# DURABILITY ASSESSMENT OF CONCRETE SPECIMENS IN THE TIDAL AND SPLASH ZONES IN FREMANTLE PORT

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**Abstract:** In 1982, reinforced concrete beams incorporating various mineral and chemical admixtures were suspended in the splash zone under Berth 8 in the inner harbour at Fremantle. The exposure programme was organised and managed by Taywood Engineering (now Gutteridge Haskins & Davies Pty Ltd.). The objective was to assess the durability of various materials and mix designs within a marine environment and a substantial amount has been reported on the initial phase of this research. This paper presents the penetrability properties of the test concretes after nearly 20 years exposure as well as the actual amount of steel lost due to corrosion. The implications of the findings for service life prediction modelling and designing maritime structures are discussed.

**Keywords:** Durability, Corrosion, Silica fume, Slag, GGBS, Hydrophobic, Admixtures

## INTRODUCTION

Premature deterioration of reinforced concrete due to chloride-induced corrosion of reinforcement is a global problem that costs billions of dollars annually. In severe maritime environments, concrete structures have often failed to achieve their required service life without major maintenance. The proposed durability section of the “Guidelines for Design of Maritime Structures” being finalized by Committee CE-030 of Standards Australia attempts to address this issue based on various protective strategies.

Fremantle Ports is the main port facility in Western Australia, and is located approximately 20 km south west from the centre of Perth. The weather in Fremantle is best characterised as a temperate Mediterranean climate with an annual average daily temperature of 22°C, consisting of a hot summer and a cool winter. Berth 8, in the Inner Harbour, was constructed in 1972 using a nominal 4000 psi concrete. Within 10 years, the soffit of the slab and beams were badly deteriorated in a strip above a sheet-piled retaining wall which caused incoming waves from passing vessels to be splashed upwards. The area concerned was repaired in 1982.

Following the repairs, it was decided to suspend reinforced concrete specimens of various compositions below the repaired section to be monitored over time and establish the relative performance of various durability enhancing materials, namely Ground Granulated Blast-furnace Slag (GGBS), Silica Fume (SF) and a proprietary hydrophobic admixture. These products were used in concrete with a cementitious content of 400 kg/m3 and a nominal w/c of 0.4 to be compared with a control containing Ordinary Portland Cement (OPC). These concretes would essentially comply with the proposed requirements of the above draft Australian Standard. Concrete with an OPC content of 250 kg/m$^3$ and w/c ratio of 0.6, which was considered representative of the concrete in the structure, was also included in the study.

There are few long-term exposure programmes in the literature where the relative performance of different concrete types have been reported. This paper presents sorptivity data as well as chloride profiles and chloride diffusion coefficients from a range of concrete types that had been exposed to the splash zone in Fremantle for nearly 20 years. The properties of the bulk concrete after long-term exposure are compared with that obtained from the previous investigation (Aldred, 2002). As the programme includes both sorptivity and diffusion modifying products, the research provides useful information on the relative importance of these two transport properties in a splash zone environment. The observed difference between the diffusion coefficients calculated from the chloride profiles after long-term exposure and after accelerated chloride penetration tests on the bulk concrete highlights the difficulty of predicting service life from laboratory tests.

## CONCRETE SPECIMENS

The mix proportions and casting dates are shown in Table 1. The test specimens were 100 mm x 100 mm x 500 mm long with cover to the sides and bottom of 30mm and 60 mm respectively. Full details of the mixes and previous investigations are given in Grace (1984), Green (1988) and Aldred (2001).

