Durability Performance of Australian Commercial Concrete Modified with Permeability Reducing Admixture

Robert L Munn[§], Gary Kao*, Z Tian Chang[§],

[§] ACCI, School of Civil & Environmental Engineering, UNSW

* Xypex Australia

ABSTRACT

Research previously undertaken examined the effect of inclusion of permeability reducing admixtures on commercial 32MPa strength grade concretes. The studies showed benefits and potential to enhance concrete durability in aggressive environments. A research program was recently completed that used 40MPa commercial concretes, typically required by AS3600 for exposure classification B2 and above, which contained three different types of cement (Type-GB 25% fly ash, Type-GB 38% slag and Type-GB 60% slag) and a permeability reducing admixture at various dose rates. The major aim was to study the effects of the permeability reducing admixture on concrete properties relating to durability performance. This paper outlines results of testing for compressive strength, drying shrinkage, sulphate resistance, chloride resistance and water permeability. Assessment of these test results indicates that, whilst concrete performance was influenced by cement type, permeability reducing admixture can also significantly improve the durability of concrete.

Keywords: Permeability reducing admixture, durability, supplementary cementitious materials, compressive strength, drying shrinkage, sulphate resistance, chloride resistance and water permeability.

INTRODUCTION

Most major cities in Australia are located in coastal climate zones where corrosion of steel reinforcement is a major factor affecting the durability of concrete structures. Concrete is inherently a porous material due to an existence of capillary pores, gel pores, and weak cement-aggregate interface zones. Chloride ions in seawater or in marine atmosphere can diffuse into concrete through the concrete pore system. Once the chloride concentration at the reinforcing steel level reaches a threshold value, initiation of steel corrosion will start.

The use of low penetrability concrete and control of cracking in concrete are among the key techniques to achieve durable concrete in marine and coastal environments. The traditional means to improve concrete durability are through reduction of water to cement ratio and/or increase of moist curing period. More recently, partial replacement of Portland cement with supplementary cementitious materials (SCMs), such as silica fume, fly ash or ground granulated blast furnace (GGBF) slag, has become popular for concrete to be used in aggressive environments. The use of SCMs in concrete has been discussed extensively in the literature (1,2,3,4).

The Australian Standard AS 3600 (Concrete Structures) requires a minimum strength grade of 40MPa for concrete structures in the exposure classification B2, which includes those permanently submerged in seawater and above ground in coastal areas (up to 1km from the coastline, but excluding tidal and splash zones). The requirement of a minimum concrete strength provides only one guideline for concrete quality suitable for marine environments. The more fundamental properties of sorptivity, permeability and diffusion of chlorides are not simply related to concrete strength but affected by other parameters. Full consideration of all relevant parameters must be considered in design of durable concrete structures in marine environments. Some other major factors to be considered include surface chloride level, chloride binding capacity, performance enhancement with time and chloride activation level.

Various types of permeability reducing admixtures (PRA) are available in the market (as described in AS1478.1 Appendix F) (5). Some of them are classified as hydrophobic admixtures due to the presence of long chain, fatty acids and vegetable oils (5), whereas others are classified as microstructure modifiers which reduce concrete permeability through crystallisation in concrete pores (6). This research project was undertaken at the ACCI in the University of New South Wales and extended the research from Stage-I which was completed in March, 2003 (7,8,9). This research program that used 40MPa commercial concretes which contained three different types of cement (Type-GB 25% fly ash, Type-GB 38% slag and Type-

GB 60% slag) and permeability reducing admixture at various dose rates to study the effects of the permeability reducing admixture on concrete properties relating to durability performance. This paper outlines results of testing for compressive strength, drying shrinkage, sulphate resistance, chloride resistance and water permeability.

MATERIALS AND TEST METHODS

Materials and Concrete Mix Proportions

A total of nine commercial concretes (Grade 40MPa) were investigated in this research program. The nine concretes were classified into three groups according to the cement types. Three cements used were Type-GB (AS3972) blended cement with 25% fly ash (AS3582.1 or ASTM C618 Class F) and two Type-GB blended cements with approximately 38% and 60% slag (AS3582.2) respectively. For each of the three groups, a control concrete mix without PRA was produced and the other two concrete mixes were modified with PRA at the dose rate of 0.8% and 1.2% by weight of total cementitious materials.

To minimise the differences in the performance between "laboratory mixed concrete" and commercial "site received concrete", all concretes (one cubic metre each) were produced in a premix concrete plant and delivered to the ACCI laboratory where testing of fresh concrete properties were carried out and concrete samples were cast and cured for testing hardened properties. All the concrete mixes were commercial concretes of 40MPa strength grade.

