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Autor: Rasheeduzzafar / Dakhil, Fahd H. / Ahmad, Fouad A.
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Corrosion Deterioration of Reinforcement in Concrete Structures

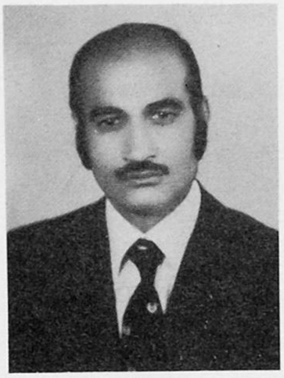
Corrosion des armatures de structures en béton armé

Korrosion an der Bewehrung von Stahlbetonbauten

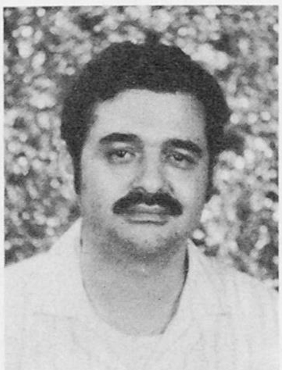
RASHEEDUZZAFAR
Professor
Univ. of Petr. & Miner.
Dharan, Saudi Arabia

Fahd H. DAKHIL
Vice Rector
Univ. of Petr. & Miner.
Dharan, Saudi Arabia

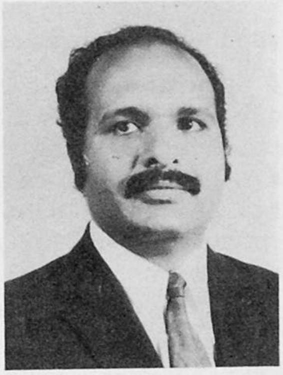
Fouad A. AHMAD
Assoc. Professor
Univ. of Petr. & Miner.
Dharan, Saudi Arabia



Rasheeduzzafar, born 1939, obtained his Ph.D. degree in Structural Engineering from University of London. Presently he is Professor of Structural Engineering at the University of Petroleum and Minerals, Dhahran, where he is teaching design of concrete structures.



Fahd H. Dakhil, born in 1942, obtained his Ph.D. degree in Structural Engineering from Pennsylvania State University. Presently he is Vice Rector for Research and Graduate Studies at UPM, Dhahran. Interests are related to durability studies of concrete construction.



Fouad A. Ahmad, born in 1941, obtained his Ph.D. degree in Surveying from University of New Brunswick, Canada. Presently he is Associate Professor at the UPM Dhahran. His research interests are in the areas of photogrammetric engineering and geodetic surveying.

SUMMARY
Concrete construction along the seaboard of the Arabian Gulf is showing an alarming degree of deterioration within a span of 10 to 15 years. Corrosion of reinforcement associated with concrete spalling outweighs other causal factors. The paper describes the methodology of condition surveys and sampling of concrete from field structures. Spalled area is measured by a photogrammetric technique and evaluations of cover, chloride content, electrical resistivity and concrete quality show strong correlation between these factors and the extent of rebar corrosion deterioration.

RESUME
La construction en béton armé au Golfe Arabique présente un degré de détérioration alarmante après une durée de 10-15 ans. La corrosion des armatures associée avec les fissures est la cause principale des dégâts. L'article décrit la méthode de mesures et d'échantillonage du béton des structures. Les fissures sont mesurées avec la méthode photogrammétrique. Le contenu de chlorure, la résistance électrique et la qualité du béton montre une corrélation forte entre ces facteurs et le degré de corrosion.

ZUSAMMENFASSUNG
Viele Betonbauten entlang der Arabischen Golfküste zeigen ein alarmierendes Mass an Zerfall nach einer Zeitspanne von 10 bis 15 Jahren. Allmähliche Korrosion der Bewehrung die die Absplitterung des Betons verursacht überwiegt andere Kausalfaktoren. Der Beitrag beschreibt die Methoden der Lagevermessung und der Entnahme von Betonproben. Abgesplitterte Betonoberflächen wurden photogrammetrisch vermessen. Der Chloridgehalt, der elektrische Widerstand und die Betonqualität wurden bestimmt. Die Resultate zeigen eine starke Korrelation zwischen diesen Faktoren und dem Grad der allmählichen Korrosion der Bewehrung.

