silica fume, and has a lower water-to-cement ratio than System 1. The addition of these materials and a lower water-to-cement ratio provides System 2 concrete with smaller pore sizes [3,4] and a better pore structure distribution, enabling superior resistance to chemical ingress. Depth of penetration on the tension side was not substantially different from the compression side; however, the ionic concentrations (see Figure 6) were higher at the centre of the beam, where the microcracking was a maximum compared to the quarter point or end points,

indicating some influence of microcracking on ionic ingress. These depth-of-penetration measurements suggest that the microcracks are probably discontinuous at lower stress levels and do not provide continuous channels for the ionic ingress.

4.2 Corrosion Measurements

The duration of the initiation stage in the corrosion process is a function of concrete properties, concentration of chloride ions, and depth of cover, and can range from a few months to a few years. The corrosion rate of reinforcement rods was estimated by employing linear polarization techniques for the bonded reinforcement [5]. In addition to the polarization-resistance measurements, direct observations were also made for the unbonded reinforcement by removing the reinforcement and observing the surface condition. The visual examination of the unbonded and bonded bars (by removing the concrete cover) at the 28th month revealed the following:

a) Unbonded Bars

- Even though the ends of the specimens (System 1 concrete with 12.7 mm cover) were sealed while being exposed to the chloride solution, the ends of the bars were rusted severely and corrosion products filled the space between the bars and the holes in concrete (for the first 2 inches from the ends), making it difficult to withdraw the bars from the specimens.
- The bars were wet for the most part, which suggests that the chlorides have penetrated the holes (perhaps diffusing in from the ends). However, except for the ends, corrosion along the length of the bars was very slight.

b) Bonded Bars

- There was no evidence of chloride-induced corrosion for the bonded bars, except for the part that was outside the concrete beam. However, the bars were thoroughly coated with products forming the protective layer. This occurred more in System 1 concrete than in System 2 concrete, as expected, because System 2 is composed of 75 percent slag and 3 percent silica fume.

5. DISCUSSION

These tests were conducted as scoping studies, as a first phase, to obtain an indication of the effect of various parameters such as microcracking, concrete quality, cover thickness and bonded and unbonded bar conditions on the corrosion of reinforcement. In the next stage, which is ongoing, the study will focus on the influence of stress levels on the reinforcement corrosion.

The test specimens have been undergoing corrosion testing for the past 28 months. Figure 5 shows that for concrete System 1 specimens with a 12.7 mm cover, the chloride ions have diffused through the concrete cover and reached the steel interface in all of the cases. This may be true for most of the specimens with a 25.4 mm cover, as the ionic penetration in 28 months exceeds 25.4 mm (Figure 5). However, the corrosion process is still in the initiation stages, where the depassivation of the steel has to occur before corrosion can

start in a major way. The ionic concentrations measured at the steel interface also show that there are enough chloride ions present to initiate the steel corrosion (Figure 6).

For both stressed and unstressed specimens made of System 2 concrete, the rate of chloride penetration is substantially lower than System 1 specimens, and the depth of penetration suggests that the chlorides have not reached the steel interface for the most part. Hence, the observed corrosion rate measurements can be related to the corrosion activities for the passivation of the steel bars. The superior resistance of System 2 stressed concrete to ionic ingress [6] compared to System 1 unstressed concrete indicates the influence of concrete quality on reinforcement corrosion.

Figures 7, 8, and 9 are plots of the rate of corrosion of the rebars (concrete cover 25.4 mm), up to 28 months of exposure. Stressed test beams made of System 1 concrete experienced higher corrosion rates compared to the unstressed specimens. However, the influence of strain (microcracking of concrete) on corrosion rate for System 2 concretes was much less than that of System 1 (see Figure 7). After an initial rapid rate of corrosion, reaching a maximum in the first few weeks, the corrosion rates of bars in System 1 gradually declined to a stable level, which suggested a tendency for the steel to repassivate in all cases [1]. The reason for this pronounced activity in System 1 concrete might be that there is a greater availability of oxygen for the corrosion process because of the higher permeability of concrete.