Table 1: Mix design characteristics for Berth 8 specimen beams (kg/m$^3$ unless noted).

| Designation | A | HPI | 10% SF | 65% SF-10% GGBS | HPI-65% GGBS | 65% GGBS | 45% GGBS | 30% GGBS |
|---|---|---|---|---|---|---|---|---|
| Type A cement[1] | 400 | 400 | 360 | 125 | 140 | 140 | 220 | 280 |
| GGBS[2] | - | - | - | 235 | 260 | 260 | 180 | 120 |
| Silica fume | - | - | 40 | 40 | - | - | - | - |
| HPI[3] | - | 30 L/m$^3$ | | | 30 L/m$^3$ | | | |
| 20 mm granite | 860 | 860 | 860 | 860 | 860 | 860 | 860 | 860 |
| 10 mm granite | 310 | 310 | 310 | 310 | 310 | 310 | 310 | 310 |
| 7 mm granite | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 |
| Dune sand | 520 | 520 | 520 | 520 | 520 | 520 | 520 | 520 |
| w/cm ratio | 0.40 | 0.47 | 0.40? | 0.40 | 0.44? | 0.44 | 0.40 | 0.40 |
| Date cast | 25/11/81 | 9/9/82 | 25/11/81 | 27/11/81 | 9/9/82 | 27/11/81 | 27/11/81 | 27/11/81 |

1. A = AS 1315 Type A ordinary Portland cement, typically now AS 3972 Type GP cement
2. GGBS = Ground granulated blast furnace slag
3. HPI = Proprietary hydrophobic admixture

The specimens were suspended beneath Berth 8 in September 1982 in an environment where there would have been as many as 600 cycles of wetting per year. The exposure site is shown in Figure 1. Cores were taken in 2001/2002 and tested for sorptivity (GHD Method), chloride profile and chloride diffusion (Nordtest NT Build 443). Chloride diffusion tests were only conducted on samples that had not been contaminated with chloride as indicated by spraying with 0.1N $AgNO_3$ solution.

The specimens containing concrete with w/c ratio of 0.6 were found to be so badly cracked and deteriorated due to corrosion of the embedded reinforcement that detailed investigation of the concrete properties was not possible. However, weight loss for the embedded reinforcing was measured.

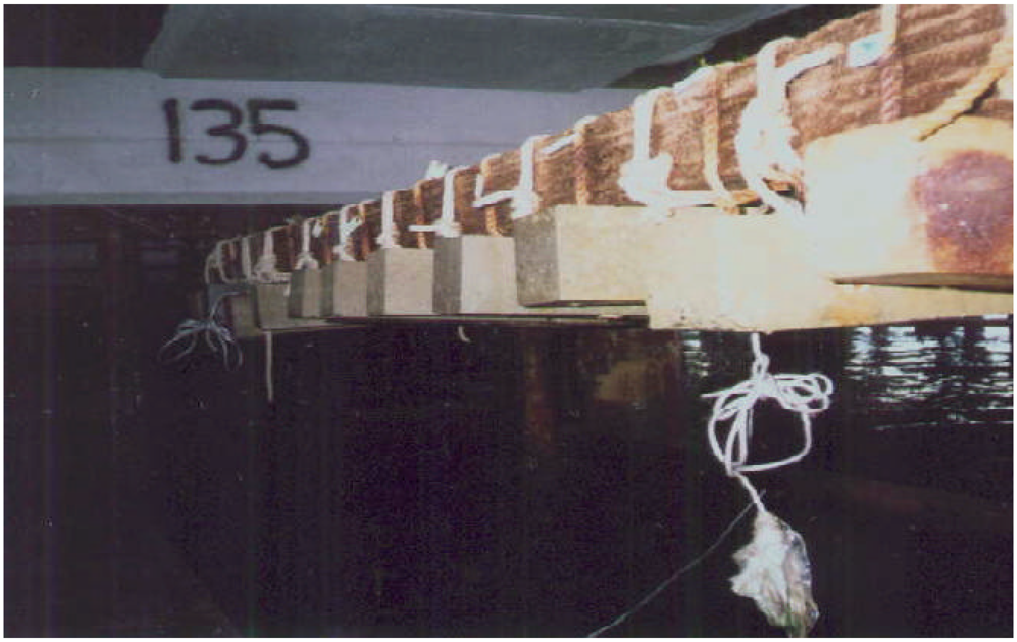


Figure 1: Exposure site beneath Berth 8 Fremantle.