1. INTRODUCTION

Studies on the field performance of concrete in the Gulf area provide a unique opportunity to evaluate parameters bearing directly on the durability characteristics of concrete construction in an aggressive service environment. The boom in the construction activity for the last two decades has brought in its wake the concrete frame and the concrete block as the most popular form of construction. There has been an unprecedented demand for concrete buildings of all kinds and the local construction industry, beset by an inadequate infrastructure, shortage of suitable materials, equipment, skilled manpower and inadequate specifications and construction practices has succeeded only in producing structures which are showing an alarming degree of deterioration within a short span of 10 to 15 years. The deterioration is accentuated by the environmental conditions which are characterized by high temperature-humidity regimes combined with severe ground and ambient salinity (1).

The data collected in this investigation is part of a large scale durability study being presently undertaken at the University of Petroleum and Minerals with objectives to evaluate the deterioration problem in the area, to comprehend its magnitude in relation to affecting parameters, to develop quantitative estimates and indices of causal factors and their relative importance, to develop recommendations for obtaining improved durability of new concrete construction and to make proposals for retarding and repairing the existing deterioration. What appears most significant is a quantitative understanding of the interactive causal factors and to develop specific rating of concrete to withstand the severe exposure conditions.

2. METHODOLOGY OF INVESTIGATION

2.1 Framework of Investigations

The first phase of concrete deterioration research planned by the authors for the Gulf region is primarily based on collection, analysis and interpretation of field data from deteriorated field structures. The methodology adopted for these investigations is sequentially based on:

(i) Condition surveys of concrete buildings in order to establish a reasonable overall picture of the extent and severity of concrete deterioration.

(ii) Case studies related to special modes of deterioration employing destructive and non-destructive testing techniques, as well as chemical and petrographic examination of concrete samples obtained from the deteriorated field structures.

(iii) Analysis and interpretation of the data.

2.2 Sampling in Field Studies

A sampling plan for evaluating the deterioration of concrete in service is bound to be significantly different from the sampling at the production and placing stages for the purpose of material control or acceptance. Whereas in case of the later a viable mechanism in compliance with statistical procedures can be devised without incurring excessive cost and effort such is not the case with the former. Sampling of field structures and subsequently concrete from service conditions which may be considered truly representative of the properties and characteristics of the relevant population seems unrealistic even on the face of it. The inherent and well recognized original variability of the fresh concrete manufactured even under significantly controlled conditions is greatly compounded by subsequent variables in placement, consolidation, curing, protection and exposure when obtained from service structures. To this factor must be added regional characteristics such as variable and poor workmanship, lack in doctrination of the work force involved and lack of supervision and control.

In view of this position the sampling plan was devised so as to examine and evaluate a sufficiently large number of samples, each of which, even when it represents only itself as part of a larger population, will yield data which, taken together for all samples and subjected to careful analysis and interpretation, will enable the investigators to estimate relevant characteristics of the larger population. Two criteria were, however, invariably invoked in the sampling procedure:

(i) the samples were always obtained in a random manner so that the selection was based strictly on the element of chance rather than the choice or decision of the investigators;

(ii) a sufficiently large sample was obtained covering as far as possible the whole range of variation in terms of intensity of a particular form of deterioration.

In terms of actual logistics the following procedure was followed:

(i) The whole area under study comprising three cities of Dhahran, Dammam and Al-Khobar was delineated on maps in terms of smaller housing localities. A random selection was made of the localities wherein structures would be located for survey.

(ii) Each randomly selected locality was surveyed for comparatively old construction and in the first round information was gathered regarding the age of the construction only. In the execution of two surveys, concrete buildings falling in age groups of 15 to 20 years and 22 to 27 years were identified. Again a random selection of two to three buildings was made from each locality under study.