Figure 8 compares the corrosion rate of bonded reinforcements (embedded in concrete) with the unbonded ones. The initial higher corrosion rate of the unbonded bars could be from the apparent rusting of the ends. The corrosion rates have declined and stabilized after the initial two months, suggesting that the unbonded condition and the initial rusting of the ends does not have a severe impact on the continued corrosion rate.

The effects of degree of microcracking formed under normal strain (normal service conditions), overloading to the yield of reinforcement and saw-cutting to simulate a continuous crack in the concrete cover of the specimens to the steel, are shown in Figure 9. The specimens loaded to the yield of the bars had visual cracks extending from the outside surface to the steel interface. It is evident from the figure that the corrosion in these specimens has advanced from the initiation stage to the propagation stage. All other specimens seem to be still in their initiation stage. It has been suggested by other researchers that a corrosion rate of 0.4 millimetres per year (MPY) or more indicates active corrosion propagation [4]. The corrosion rate of highly stressed specimens made of System 2 concrete and that of specimens with saw-cuts (made of System 1 concrete) are comparable, indicating that at higher stress levels the quality of concrete has less influence on the corrosion rate of the steel bars.

The average rate of corrosion of reinforcing bars in the concrete specimen at the 28th month of testing is shown in Figure 10. The corrosion rate is relatively high for the variably stressed specimens, compared to the unstressed specimens. A further confirmation of the influence of the microcracking on the initiation of the steel corrosion process was obtained from the specimens with a saw-cut to the steel rebars. The presence of the saw-cut initiated substantial corrosion almost immediately and maintained the rate for the rest of the time period.

6. CONCLUSIONS

1. The rate of ingress of chloride ions into concrete and ionic concentration is stress-dependent and is higher for stressed specimens.
2. Specimens made of a blend of blast-furnace slag, silica fume and type 50 cement, both stressed and unstressed, showed superior resistance to chloride ingress and had lower values of corrosion parameters than concrete made with CSA type 10 cement (ASTM Type I). This suggests that the quality of concrete has a substantial influence on reinforcement corrosion at lower stress levels; however, this reduces at higher stress levels.
3. Microcracking is discontinuous (at lower stress levels) and does not provide continuous channels for ionic ingress.
4. The corrosion rate of rebars in System 1 concrete specimens (less than 0.4 MPY) indicates that the process is going through the initiation stage, chlorides having reached the steel interface.
5. Initial reinforcement corrosion rates (corrosion due to passivation of steel) are similar for stressed and unstressed specimens of concrete containing a blend of blast-furnace slag and type 50 cement and silica fume.
6. Unbonded rebars experience higher initial corrosion than the bonded bars.
7. Longer-term data are required to determine the limits of the initiation stage and to characterize the propagation stage.

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Table 1: Oxide Analysis of Cements, Silica Fume and Slag

	<u>Portland cement type</u>		Slag	Silica fume
	10	50		
SiO ₂	19.43	20.71	35.30	95.17
Al ₂ O ₃	4.18	3.77	10.62	0.21
Fe ₂ O ₃	3.20	4.36	0.58	0.13
CaO	61.21	62.46	36.94	0.23
MgO	4.09	3.35	13.32	0.15
Na ₂ O	0.45	0.35	-	0.10
K ₂ O	0.89	0.87	-	0.27
C				1.56
L-O-I	1.53	0.88	1.16	2.30
SO ₃	3.93	2.46	1.41	0.12
Free lime	1.15	0.70	-	-

Table 2: Concrete Data

System 1 Concrete S1, Mix 3 (kg/m³)		System 2 Concrete S2, Mix 2 (kg/m³)	
Type 10 Cement	335	Cement content	358.8
Sand	744.6	Cement (Type 50)	78.8
Stone	1117	Blast-Furnace Slag	269
Super Plasticizer	1.87	Silica Fume	11
Air	6.5%	Sand	738
W/C	0.5	Stone	1107
Slump	143.8 mm	Super Plasticizer	2.16
		Air	5.3%
		W/C	0.4
		Slump	143.8 mm

Table 3: Concrete Properties

	System 1, Mix 3 w/c 0.5	System 2, Mix 2 w/c 0.42
a) Porosity Measurements on pastes (vol/vol)%	44.3	15.5
b) Porosity Measurements Intrusion %, with mercury	35.9	23.7
c) Compressive strength of concrete (Mpa)		
1 day	18.85	1.97
3 days	23.43	12.68
7 days	26.13	19.41
28 days	32.13	36.11
56 days	32.84	40.20