Table-1 summarises the mix proportions of nine concrete mixes using different cements and admixtures. Because the nearby premix plants did not store Type-GB cements containing 60% slag in bulk, a GGBF slag product (Ecocem) was blended with Type-GP (SL) cement at the premix plant to produce the three concretes with 60% slag component in the cement. AS1478.1 Type-WR water reducing admixture, Pozzolith 370 (Pozz370), was used to achieve a target slump of 80$\pm$10mm for all the concrete mixes. PRA was added into the selected concrete batches at the batching plant according to the manufacturer's recommendations.

Table-1 Concrete Mixture Designs

Mix Code	W/C Ratio	Cement Type and Content (kg)	Permeability Reducing Admixture (% of Cement Content)	Water Reducer (Pozz 370) (L/m^3)	Aggregate/Cement Ratio
2F1	0.40	25%FA (435)	Nil	1.35	3.93
2F2	0.40	25%FA (435)	0.8% PRA	1.35	3.93
2F3	0.40	25%FA (435)	1.2% PRA	1.35	3.93
2LS1	0.40	38% Slag (435)	Nil	1.35	3.96
2LS2	0.40	38% Slag (435)	0.8% PRA	1.35	3.96
2LS3	0.40	38% Slag (435)	1.2% PRA	1.35	3.96
2HS1	0.40	60% Slag (435)	Nil	1.35	-
2HS2	0.40	60% Slag (435)	0.8% PRA	1.35	-
2HS3	0.40	60% Slag (435)	1.2%PRA	1.35	-

Test Methods

The following test methods were used in the investigations described in this paper.

Compressive Strength: Compressive strength was tested with 100mm diameter cylinder samples after standard curing for 3, 28, and 91 days in accordance with AS1012.9.

Drying Shrinkage: Drying shrinkage samples were cast, cured and exposed to standard drying conditions according to AS1012.13. Drying shrinkage was measured every 7 days until 56 days of drying.

Length Change in Sulphate Solution: Prism samples were cast, cured and immersed in the standard sulphate solution according to AS2350.14. Expansions of prisms were measured using a comparator every 2 weeks after immersion in refreshed sulphate solution. Final readings were taken after 16 weeks of immersion.

Nordtest (NT BUILD 443, 1995): The Nordtest (NT BUILD 443, 1995) (10) is an accelerated test method for assessment of chloride diffusion into hardened concrete. It is based on immersion of cylinder samples in 16.5% NaCl solution for at least 35 days. A 35 days immersion period was adopted in this test program. The cylinder samples are coated with epoxy or polyurethane on all surfaces except for the top surface. After the immersion period, powder samples are extracted at different depths from the exposed surface for analysis of chloride contents. The chloride content profile in the concrete is plotted and used to determine the chloride diffusion coefficient by analysis against Fick's Second Law (11,12,13).

ACCI Water Permeability Test: The ACCI test apparatus was modified from the Taywood water permeability test apparatus. Samples were lime-water cured for 14 days followed by 77days air drying and were subjected to testing at age of 91 days. An epoxy resin (Sikadur 52) was used for sealing the side of concrete sample during sample preparation. Water pressures of 6 bars and 10 bars (60 metres and 100 metres water head) were applied to one surface of the 50mm thick samples during the test period. The amount of water flow through the samples under the pressure was measured. The water permeability coefficient was calculated using Darcy's equation and shown in the unit of m/s.

$$k = \frac{Q}{A} \times \frac{L}{H}$$

where k = water permeability coefficient (m/s);

Q = flow rate (m^3/s);
L = depth (thickness) of specimen (m);
A = specimen area under pressure (m^2);
H = head of water (m)

EXPERIMENTAL RESULTS AND DISCUSSIONS

Compressive Strength (AS1012.9)

The compressive strength test results are shown in Table-2 for all the concretes at the ages of 3, 28, and 91 days after standard curing in limewater. The compressive strengths of the PRA modified concretes are also expressed as ratios to that of their control concretes tested at the same age.

Compressive strengths of all high slag (60%) concretes were generally lower at all comparable ages than the fly ash and low slag (38%) concretes. The concrete Mixes-2F1, 2HS1 and 2HS2 recorded compressive strengths at 28 days slightly lower than the target strength of 40MPa. The reasons for these lower strengths are not known but it is likely to be a result of accidental variation in the relatively small batches of commercial concrete used in this investigation. As this research program is primarily concerned with relative rather than absolute performance these lower strength results are not considered detrimental.

Table-2 Results of Compressive Strength at All Ages

	Compressive Strength (MPa)		
	3 days	**28 days**	**91 days**
2F1	21.9	36.2	46.7
2F2	22.1	44.1	53.8
2F3	28.0	47.5	58.0
2LS1	28.1	49.9	64.8
2LS2	28.6	52.7	65.7
2LS3	28.6	52.9	66.3
2HS1	14.2	38.1	49.3
2HS2	12.4	36.5	47.8
2HS3	15.7	42.0	53.4

The influence of PRA on the compressive strengths of concretes made with fly ash blended cement is shown in Fig-1. PRA modified concrete Mix-2F2 had similar 3 days but higher compressive strength than the control Mix-2F1 by 15% and 22% at 91 and 28 days respectively. Mix-2F3 modified with 1.2% PRA recorded even higher strength by 24% to 31% than the control mix at all the three ages.