(iii) For each randomly chosen structure the owner was approached for permission and in most cases his cooperation was forthcoming. Each structure was first condition surveyed and the observations were recorded on two types of survey forms as suggested by Idorn (2). Proforma I is designed to record background information related with structure identification, construction type, site topography, exposure conditions, material data and relevant information about contractor, equipment, field force and, the degree and quality of workmanship and supervision. Proforma II recorded the general condition rating of the structure on a six point scale, extent and type of deterioration and the degree of repairs needed. Eighteen types of possible forms of deterioration were listed in Proforma II inviting related observations; the definitions of all these forms of deterioration were adequately established and illustrated with the help of photographic documentation.

Feedback at the initial stages of survey revealed difficultues in obtaining information on the initial quality of concrete, constituent materials, compositional aspects and construction practices. In the face of this difficulty, wherever necessary, initial concrete quality was rated on a three point scale as "poor", "good", and "excellent". These terms have been defined in relation to strength and concrete denseness. Reasonably settled standards of the degree of severity of each deterioration type were established by visual inspection with the help of preliminary case studies undertaken only for the prupose of practice inspections and by supplementing with photographic documentation. A little observational skill, developed with some measure of practice, provided satisfactory and meaningful rating of a particular deterioration.

(iv) Of the 62 surveyed structures 20 structures were selected randomly for an in-depth investigation of the causal factor identified from the condition survey. In the case of rebar corrosion studies, follow up investigations comprised:

(i) measuring precisely the area affected by corrosion deterioration in terms of concrete spalling and delineating regions according to deterioration ratings on the six point scale;

(ii) drilling concrete cores from randomly selected areas of deterioration in such a manner as to provide samples which represented individual points in the structure covering in each case, as far as possible, the range of deterioration spanned by the six point scale;

(iii) obtaining cover measurements non-destructively on partially spalled concrete floor slabs using an electromagnetic covermeter;

(iv) developing strength, concrete absorption and pulse velocity data from the cores removed from field structures;

(v) determining chloride content of the cored concretes; and

(vi) measuring the electrical resistivity characteristics of concrete.

2.3 Techniques

2.3.1: Photogrammetric Technique for Measuring Area and Depth of Concrete Spalling at Inaccessible Locations:

A simple pictorial technique has been developed to measure the three dimensions of an object at any distance from 5 to 20 meters. A mirror stereoscope is mounted in front of a normal hand-held non-metric camera as shown in Fig.1. Two pictures will appear on the same photographic slide. Since the two photographs are not taken from the same point the two pictures will not be exactly identical and a part of the object will appear twice.

Referring to Figs.1 and 2 the distance between the centers of the two apertures of the mirror stereoscope is the stereoscopic base B. This produces a parallax P_x which is the difference between the two locations of the same photographed object. It is equal to (M - N) where M is the distance between the centers of the two pictures and N is the distance between the two object photographs. If the focal length of the camera is F and the coordinate system is chosen as shown in Fig.2, the space coordinates of a point object are computed from:

$$Y = \frac{FB}{P_x} \qquad (1)$$

$$X = \frac{Y}{F}\,x \qquad (2)$$

$$Z = \frac{Y}{F}\,z \qquad (3)$$

where x and z are the photo-coordinates of the object in the left photograph. The first equation is used in the determination of the scale factor S=Y/F for a body object at an average distance of Y which includes the distance C between the two parallel mirrors. The components of the object dimensions can be obtained from the first derivatives of equations (1) to (3).

$$dY = \frac{F}{(M - N)}\,S \;\; dP_x \qquad (4)$$

$$dX = S\,dx \qquad (5)$$

$$dZ = S\,dz \qquad (6)$$

dP_x, dx and dz can be measured from the pictures by using a special 0.1mm optical scale. If the photographic slide is placed on an illuminated table the measurements can be conveniently carried out to the nearest 0.02mm by estimation.

The view can be observed stereoscopically by placing the slide in a special viewer which operates in a reverse concept.

