In-situ Assessment of Reinforcement Corrosion in Concrete Structures

Evaluation in situ de corrosion des armatures dans les structures en béton

Bestimmung der Bewehrungskorrosion an Betonbauwerken

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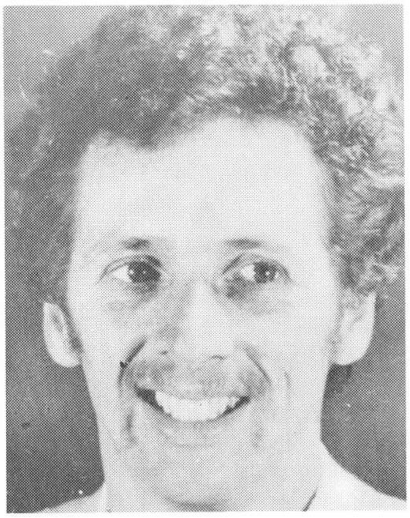

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SUMMARY

This paper reports on the preliminary results of three corrosion durability studies on reinforced concrete structures recently constructed in high risk, chloride rich environments. Various permeability and electro-chemical methods have been used to monitor the corrosion performence of each structure. The results to date suggest that the use of pozzolanic cement replacements and of hydrophobic pore blocking admixtures, together with high quality concrete, will allow the risk of corrosion to be reduced to an acceptable level.

RÉSUMÉ

Cet article rapporte les résultats préliminaires de trois études sur la durabilité face à la corrosion des structures en béton armé récemment construites dans des milieux à grand risque et riches en chlorure. Diverses méthodes de perméabilité et d'électrochimie ont été utilisées afin de saisir l'évolution de la corrosion de chaque structure. Les résultats à ce jour suggèrent que l'utilisation des ciments pouzzolaniques, d'adjuvants à pores bloqués hydrophobes, conjugués à un béton de haute qualité, permettront de ramener le risque de corrosion à un niveau acceptable.

ZUSAMMENFASSUNG

Dieser Beitrag beschreibt die Ergebnisse dreier Korrosionsuntersuchungen an Stahlbetonbauwerken in chloridreicher Umgebung. Verschiedene Durchlässigkeits- und elektrochemische Methoden wurden angewendet, um das Korrosionsverhalten jedes Bauwerks zu überwachen. Die bisherigen Resultate deuten an, dass durch die Verwendung von pozzolanhaltigem Zement und von hydrophoben Dichtungszusätzen, zusammen mit qualitativ hochwertigem Beton, das Risiko der Korrosion auf ein annehmbares Mass vermindert werden kann.

1. INTRODUCTION

The use of reinforcing steel or prestressing steel in concrete structures liable to chloride attack can lead to high risk of failure due to corrosion of the steel. The risk of chloride induced corrosion is particularly large when the chlorides have ingressed through the hardened concrete rather than being present as contaminants or additives in the original concrete mix. The majority of chlorides ingressing through the concrete cover are available to promote corrosion, rather than being chemically bound into the cement matrix [1]. Although there may be a considerable durability risk from using steel reinforcement in a chloride rich environment, its use leads to lightweight, efficient structures. Furthermore, if accidental load damage occurs at any time, the inclusion of reinforcing steel means that the structure may be more readily repaired than if unreinforced.

Corrosion of reinforcing steel is a two phase process [2]. During the first phase chlorides diffuse or permeate through the concrete cover until the passive oxide layer on the surface of the steel is disrupted and corrosion commences. During the second phase anodic and cathodic sites are established and active corrosion leads to loss of section of the reinforcement and spalling of the cover. The corrosion rate is controlled by oxygen diffusing through the concrete cover and by the flow of hydroxyl ions from the cathode to the anode. Methods of enhancing the durability performance of concrete must either restrict the flow of chlorides into the concrete during the first phase or limit some part of the corrosion cell once it has become established.

This paper discusses the effects of using a pozzolanic cement replacement and also of using a durability enhancing admixture on the durability performance of a number of structures located in chloride rich environments.