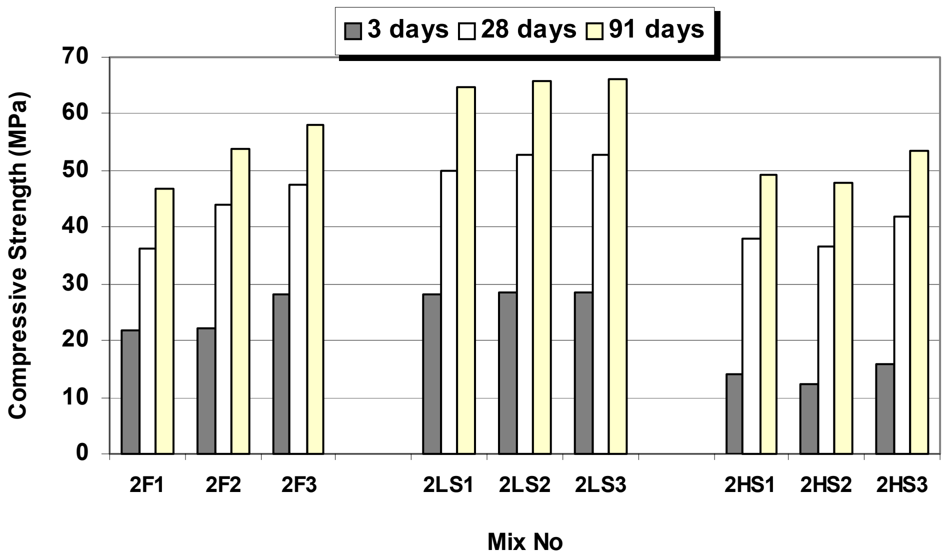

Fig-1 Comparison of Compressive Strengths of All Concretes

Fig-1 also shows the compressive strengths of the three low slag (38%) concrete mixes. At all three ages, the two concretes (Mix-2LS2 and Mix-2LS3) modified with 0.8% and 1.2% PRA respectively each had slightly higher strengths than the control Mix-2LS1. The effect of PRA on strength increase in the low-slag cement concretes was much less significant that in the fly ash concretes. The difference in strength development was also negligible between Mix-2LS3 and Mix-2LS2 at all ages. Of the three high slag (60% slag) concrete mixes, Mix-2HS2 modified with 0.8% PRA recorded slightly lower strengths than the control Mix-2HS1 by 3% to 13%. It was noted that Mix-2HS2 was delivered at a higher slump of 125mm compared to that of 100mm of the control Mix-2HS1. The slightly lower strengths of Mix-2HS2 could be due to slightly higher water content in Mix-2HS2 than that of the control Mix-2HS1. For Mix-2HS3 modified with 1.2% PRA, its strengths at all the ages were higher than the control Mix-2HS1 by 8% to 11%.

All PRA modified concretes, except Mix-2HS2, had higher compressive strengths than the control concrete mixes. In particular, the effect of PRA on strength increase was more significant in the fly ash concrete mixes, in which a high dose rate of PRA also increased strength at all the three ages.

Drying Shrinkage (AS1012.13)

Table-3 presents the drying shrinkage results of all the concrete mixes measured after 28 days and 56 days of standard drying according to AS1012.13.

The drying shrinkage results of three Type-GB fly ash (25%) cement concretes are shown in Fig-2. The concretes modified with PRA (Mix-2F2 and Mix-2F3) had significantly lower shrinkage by 20% to 25% compared to the control Mix-2F1 at each age. However, the difference in drying shrinkage was insignificant between the two mixes containing 0.8% and 1.2% PRA by weight of cement.

Table-3 Shrinkage after 28 Days and 56 Days of Standard Drying

Mix No	*28 Days*	*56 Days*
2F1	617	719
2F2	474	577
2F3	463	562
2LS1	707	814
2LS2	572	689
2LS3	587	711
2HS1	664	803
2HS2	633	772
2HS3	661	772