Nikon F3 with a normal 50mm lens was used in the present investigations. If it is focussed to infinity the minimum photographing distance, corresponding to a circle of confusion of 0.05mm, is 5m. The base B of the mirror stereoscopic adapter was chosen approximately to be 70cm. Experiments were carried out to find with high precision the most probable values of the three constants, namely; the focal length F, the base B of the mirror stereoscope and the distance between the centers of the slide stereopairs M. A test area was established where distances to 25 scales were measured precisely with a steel tape. The total length of each scale was 4 meters and residual equations are formed from equations (1), (2) and (3). The required unknowns have been determined from the least squares solution and found to be: F = 4.975mm, B = 70.740mm and M = 18.641mm. These values are used in Equations 1, 2 and 3 to determine the object dimensions. Experiments show that the standard error (in mm) of the object dimensions in a plane perpendicular to the camera axis is given by 4 X Y (X and Y are in meters).

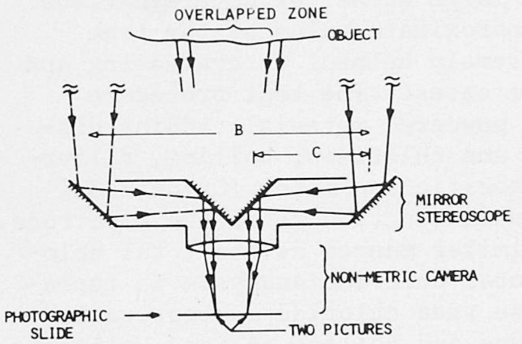


Fig.1: The mirror stereoscopic photographic arrangement

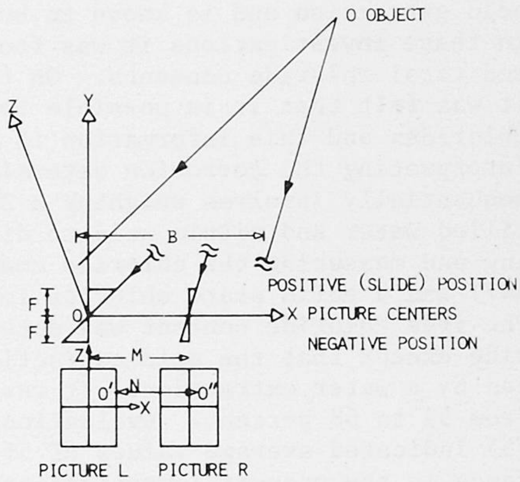


Fig.2: The geometry of the photogrammetric technique

2.3.2: Depth of Concrete Cover:

Results of condition surveys show that in most cases the corrosion and severe concrete spalling could be attributed to atleast one of the many possible parameters - insufficient concrete cover to reinforcement. Cover measurements were made non-destructively on partially spalled concrete slabs using an eletromagnetic covermeter which requires only a knowledge of the rebar diameter. Cover measurements were made on a grid system over the concrete surface and this enabled equi-depth of cover contours to be drawn for the area under study.

2.3.3: Chloride Analysis of Concrete Samples:

In the coastal flats of the Gulf calcium, magnesium and sodium salts of sulfates, chlorides and carbonates extensively contaminate the ground, groundwater and the moisture-laden environment. Consequently, salts permeate concrete, firstly, through the contaminated aggregates, brackish mix and curing water and subsequently as a result of ingress through cracks and pores. Concrete construction on the Gulf seaboard is continually exposed to ground and atmosphere charged with salt. Aided by capillary action, dew and high humidity conditions the salt contaminated groundwater and the salt-laden airborne moisture find an easy ingress in the exposed concrete matrix. The unusual high incidence of rebar corrosion against the backdrop of a highly salt-polluted environment puts chloride ion as the most important potential cause for reinforcement corrosion. Chloride ion, inducted into concrete through salt permeation, is a specific destroyer of the protective gamma ferric oxide film surrounding the reinforcement and is especially effective in eliminating passivity against corrosion. This activates the electrochemical process wherein corrosion cells are formed due to non-uniformities either in the rebar material structure or in its enveloping environment. Chloride ion determinations in the sampled concrete, therefore, constitute an important part of the evaluation test program. Chlorides can be present in concrete in three forms (3):

(i) Free chloride ion

(ii) Chloride bonded strongly with the calcium silicate hydrates

(iii) Chloride combined in compounds such as calcium aluminate chlorides.