2. ASSESSMENT OF CORROSION IN REINFORCED CONCRETE

A number of techniques were used in these studies to assess corrosion performance. Some of these were aimed at determining if corrosion had been or was likely to be initiated. Other methods assessed actual or probable corrosion rates, once corrosion had commenced.

The permeability of concrete will be related to the ease of ingress of chlorides, moisture and oxygen through the cover. Two simple tests were used to evaluate the permeability of the cover concrete. The Initial Surface Absorbtion Test [3] (I.S.A.T.) was adopted to measure the rate at which water is absorbed into the concrete. The Figg gas permeability test [4] was also used to assess the ease with which gas can flow inside the concrete. Both tests are highly sensitive to the existing moisture content of the concrete and hence are best conducted on moisture conditioned cubes or other laboratory specimens.

Chemical analysis of concrete samples taken at incremental depths can also be used to assess directly the ingress of chlorides, causing depassivation of the reinforcement.

The initiation of a corrosion pit in the steel reinforcement is characterised by the establishement of an anodic corroding region, surrounded by a cathodic region. The electrical potentials can be mapped using the half-cell technique [5] and, with skill, potential maps can be used to locate where corrosion has been initiated.

Assessing the rate of active corrosion in reinforced concrete structures is rather more difficult. Concrete resistivity measurements have been related [6] to probable corrosion rates if used in conjunction with potential mapping. Alternatively the rate of corrosion on steel samples cast into the concrete during construction can be measured using the a.c. impedance method [7].

However this is a difficult and expensive technique and is only suitable for laboratory or special site studies.

3. MONITORING OF HIGH RISK STRUCTURES

The techniques described have been used in conjunction with regular visual and photographic surveys to monitor the corrosion durability performance of three different types of structure, constructed over the past five years in aggressive chloride rich environments.

The first site comprises some 2500 reinforced concrete coastal armour units, located on man-made offshore reefs and on shoreline wave absorbtion slopes (Fig. 1). Approximately half of these units were cast using a 30% pulverised fuel ash cement replacement. This was done to reduce cracking due to the heat of hydration and also for economic reasons, but it provides an excellent case study on the durability effects of using pozzolanic cement replacement. A concrete cube strength of 55 N/mm^2 and cover of 60 mm were specified.

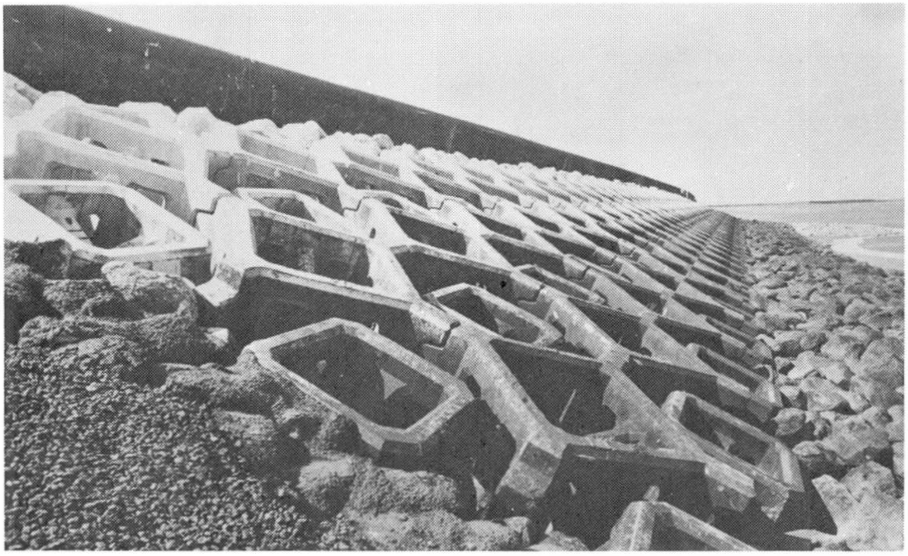

Fig. 1 View of Diode unit revetment

The second site comprised a sewage pumping station located on the shoreline. A line of 20 tonne reinforced concrete Mermade units were positioned to make a 4.5 m high retaining wall, that also acted to absorb wave energy (Fig. 2). Concrete cube strengths were 55 N/mm^2 and cover of 55 mm was used. A trial hydrophobic pore blocking (h.p.b.) admixture was used in three of the units to study the effect on corrosion durability. Trial exposure beams with varying cover, cracking and water-cement ratio were also cast with a.c. impedance inserts to measure direct corrosion rates. A number of wall units were also cast with similar inserts.