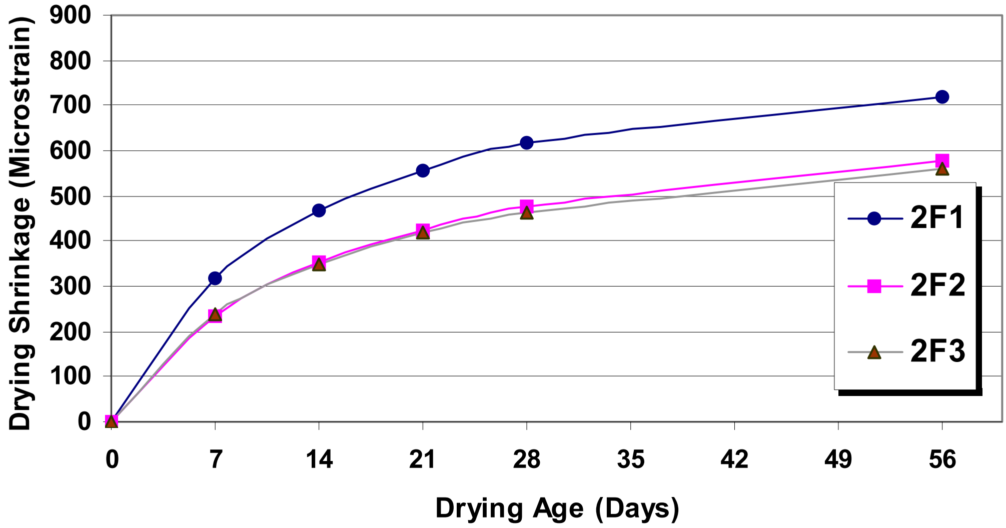

Fig-2 Drying Shrinkage of Type-GB Fly Ash Blended Concretes

Fig-3 shows the drying shrinkage of Type-GB low slag (38%) cement concretes (Mix-2LS1, Mix-2LS2 and Mix-2LS3). The PRA modified concretes (Mix-2LS2 and Mix-2LS3) had significantly lower shrinkage than the control concrete Mix-2LS1 by 13% to 19% at each age. Again, the difference in drying shrinkage was not significant between the two mixes containing 0.8% and 1.2% PRA by weight of cement.

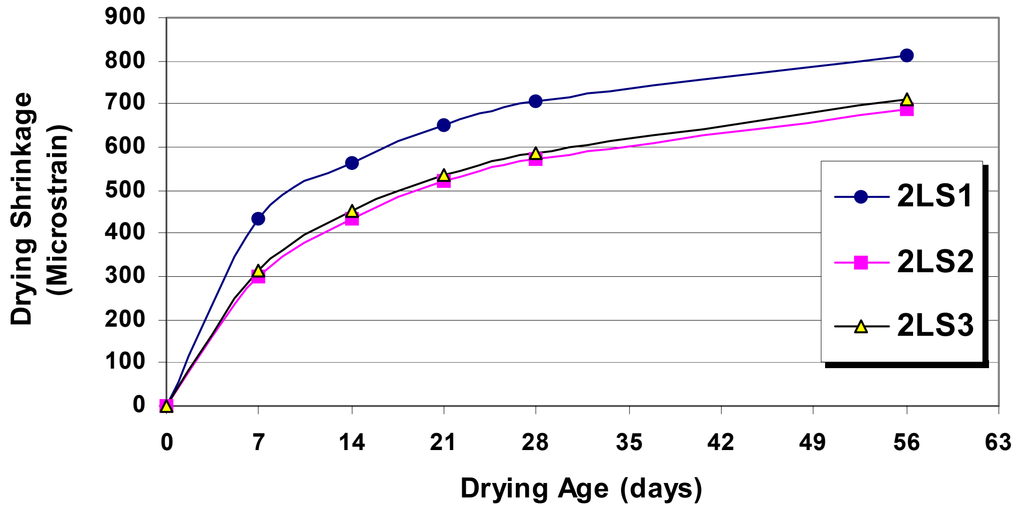

Fig-3 Drying Shrinkage of Type-GB Slag (38%) Blended Concretes

Fig-4 shows the drying shrinkage results of Type-GB high slag (60%) cement concretes (Mix-2HS1, Mix-2HS2 and Mix-2HS3). The drying shrinkage of PRA modified concretes Mix-2HS2 and Mix-2HS3 were less than or equal to that of the control concrete Mix-2HS1 at each age.