Although it is the quantum of free and weakly bonded chloride which is the operative parameter in the corrosion process, its determination in concrete is rendered uncertain by the sensitivity of the test to a large number of procedural parameters such as sample size, extraction medium, soaking time, temperature, etc. As against this the total chloride determination involves a nitric acid extraction and is known to be unaffected by the aforesaid factors. However, in these investigations it was found useful to determine both the free chloride and total chloride contents. On the basis of a large number of determinations it was felt that it is possible to measure an approximate value of the free chlorides and this information is sometimes extremely helpful in evaluating and interpreting the corrosion determination in some cases. The test procedure sequentially involves weighing a 3-gm sample of powdered material, adding distilled water and nitric acid to dissolve cement and chlorides, boiling, filtering and measuring the chloride content with a specific ion meter (Orion Model 407) and a solid state chloride ion activity double junction reference electrode. The free chloride content was determined in a similar manner as the total chloride except that the acid extraction used for total chloride analysis is replaced by a water extraction. It was found that the free chloride content varied from 52 to 68 percent. Evaluations made by Browne and Bolling (4) and Lolivier (5) indicated average values of 55 and 65 percents respectively. The variation range in the present investigations is based on the fact that the proportion of free chlorides depends on the total chloride content and on the source of the chlorides i.e. whether inducted at the mixing stage or at a later stage by ingress through pores and cracks.

2.3.4: Electrical Resistivity Measurements:

The electrical resistivity of concrete ranges from around 10^3 ohm-cm when saturated to 10^{11} ohm-cm when oven dried. Rebar corrosion is an electrochemical reaction necessitating a potential difference along the bar in order to activate a current from the anode to the cathode. The magnitude of the corrosion current is primarily controlled by the resistivity of the concrete. High resistivity reduces current and also the probability of corrosion. Resistivity measurements on concrete samples were made according to a set up shown in Fig.3, using an integrated and compact instrument commercially available as Nilson 400. The instrument is a 4 terminal null balancing ohm-meter (0.01 ohm to 1.1 meg-ohms) which generates a low voltage 97 HZ square wave current between the binding posts C_1 and C_2 (Fig.3). The detector with its input connected between binding posts P_1 and P_2 is only responsive to 97 HZ and remains insensitive to any spurious potentials or stray currents. This eliminates a frequently occuring source of error. Copper pins were inserted in concrete cores and were directly connected to binding posts P_1 and P_2 for voltage drop measurements. The cores were held horizontally in a steel frame with end plates made of copper and covered with a cloth pad which was kept wetted with water. The copper plate-wet cloth combination ensured a uniform distribution of current density across the face of the core.

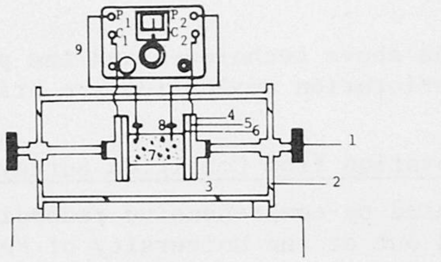


Fig.3: Electrical Resistivity Measurement of Concrete.

2.3.5: Tests for the Evaluation of Concrete Quality:

As pointed earlier, sufficient information was not available on the concrete samples from field structures in terms of mix specifications and constructional parameters such as placement, consolidation, curing, etc. which significantly influence concrete quality. Therefore concrete quality was evaluated in terms of pulse velocity and water absorption measurements corroborated, wherever possible, with compressive strength determination on cores.

Proprietary Pundit equipment was used with 82 KHZ transducers coupled to the smooth end faces of a core with the help of sticking grease. Care was exercised in ensuring good acoustic coupling between the transducer face and the surface of the core as well as in measuring the path length and transit time. In general the higher the velocity of the pulse the higher the concrete quality.