The third site was a storage barn for road deicing salt in Nottinghamshire (Fig. 3). Prestressed concrete wall panels, 110 mm thick were used in the construction of the barn. Concrete cube strengths of over 80 N/mm^2 were achieved at 28 days, with a cover to the prestressing tendons of 30 mm. The same h.p.b. admixture was used in all of the panels, with the exception of two control panels which were cast from an unmodified concrete mix.

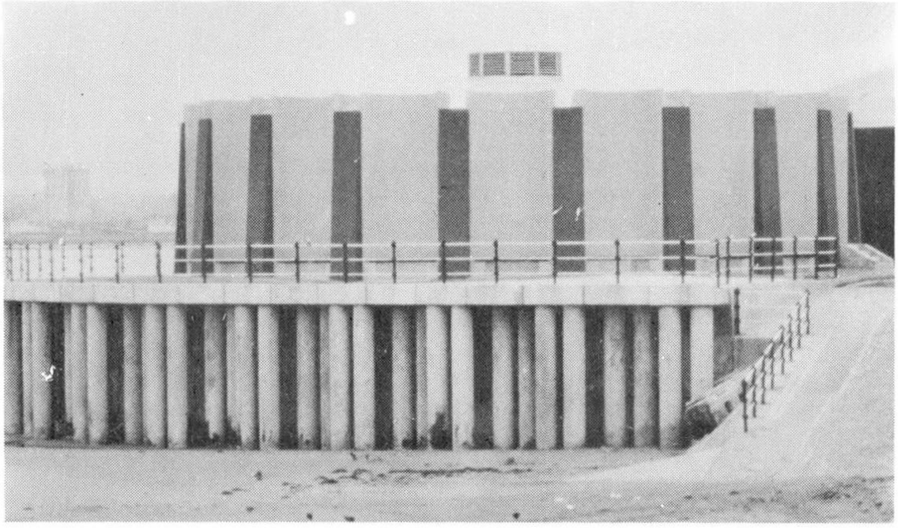

Fig. 2 View of Mermade wall and sewage pumping station

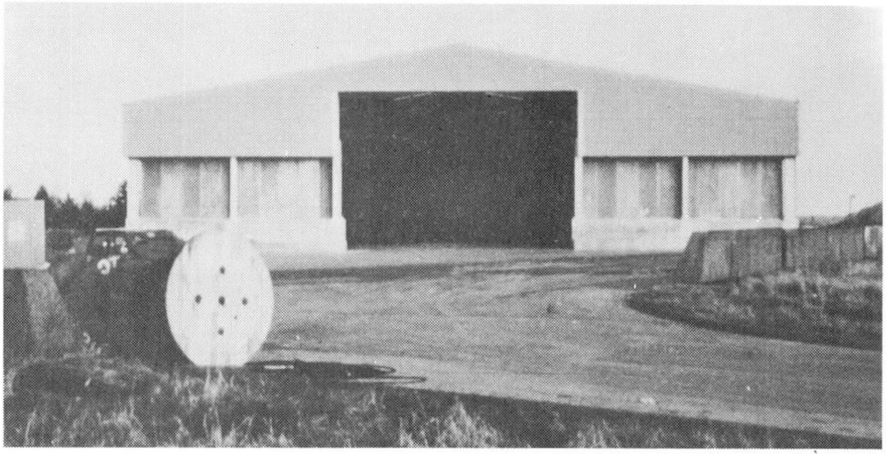

Fig. 3 View of Nottinghamshire salt barn

4. PRELIMINARY RESULTS

A durability project will inevitably be a medium to long term study. The results given below are only those obtained in the first two to five years after construction and may not necessarily reflect the long term trends. However, some initial findings are:

- Almost all of the coastal armour units sampled have potential results in the range 0 to -200 mV, with respect to a copper/copper sulphate half-cell. There are no significant potential differences or large potential gradients. This would imply that chlorides have not yet depassified the steel reinforcement.