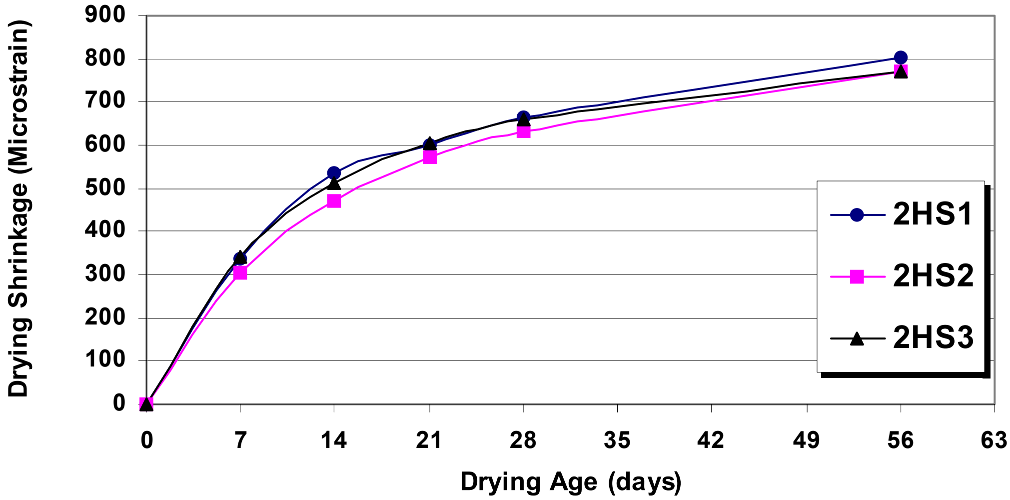

Fig-4 Drying Shrinkage of Type-GB Slag (60%) Blended Concretes

Overall, PRA modified concrete mixes were found to have significant lower drying shrinkage compared to control mixes made with Type-GB fly ash blended cement and 38% slag blended cement. Slightly lower shrinkage was found with PRA modified high slag (60%) cement concretes compared to the control concrete.

Length Change in Sulphate Solution (AS2350.14)

Potential expansion of concrete in sulphate environments was assessed in accordance with AS2350.14 by immersing mortar samples (sieved out of each concrete) in a sulphate solution over 16 weeks. The proposed assessment criterion of the AS 2350.14 test for acceptable sulphate resistance is that the sample expansion should be no more than 900 microstrains after 16 weeks immersion in the sulphate solution. Table-4 summarises the test results of samples of all concretes included in this investigation.

Fig-5 shows the length change of mortar samples from the 25% fly ash cement concretes. The samples of the control concrete (Mix-2F1) recorded good sulphate resistance with expansion of 495 microstrains after 16 weeks immersion in the sulphate solution. However, even lower expansions were recorded with the samples of the PRA modified concrete Mix-2F2 and Mix-2F3. While Mix-2F2 containing 0.8% PRA in cement had 40% lower expansion than control Mix-2F1, Mix-2F3 containing 1.2% PRA in cement recorded a very low expansion of only 227 microstrains which was 54% lower than that of the control Mix-2F1.

Table-4 Expansions after 16 Weeks in Sulphate Solution

Mix No	*Length Change in Sulphate Solution* (10^{-6})
2F1	495
2F2	295
2F3	227
2LS1	322
2LS2	284
2LS3	272
2HS1	557
2HS2	471
2HS3	303

The outstanding sulphate resistance of Mix-2F3 together with its high early strength gain indicated significant benefits of using PRA at the higher dose rate (1.2%) to enhance the sulphate resistance of fly ash concrete.

Fig-6 shows the length change of mortar samples from Type-GB low slag (38%) cement concrete mixes. The samples of all the three concretes had low expansions in the range of 272 to 322 microstrains. The PRA modified concretes (Mix-2LS2 and Mix-2LS3) recorded lower expansions by 12% and 16% compared to the control Mix-2LS1.