Concrete permeability is the pre-eminent criterion governing its durability performance in aggressive environments. Mechanisms of rebar corrosion and sulfate attack which dominate concrete deterioration in the Gulf environment are extremely permeability oriented. It follows that in the Gulf conditions concrete should be sufficiently dense and impervious for high durability performance. Concrete permeability determination in the field has met with little success and even in the controlled conditions of the laboratory it is a difficult test to perform. Water absorption measurements being known to be intimately connected with the permeability characteristics, these investigations have largely relied on a 30-minute absorption test and on initial surface absorption test developed by Levitt (6). Both these tests are fully described in BS 1881 Part 5. Although there is a degree of arbitrariness associated with the results of these tests, on the basis of a large number of measurements Table 1 has been formulated for an interpretation of concrete quality. Whereas a broad correlation has been obtained between the two techniques, experience shows the initial absorption test to be more consistent compared to the 30-minute absorption test.

Ratings on the basis of 30-min Absorption Test		Suggested limits of ISAT for good quality concrete	
30-minute Absorption Value %	Concrete Quality	Duration of Test (Minutes)	Max.ISAT limits ml/sq.m/s
2.5 and lower	Good	10	0.40
Between 2.5 and 5	Medium	60	0.20
Between 5 and 10	Poor		
Above 10	Very Poor		

Table 1: Absorption values and concrete quality.

3. RESULTS

Typical applications of the above techniques and the possible interpretations in terms of corrosion deterioration evaluation are briefly discussed in this section.

3.1: Evaluation of Deterioration from Condition Surveys:

Condition surveys accompanied by comprehensive recordings and photographic documentation were carried out at the University of Petroleum and Minerals on 42 concrete framed structures located in Al-Khobar, Dhahran, and Dammam habitations along the Gulf coast in the Eastern Province of Saudi Arabia. The objectives were limited to an establishment of the boundaries and parameters of the concrete deterioration problem and an investigation of the relative importance of the operative causal factors. The results show an alarming condition of structures constructed 15-20 years hence. The surveyed structures were constructed during the years 1960-64. Although the general condition of each structure was recorded as comprehensively as possible, the detailed deterioration recordings were made only on concrete exposed to the ambient environment. This made it possible to hold at least two variables - age and inservice exposure - reasonably constant in order to study the effect of other variables on concrete deterioration. Fig.4 classifies on a six point scale the general condition rating of 168 study areas from these 42 structures. The figure shows that 48% of the observations group in the classifications 5 and 4 which corresponds to a very unsatisfactory condition range of the rating and about 19% in classifications 3 which is also far from satisfactory. Only 36% manifest slight or no deterioration. Illustrations of classifications 4 and 2 are shown in Figs.5 and 6 respectively.

Legend on Classification of Deterioration

Classification	Extent of Deterioration
0	No visible sign of deterioration.
1	Slight in severity and extent
2	Severe but limited in extent
3	Slight but extending over major portion of area under study.
4	Moderate over whole area of inspection
5	Severe, overall deterioration

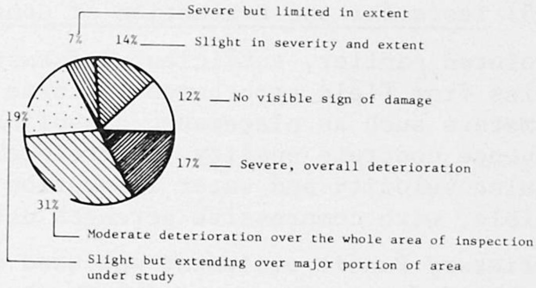


Fig.4: Classification of condition of 168 observations from concrete structures located in Eastern Saudi Arabia.

3.2: Evaluation of Concrete Spalling Areas due to Rebar Corrosion:

Figs. 5 and 6 show two structures which were condition surveyed and where concrete spalling has occurred as a direct outcome of visible heavy rebar corrosion. In each of these figures two pictures appear of the same structure on one photographic slide. Photogrammetric technique has been used for measuring the area of spalling and the results are shown in Table 2.

Structure No.	Total area under observation (m^2)	Area showing cracking and initiation of Spalling (m^2)	Spalled Area (m^2)
1	4.65	1.19 (26%)	1.77 (38%)
2	4	0.13 (3%)	1.35 (34%)

Table 2: Evaluation of concrete spalling areas due to rebar corrosion.