## TEST PROCEDURES

The water sorptivity test measures the transport of water (and any dissolved salts) through pores by capillary suction. Sorptivity was measured in accordance with the GHD Method (LP/PEN02). Cores were trimmed and oven dried at 105ºC to constant weight before being placed in contact with water. The volume of water absorbed per unit cross-section at time intervals up to 4 hours and these values are plotted against the square root of time. The gradient of the line is the sorptivity, which is reported in $mm/min^{0.5}$.

Chloride profiles were measured from 75mm diameter cores which were cut to the following depth increments: 0-10mm, 10-25mm, 25-50mm, and 50-75mm. The acid soluble chloride contents for these increments were used to estimate the effective diffusion coefficient based on Fick's second law after Collepardi (197_).

Chloride diffusion was also measured in accordance with the Nordtest NT Build 443. Cores were sprayed with silver nitrate to determine the approximate depth of chloride penetration. Only samples that had not been contaminated by chlorides were used for the Nordtest. After immersion in 3M sodium chloride solution for 35 days, the specimens were profile ground and the diffusion coefficient was calculated based on Fick's second law.

The 28mm diameter reinforcement bars were removed from the specimens for visual assessment. They were then trimmed to 391mm and cleaned in accordance with ASTM G1 – 1990, the standard practice for preparing, cleaning and evaluating the corrosion test specimens. The cleaned bars were weighed to determine the estimated mass loss.

## TEST RESULTS

The sorptivity results are summarised in Figure 2. OPC and GGBS concrete containing the proprietary hydrophobic admixture (HPI) had significantly lower sorptivity than the other concretes. Silica fume tended to reduce sorptivity and GGBS to increase it.

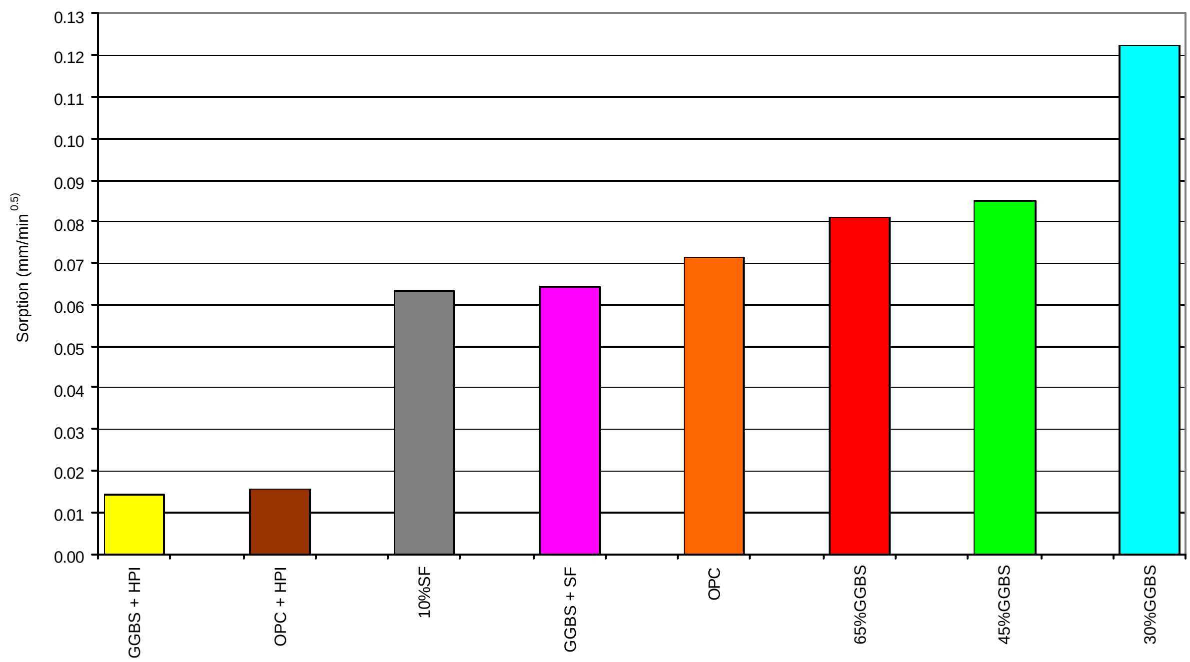


Figure 2: Sorptivity results from concrete after 19 years field exposure.