Environmental Intrusion

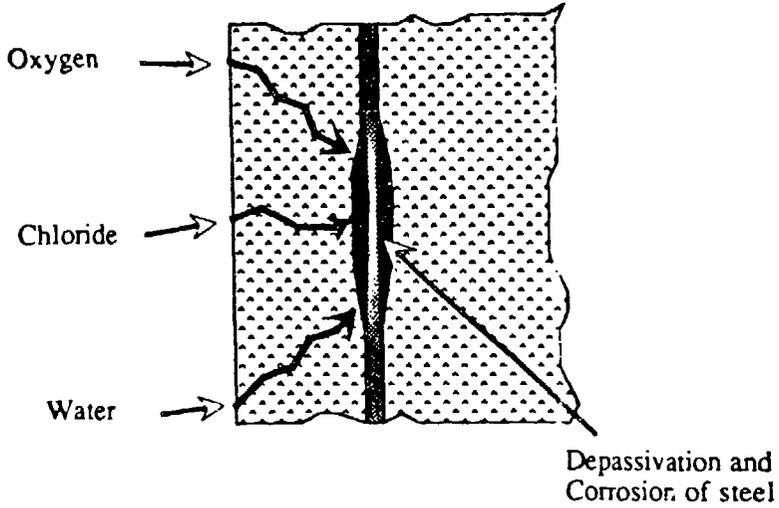


Figure 1: Schematic Model of Steel Corrosion Process in Reinforced Concrete

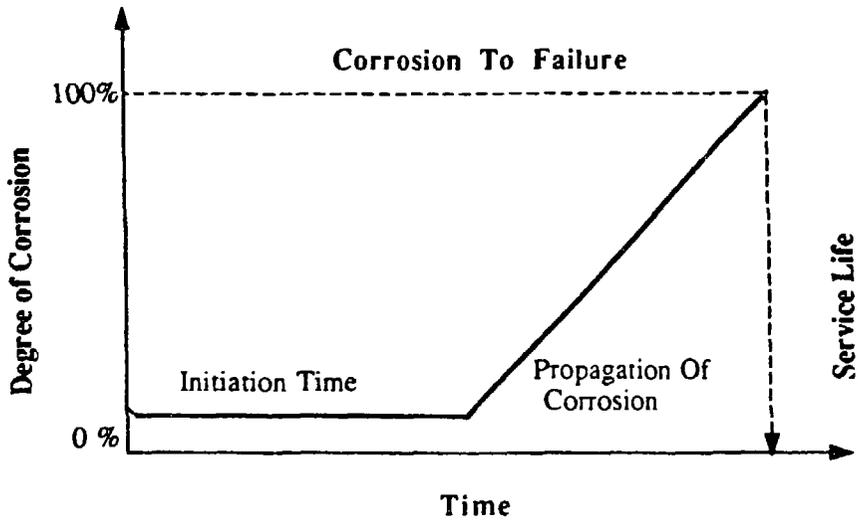


Figure 2: Idealized Corrosion - Time Profile for Steel Reinforcing Bars in Concrete