- The only exceptions to the above are the cases of three units that have suffered moderate impact damage, exposing the steel. High potential values of -400 mV to -500 mV and steep potential gradients were recorded in the vicinity of visibly corroding steel. One year after repair with a polymer mortar, these units had become repassivated and displayed no significant potential results.

- The apparent resistivity of the ordinary concrete armour units is 5 kΩ.cm to 20 kΩ.cm, which would place them in a high risk category [6]. The units using a pozzolanic cement replacement had significantly higher resistivities in the range of 10 kΩ.cm to 100 kΩ.cm. This places them in the medium to low risk category.

- The retaining wall units would not be expected to be showing signs of corrosion activity just 18 months after construction. However, a.c. impedance studies on the exposure beams cast at the same time are showing significant corrosion activity in the ordinary concrete specimens that are either cracked, have low cover or have a high water-cement ratio. Each of these features may be expected to increase the risk of depassivation. A high water-cement ratio will lead to high permeability whilst low cover will decrease the time for chlorides to reach the reinforcement generally. Cracks will provide easy localised access to the steel for both chlorides and carbonation. There is no activity in any of the specimens using the h.p.b. admixture.

- Preliminary potential mapping of the salt barn panels have shown no anodic regions to date on either the unmodified concrete control panels (01 and 02) or on the panels containing h.p.b. admixture (C1 and C2). The results of I.S.A.T. and Figg permeability tests together with resistivity measurements on dried test cubes cast with each panel are shown in Table 1.

Concrete Specimen	Mean Figg result (secs.)	Mean I.S.A.T. result ($ml/m^2/sec$)			Mean Resistivity (kΩ.cm)
		@ 10 mins	@ 30 mins	@ 60 mins	
01	4471	0.190	0.125	0.095	29.5
02	2200	0.165	0.100	0.075	30.6
C1	7188	0.023	0.018	0.001	39.7
C2	6026	0.006	0.003	0.002	48.2

Table 1 Test results from salt barn panels

Both the permeability tests indicate that the concrete with h.p.b. admixture is several times less permeable than the unmodified control concrete. The I.S.A.T. water permeability test is considerably more sensitive to presence of the admixture. This was attributed to the hydrophobic properties of the concrete provided by the admixture. The electrical resistivity of the concrete with the admixture was also some 50% higher than that of the control concrete. The measurements indicate that the concrete containing h.p.b. admixture will be better able to resist the ingress of chlorides. Furthermore, if depassivation of the reinforcing steel does occur then the higher resistivity of the modified concrete should result in a significantly lower rate of corrosion due to the restricted flow of hydroxyl ions from cathode to anode regions. The lower permeability will also restrict oxygen passing through the concrete cover and fuelling the cathodic reaction.

5. CONCLUSIONS

Using steel reinforced concrete in chloride rich environments will often place the structure at high risk from corrosion attack. To minimise this risk use must be made of high strength concretes with large covers to the reinforcement. High quality workmanship must also be used to ensure an impermeable, uncracked concrete is obtained. The preliminary experimental results also suggest that using a modified concrete mix with a pozzolanic cement replacement or a h.p.b. admixture will further reduce the corrosion risk. In the case of pozzolanic cement replacements the rate of corrosion activity is likely to be reduced as the result of the higher resistivity. Although the resistivity increase with h.p.b. admixtures is more modest, the accompanying reduction in permeability should significantly reduce ingress of chlorides, carbonation penetration, and oxygen flow. However more longer term results are awaited before these initial trends can be confirmed.

6. ACKNOWLEDGEMENTS

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