The test specimens allowed chloride penetration from all faces and therefore it was only possible to determine a chloride penetration profile in concretes where the cross section had not been fully penetrated. Chloride profiles for the GGBS and silica fume concretes are shown in Figure 3. The silica fume concretes exhibited no significant chloride measured beyond 10mm.

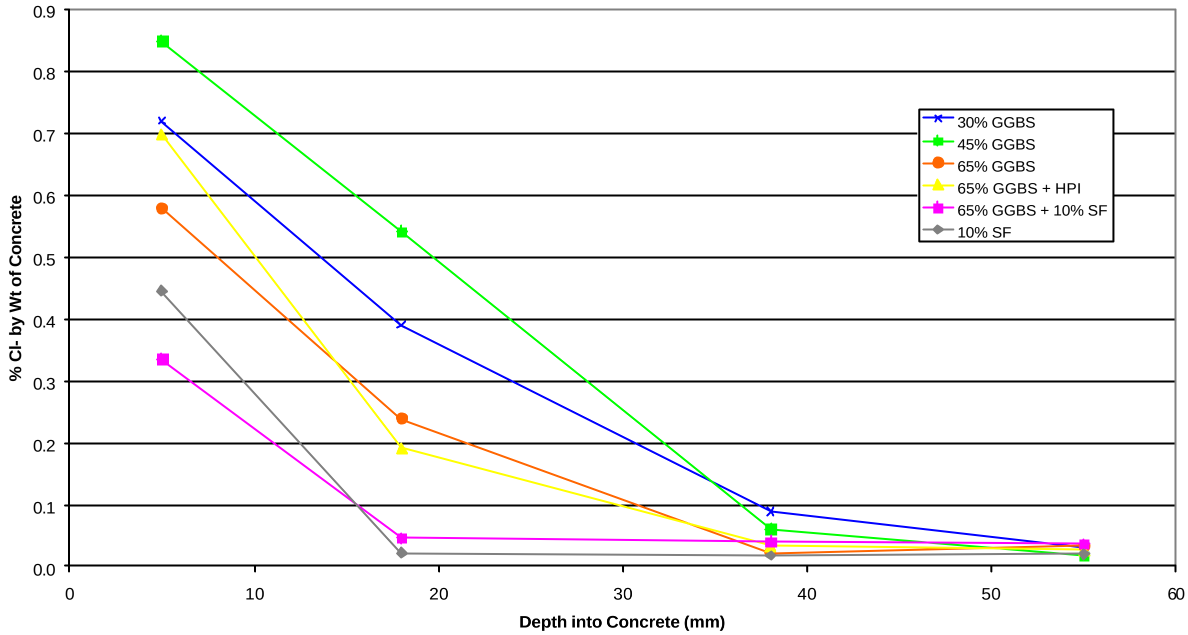


Figure 3: Chloride Penetration into Berth 8 Beams after 19 years

The chloride profiles into the uncontaminated 20 year old concrete after testing in accordance with the requirements of Nordtest NT Build 443 are given in Figure 4. The better performers were the silica fume in OPC and 65% GGBS with and without HPI. However, concrete containing both silica fume and 65% GGBS had significant chloride content measured through to the final increment at 14-16mm.