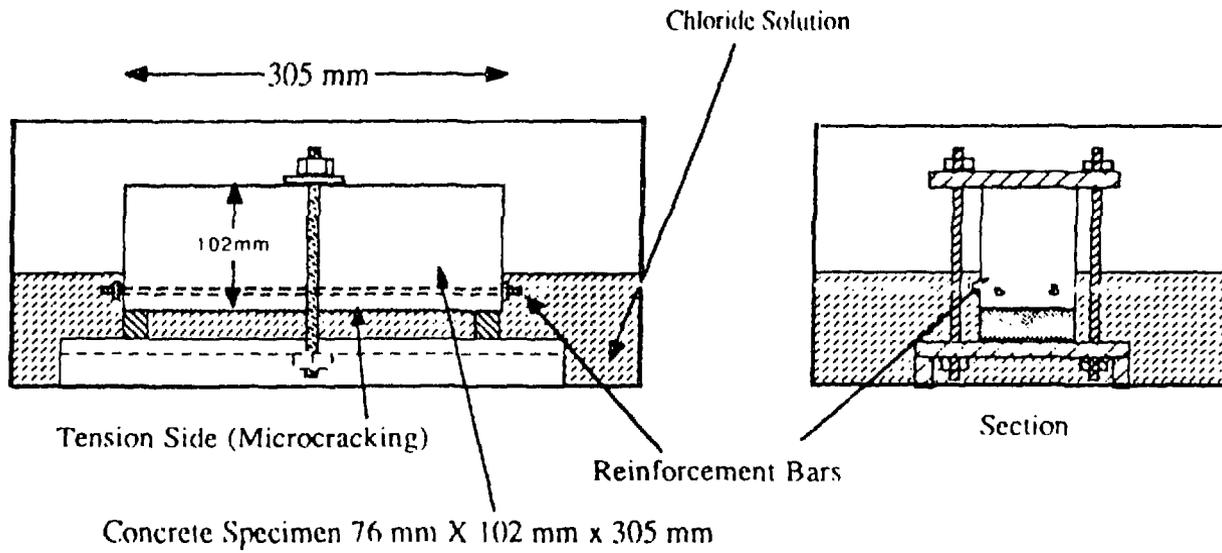


Figure 3: Stressed Concrete Specimen in Chloride Bath

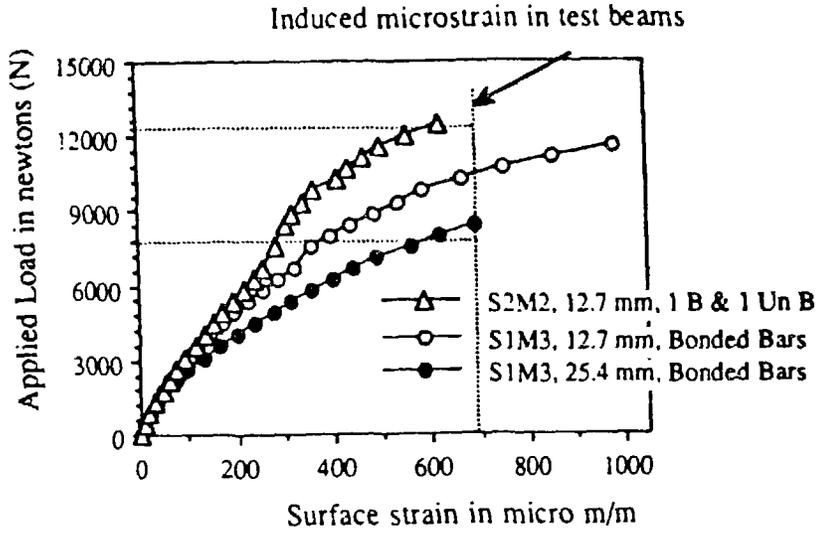


Figure 4: Load vs. Surface Strain in Concrete Test Specimens

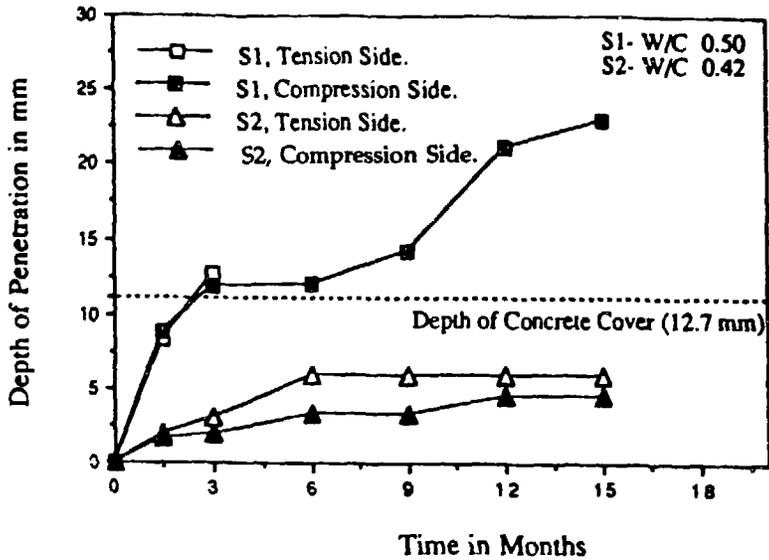


Figure 5: Chloride Ion Ingress vs. Time in Concrete Test Specimens

* (Measured at steel interface S1, Cover 12.7 mm)