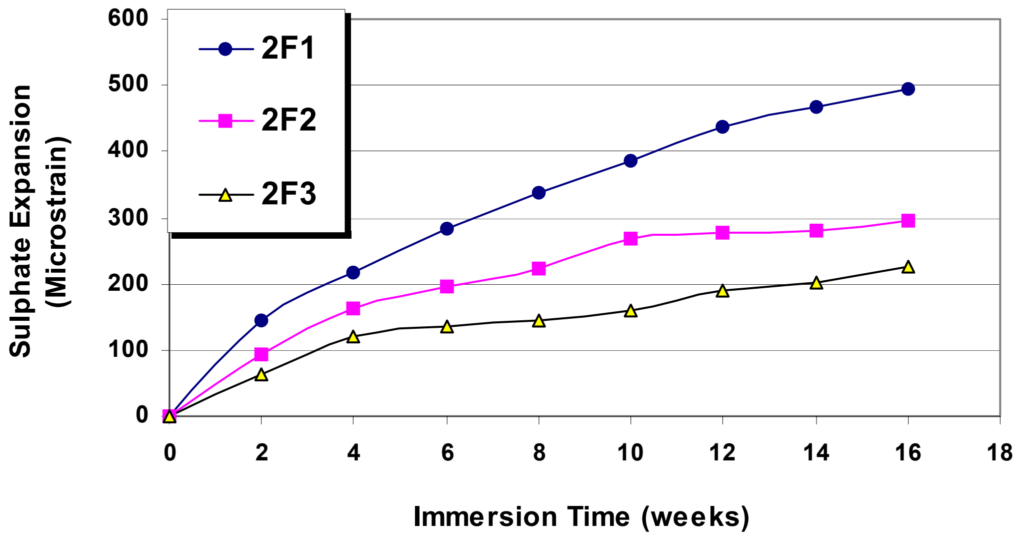

Fig-5 Expansion in Sulphate Solution of Samples of Fly Ash Concretes

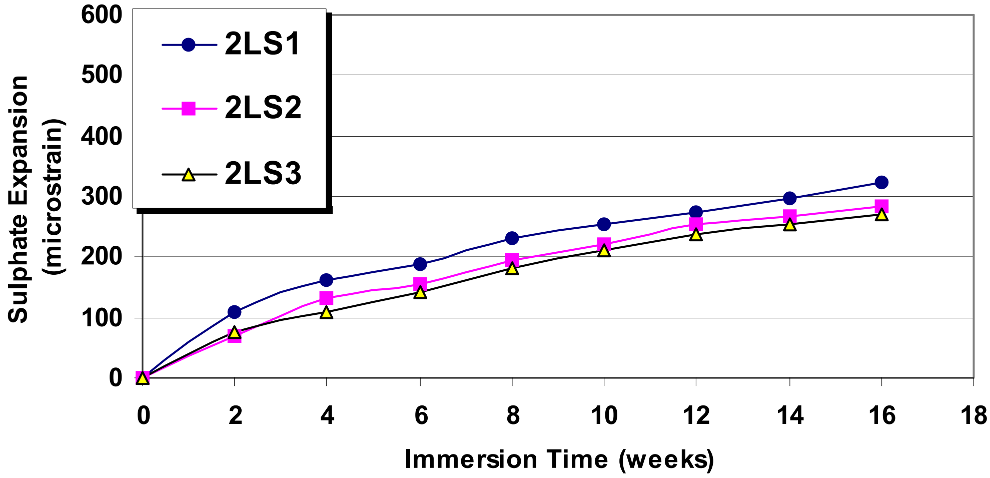

Fig-6 Expansion in Sulphate Solution of Samples of Slag (38%) Concretes

Fig-7 shows the length change of mortar samples from Type-GB high slag (60%) cement concretes. The samples of all the three concretes recorded expansions in the range of 303 to 557 microstrains. While the concrete Mix-2HS2 had 15% lower expansion compared to the control Mix-2HS1, Mix-2HS3 recorded a significant reduction in expansion of 46% compared to Mix-2HS1.

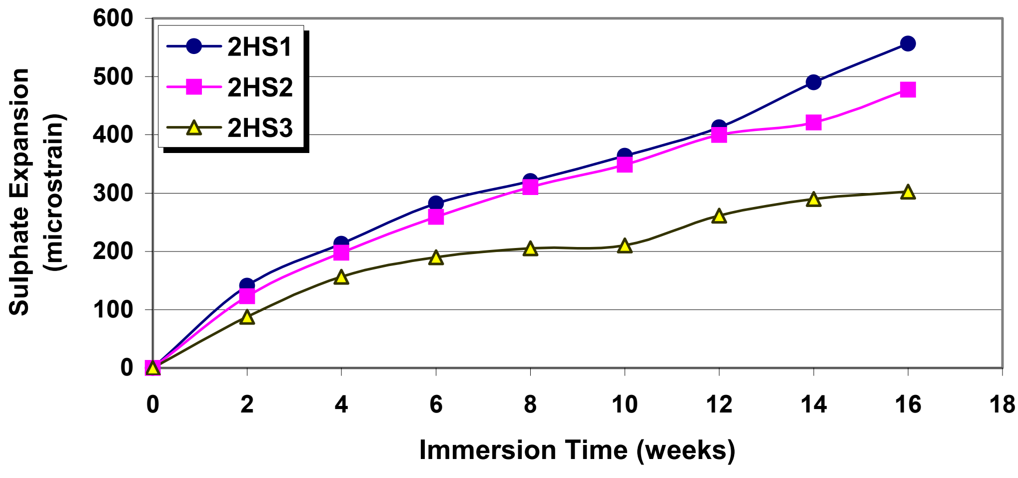

Fig-7 Expansion in Sulphate Solution of Samples of Slag (60%) Concretes

In general, the use of PRA demonstrated significant improvements in sulphate resistance of concretes using the Type-GB fly ash (25%) cement and the two slag (38% and 60%) cements. The use of higher dose rate of 1.2% PRA generally resulted in further lowered expansion in the sulphate solution.

Chloride Diffusion by Nordtest Method (NT BUILD 443)

The Nordtest NT BUILD 443, 1995 is a standard method for evaluation of the chloride diffusion coefficient of concrete by accelerated laboratory testing. All concrete mixes in this investigation were tested according to the Nordtest procedures. Table-5 summarises the chloride diffusion coefficients as the results of the Nordtest. The chloride diffusion coefficients were calculated according to Fick's Second Law and based on the chloride content profile in the concrete samples after 35 days immersion in 16.5% sodium chloride solution.

Table-5 Results of Chloride Diffusion Coefficients from Nordtest

Mix No	Nordtest – Chloride Diffusion Coefficient ($10^{-12} m^2/s$)
2F1	12.0
2F2	9.0
2F3	9.0
2LS1	6.0
2LS2	1.5
2LS3	2.0
2HS1	5.5
2HS2	3.2
2HS3	2.6

Fig-8 shows the chloride content profiles in the three types of concretes after the Nordtest. The chloride content in the relevant PRA modified concretes decreased more rapidly with distance from the exposure surface than that in the three control concretes, Mix-2F1, Mix-2LS1, and Mix-2HS1 indicating superior resistance to chloride penetration for PRA modified concretes.