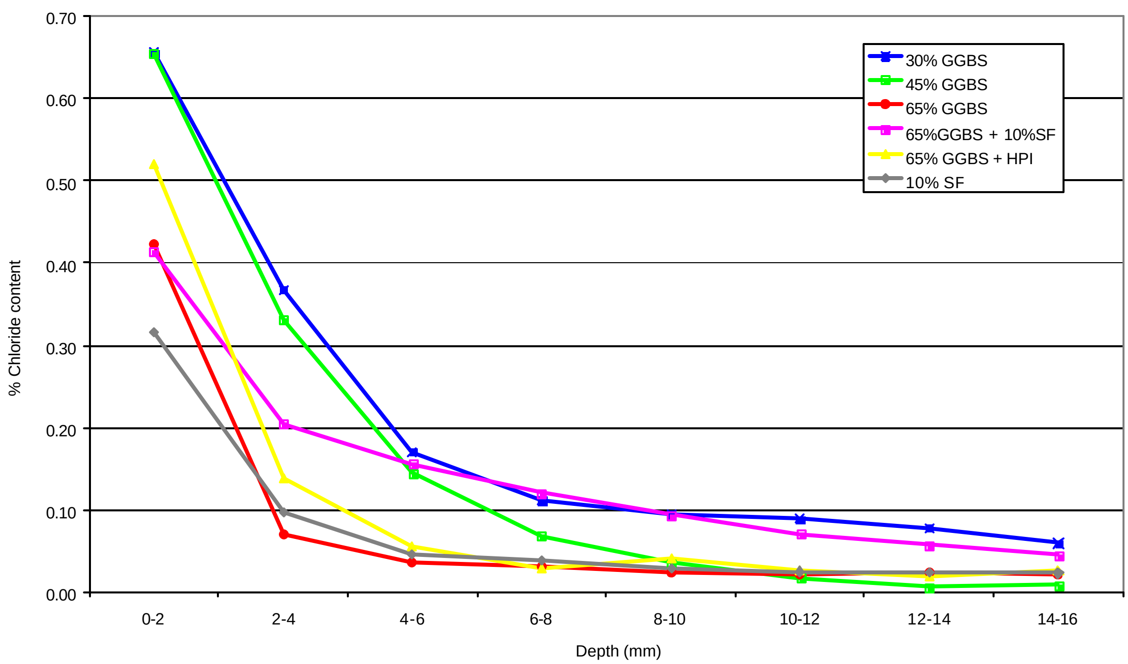


Figure 4: Accelerated chloride penetration into uncontaminated concrete core

The diffusion coefficients calculated from the chloride profiles measured at different ages are compared with those from the Nordtest procedure in Table 2. It can be seen that the accelerated test procedure resulted in a significantly calculated diffusion coefficient than calculated from ambient exposure over 19 years.

Table 2: Summary of chloride diffusion data from Berth 8 specimens.

| | Dce (based on Cl profile) | | | Dc (Nordtest) | Ratio |
|---|---|---|---|---|---|
| Mix Age (years) | 2 | 6 | 19 | 20 | Dc/Dce |
| OPC | 5.10E-12 | 1.09E-11 | n/a | n/a | n/a |
| OPC + HPI | - | 1.83E-12 | n/a | n/a | n/a |
| 30% GGBS | 2.28E-12 | 4.30E-13 | 4.05E-13 | 3.72E-12 | 9.19 |
| 45% GGBS | 2.45E-12 | - | 4.40E-13 | 2.28E-12 | 5.18 |
| 65% GGBS | 1.10E-12 | 1.34E-12 | 2.30E-13 | 2.04E-12 | 8.87 |
| 65% GGBS + HPI | - | 3.50E-13 | 1.41E-13 | 1.60E-12 | 11.35 |
| 65%GGBS + 10% SF | - | - | 6.50E-14 | 1.16E-11 | 178.46 |
| 10% SF | - | 1.45E-13 | 5.30E-14 | 2.54E-12 | 47.92 |

The visual examination of embedded reinforcement indicated significant corrosion had occurred in OPC concretes with w/c ratio of 0.6. The estimated loss of steel after 20 years was 500 micrometres which is equivalent to approximately 7% of steel section. One bar in the OPC concrete with w/c ratio of 0.4 exhibited significant corrosion but cracking of the specimen had not occurred. Minor corrosion in the other specimens appeared related to discontinuities caused by the PVC supports of reinforcement.