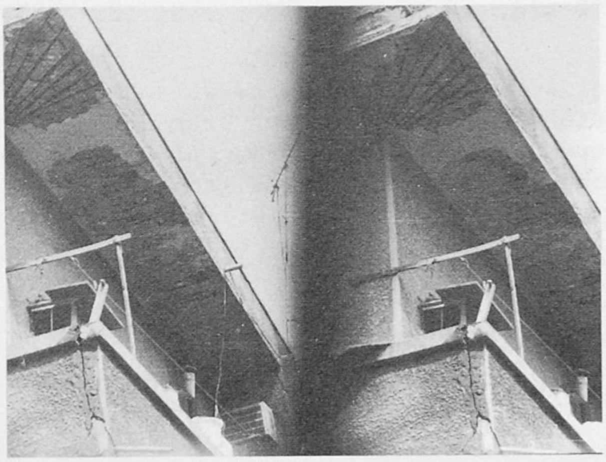


Fig. 5 Structure 1 showing concrete spalling due to rebar corrosion

Fig. 6 Structure 2 showing concrete spalling due to rebar corrosion

3.3: Metal Loss of Reinforcement and Chloride Content:

Concrete cores from exposed slabs of 24 structures 17-22 years old were obtained for laboratory analysis of chloride levels at the steel-concrete interface. Fragments of concrete were removed from the steel-concrete interface and were analyzed for chloride content. For each sample six to ten points were obtained and standard deviations worked out for this data. Steel corrosion was measured by removing from each specimen six to ten 7.5cm pieces of rebars. The loose rust was removed by an emery paper and the weight loss was measured. The results of this analysis for selected samples pertaining to 1.25cm cover are plotted in Fig.7. As concrete quality, cover, electrical conductance characteristics, and the soluble chloride content are the four supposedly dominant parameters affecting corrosion, samples were selected for the plot which enabled the first three variables to be held reasonably constant. Understandably, from among one hundred available observations only a few met the aforesaid criterion (Fig.7). Concrete

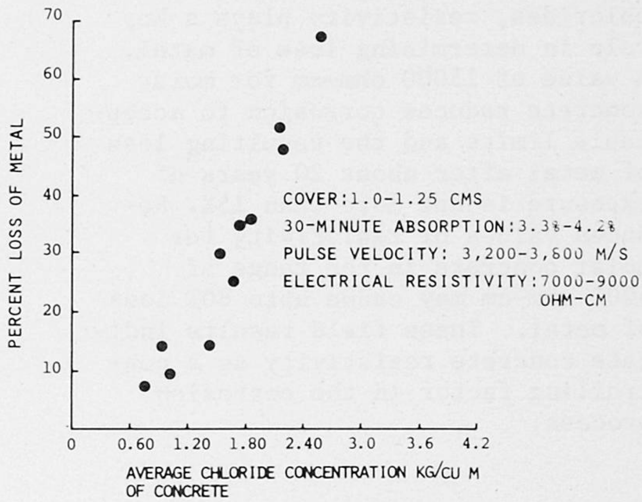


Fig.7: Relationship between Chloride content and metal loss.

quality was ascertained on the basis of a 30 min. water absorption test (BS 1881) and the pulse velocity measurements.

It would be difficult and an oversimplification to read obvious cause and effect relationships between certain causative factors and deterioration from this presentation. However, certain broad features of the deterioration problem as affected by the presence of chlorides in concrete can be inferred from this data analysis.

(i) The chloride ion and its concentration in concrete have a very definite influence on corrosion deterioration.

(ii) For a 1.25cm cover the threshold chloride concentration for the exposure conditions of Eastern Saudi Arabia is about 0.6 kg/m^3. This value is close to the concentration of chlorides permitted by ACI Committee 201 on Durability of Concrete.

(iii) Gulf concretes generally show a high chloride concentration.