Significant reductions in the chloride diffusion coefficients were found with all the PRA modified concretes made of the three Type-GB cements. The PRA modified Type-GB fly ash (25%) cement concrete Mix-2F2 and Mix-2F3 each had 25% lower chloride ion diffusion coefficients than the control Mix-2F1. The PRA modified low slag (38%) concrete Mix-2LS2 and Mix-2LS3 had 75% and 67% lower diffusion coefficients than the control Mix-2LS1. The PRA modified high slag concrete Mix-2HS2 and Mix-2HS3 recorded 42% and 53% lower diffusion coefficients than the control Mix-2HS1.

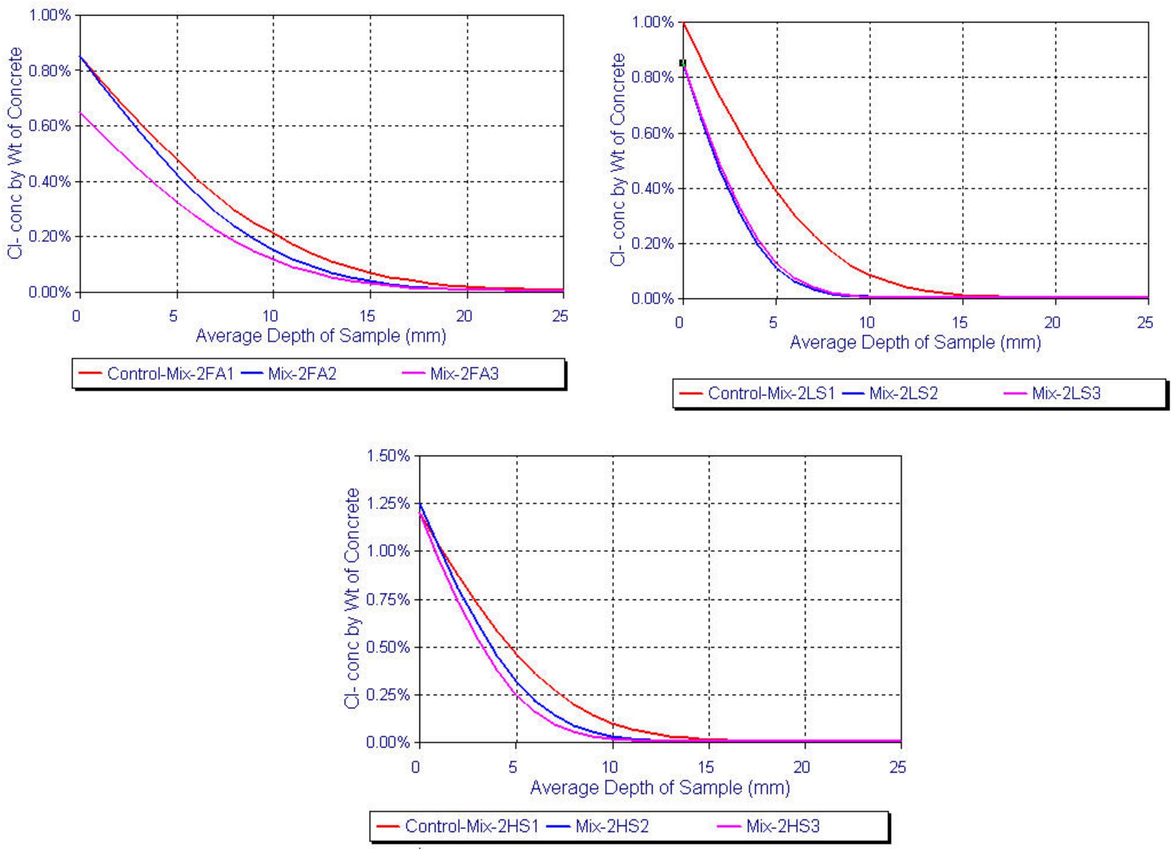

Fig-8 Chloride Diffusion Profiles of Concretes from NordTest

Water Permeability Test (ACCI Method)

All the concrete mixes in this research were tested for water permeability by the ACCI method under water pressure up to 10 bars (100 metres water head). The concrete samples were cured in limewater for 14 days followed by 77 days of air curing at 23 °C and tested for water permeability at concrete age of 91 days.

Table-6 presents the water permeability test results expressed in terms of the permeability coefficient. During the water permeability tests, the concrete samples of PRA modified Type-GB 25% fly ash cement concretes, Mix-2F2 and Mix-2F3, showed significant reductions of water penetration under the pressure of 100 meters water head. There were no signs of physical water transmission through any of sample of three Type-GB slag (38%) mixes under 100 meters water head. Because the water permeability in these 38% slag concretes was negligible under the testing pressure, water penetration depth in split concrete samples was measured at the end of water permeability tests using methylene blue indicator as used in the RTA water sorptivity test (Section 3.2.5).