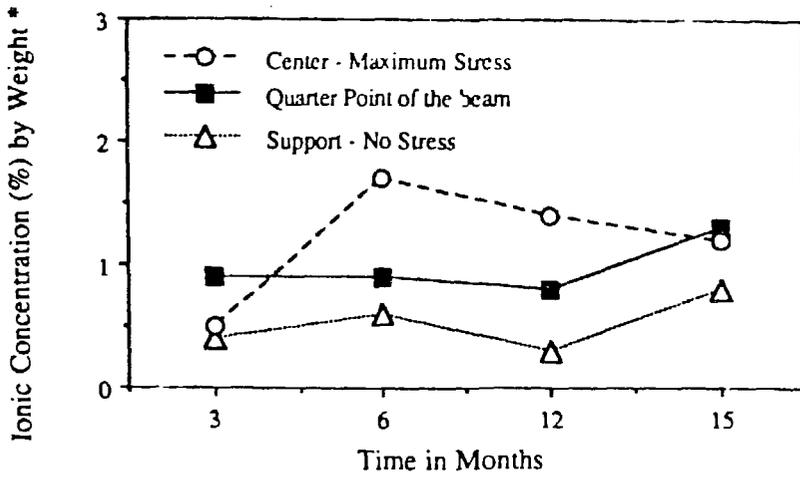


Figure 6: Chloride Ion Concentrations vs. Time at Three Stress Levels for Concrete Test Beams

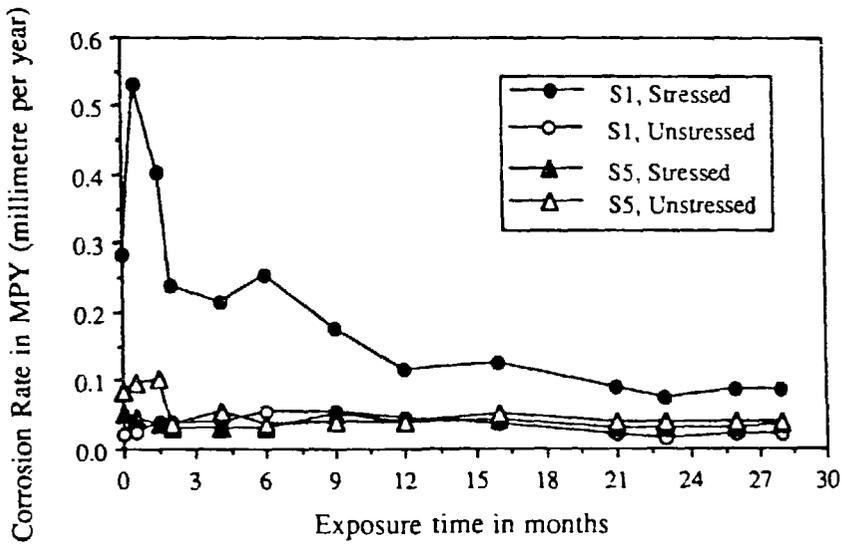


Figure 7: Corrosion Rate vs. Exposure Time - Concrete with Varying Quality and Degree of Microcracking