3.4: Electrical Resistivity of Concrete and Rebar Corrosion Deterioration:

The significant effect of concrete resistivity on corrosion is seen in Fig.8 where the loss of metal is plotted against resistivity for narrow variations in the values of cover to reinforcement, chloride content and concrete quality. The results show that given sufficient chlorides, resistivity plays a key role in determining loss of metal. A value of 15000 ohm-cm for moist concrete reduces corrosion to acceptable limits and the resulting loss of metal after about 20 years of exposure is not more than 15%. Reduced values of resistivity for moist concrete in the range of 6000 ohm-cm may cause upto 80% loss of metal. These field results indicate concrete resistivity as a controlling factor in the corrosion process.

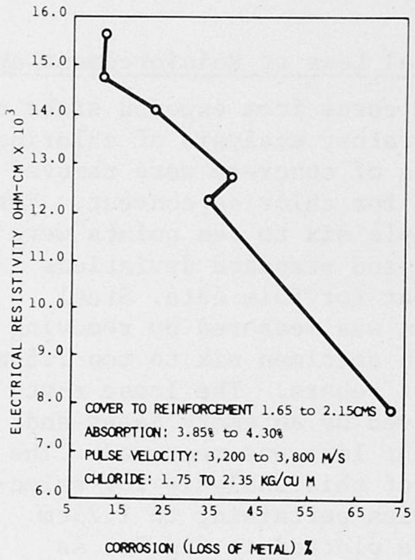


Fig.8: Relationship between electrical resistivity of concrete cored from field structures and metal loss.

3.5: Cover to Reinforcement and Corrosion Damage in Terms of Concrete Spalling:

In the condition survey carried out on 42 concrete framed structures 15-20 years old, 76 spalls of varying dimensions and severity were observed during 168 observations covering approximately 112 sq.m. of concrete area. In 68% of the observed spalls the thickness of concrete cover was less than 1.25 cms, in 53% it was less than 0.95 cms and in 18 observations it was less than 0.65 cms. There were 7 cases (9.2%) where there was almost no cover to steel reinforcement. Fig.9 shows the distribution of concrete cover observed in spalled concrete. Fig.10 is the typical presentation of cover measurements on floor slabs with partial spalling. The spalls were found to be invariably located in regions of insufficient concrete cover.

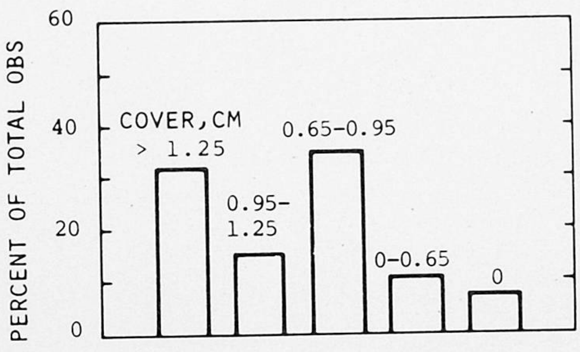


Fig.9: Distribution of concrete cover in spalled concrete

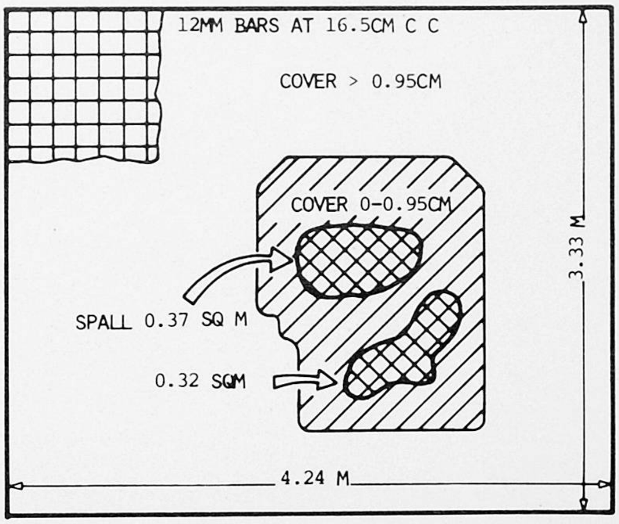


Fig.10: Concrete spalls related to inadequate cover.

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