## DISCUSSION

The exposure condition beneath Berth 8 was severe and had resulted in severe deterioration of the structural concrete within 10 years. Comparable quality of concrete with a w/c ratio of 0.6 had also undergone severe corrosion after nearly 20 years exposure. Well cured concrete containing an OPC cement content of 400 kg/m³ and a w/c ratio of 0.4 had been penetrated by chloride through the 150 mm square section but showed no visible signs of deterioration. Corrosion had begun in this concrete but had not caused cracking. Aldred (2001) showed that corrosion measurements indicated initiation had occurred in the OPC concrete containing HPI but examination of the reinforcement did not indicate significant corrosion. The higher resistivity of the OPC-HPI concrete coupled with its lower effective diffusivity may have limited corrosion.

OPC and GGBS concretes containing HPI had significantly lower sorptivity than the other concretes tested. This demonstrates that the hydrophobic ingredients were able to persist within the concrete after prolonged maritime exposure. Concretes containing silica fume had lower sorptivity than those containing GGBS as has been observed by others. All sorptivity values were lower than expected, presumably due to progressive densification after 20 years exposure.

All concretes incorporating blended cement had greatly reduced chloride penetration compared to concrete with OPC only. The effective diffusion coefficients for all blended cement concretes were low ($<10^{-12}$ m²/s). Concrete containing silica fume had the lowest chloride penetration followed by concretes incorporating 65% GGBS with and without HPI. The chloride diffusion coefficients calculated for the Nordtest accelerated chloride penetration of the uncontaminated concrete were generally a order of magnitude higher. The diffusion coefficient for the specimen incorporating both silica fume and GGBS was two orders of magnitude higher than that calculated from chloride profile. These data suggest that the improvement in effective diffusion coefficient with time cannot be fully explained by continued hydration and suggests surface effects may be dominant. Bamforth (1998) has found a similar effect. The high chloride diffusion for the ternary blend with GGBS and silica fume under accelerated test may be an aberrant result but suggests further research into ternary blends is necessary.

Many current specifications require accelerated chloride diffusion testing on trial mixes as a basis for service life prediction. This research has shown that the accelerated procedure gave significantly higher chloride diffusion coefficients to those obtained from field chloride profiles. Accordingly value of predictions based on early age accelerated testing in pure sodium chloride solutions may be limited and more research should be conducted on surface effects.

In spite of considerable chloride penetration and initiation of corrosion, there was little visible deterioration in the OPC concrete with a w/c ratio of 0.4 and a minimum cover of 30 mm after nearly 20 years in a severe environment.

This demonstrates the importance of the propagation phase of the corrosion process. The owner/manager of a maritime structure is ultimately interested in the serviceability of his structure. The presence of chlorides at the level of the reinforcement is important when the resultant corrosion causes distress.

This research was initiated by the premature deterioration of a small strip on the soffit of the berth where the localised microclimate was severe. While this area had to be repaired over 20 years ago, the neighbouring soffit areas which had been cast with concrete of the same inferior quality are showing no signs of distress after 30 years in service. This highlights the importance of assessing the exposure conditions to which specific elements or parts of elements are exposed.

## CONCLUSIONS

1. The proprietary hydrophobic admixture significantly reduced sorptivity in concrete that had been exposed to a splash zone for nearly 20 years.
2. Blended cements containing ground granulated blast furnace slag and/or silica fume were found to reduce the chloride penetration. Concretes containing silica fume exhibited the lowest chloride penetration.
3. Diffusion coefficients based on accelerated chloride penetration tests on cores taken from the specimens were significantly higher than those from chloride profiles.

4. There was no significant corrosion of the reinforcement embedded within OPC concrete containing the hydrophobic admixture or the concretes incorporating blended cements.

5. The results presented in this paper suggest that diffusivity had more influence on chloride penetration in this splash zone environment than sorptivity.

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## KEYWORDS:

Durability, Corrosion, Silica fume, Slag, GGBS, Hydrophobic, Admixtures