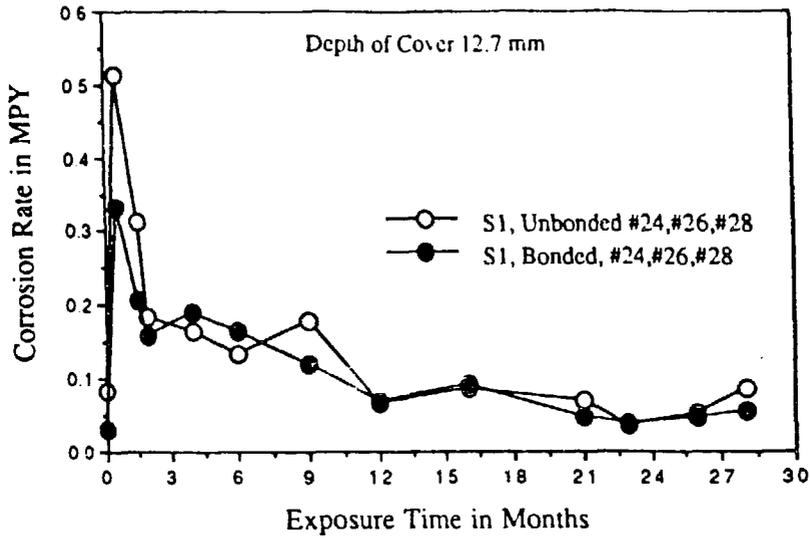


Figure 8: Corrosion Rate vs. Exposure Time for Rebars with Varying Bonding Condition

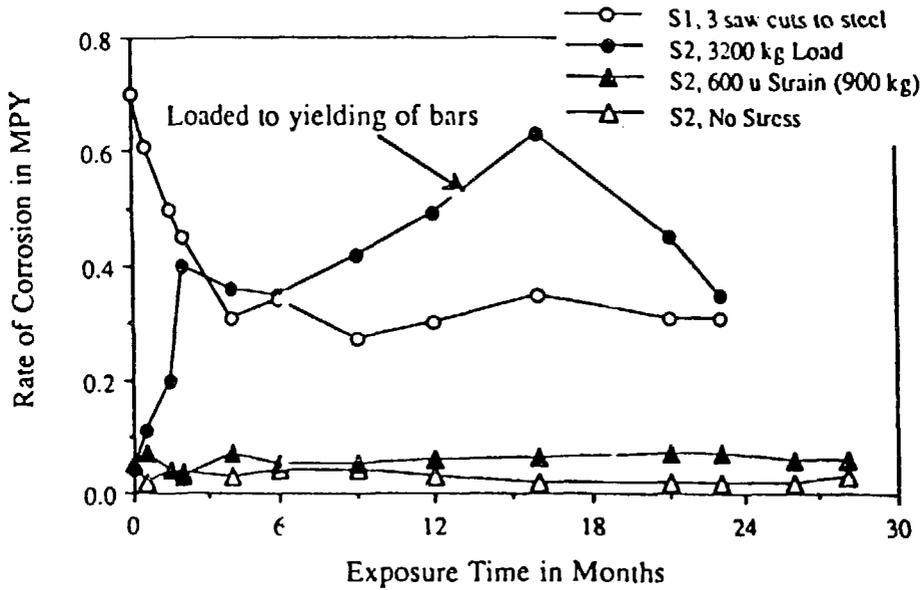


Figure 9: Corrosion Rate vs. Exposure Time for Concrete Loaded to Varying Stress Levels

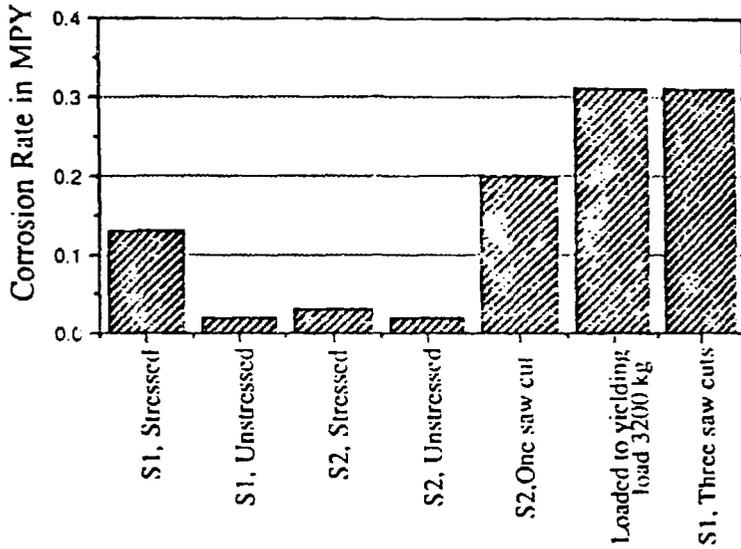


Figure 10: Corrosion Rate of Rebars in Concrete Specimens Loaded to Varying Stress Levels at the 28th Month of Exposure

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