Table-6 Water Permeability Coefficients or Water Penetration Depths

Mix No	Water Permeability Coefficient (m/s) OR Water Penetration
2F1	2.664×10^{-12}
2F2	7.871×10^{-13}
2F3	1.834×10^{-13}
2LS1	Water penetration depth: 12.8mm
2LS2	Water penetration depth: 10.7mm
2LS3	Water penetration depth: 7.2mm
2HS1	1.008×10^{-11}
2HS2	1.648×10^{-11}
2HS3	6.167×10^{-12}

The samples of control Mix-2LS1 had an average water penetration depth of 12.8mm whereas Mix-2LS2 and Mix-2LS3 showed water penetration depths of 10.7mm and 7.2mm respectively. The water penetration depths in the PRA 38% slag concrete Mix-2LS2 and Mix-2LS3 were 16% and 44% lower than that in the control concrete Mix-2LS1.

Water transmission was measured with three Type-GB slag (60%) concretes and the water permeability in these concretes was higher than in the other concretes made with Type-GB fly ash (25%) and Type-GB slag (38%) cements. This appeared to indicate that the permeability of high slag (60%) concretes could be more sensitive to curing regime. In this water permeability investigation, the concrete samples were cured in limewater for 14 days followed by 77 days of air curing at 23 °C. The samples of 0.8% PRA modified concrete Mix-2HS2 were found to have higher a water permeability coefficient than the control Mix-2HS1. As discussed in the Section 3.2.1 on compressive strength, the higher slump of 125mm of Mix-2HS2 might be related to its higher water permeability. However, Mix-2HS3 modified with 1.2% PRA showed a 39% reduction in the water permeability coefficient when compared with the control Mix-2HS1. Generally, the use of a higher dose rate, 1.2% compared with 0.8%, of PRA in concretes showed further reduction in water permeability.

Taywood Engineering proposed criteria for assessment of concrete quality based on water permeability coefficients, which were adopted by the British Concrete Society Committee on Insitu Permeability of Concrete. It was proposed that concretes with water permeability coefficients in the range of 1×10^{-10} to 1×10^{-12} m/s have acceptable quality, while concretes with permeability coefficient greater than 1×10^{-10} m/s have poor quality. Concretes with permeability coefficients less than of 1×10^{-12} m/s are regarded as very good concretes for use in severe environments. According to these criteria, all the PRA modified fly ash (25%) and slag (38%) concretes are ranked as having very good quality and suitable for severe environments, while the PRA modified high slag (60%) concretes are ranked as of acceptable quality.

CONCLUSIONS

This limited research program investigated the durability and compatibility of concretes modified with the permeability reducing admixture (PRA). Two dosage rates (0.8% and 1.2%) were used with three types of cement in commercial concretes with nominal strength of 40MPa. The selected test results and conclusions are summarised with respect to cement type as follow:

1. For Type-GB cement concrete (25% Fly Ash) cement concretes, mixtures modified with the PRA admixtures have shown significant improvements in strength development and drying shrinkage. The PRA modified concretes show lower chloride penetration and chloride diffusion rates in the Nordtest, and lower expansion in sulphate test compared with control concrete.
2. For Type-GB cement concretes (38% slag), mixtures modified with PRA admixture have shown marginal increase in compressive strength and reduction in drying shrinkage. Expansion in sulphate solution is further reduced compared with the already very low expansion of control concrete. The PRA modified slag concretes show significantly lower chloride penetration and chloride diffusion rates in the Nordtest.
3. For Type-GB cement concrete (60% slag), mixtures modified with PRA admixture have shown modest improvements in the strength and drying shrinkage. Sulphate expansion and chloride diffusion rates were significantly reduced in the PRA modified concretes.

In summary, three types of concretes modified with PRA were found to have significantly improved properties compared to control concretes. Whilst drying shrinkage and sulphate expansion were reduced, chloride penetration and diffusion properties were the most significantly improved by inclusion of the PRA in concretes. The use of a higher dose rate, 1.2% compared to 0.8%, of PRA was found to achieve a further improvement in concrete performance, however, this was more effective in the fly ash (25%) cement concrete than in the slag (38% and 60%) cement concretes. The results of this investigation confirmed the benefits achieved by using PRA to improve concrete durability for aggressive environments with respect to the structures exposed to chloride induced corrosion of reinforcing steel. The improved chloride diffusion coefficients for strength grade 40 concretes containing PRA are such that the design life of structures located in such environments will be significantly increased, by comparison with similar concretes without PRA.

ACKNOWLEDGEMENTS

The authors also wish to express their gratitude to the Xypex Australia for their materials supply and technical assistance throughout the research project.

REFERENCES

1. Plowman, C., "The Use of Fly Ash to Improve the Sulphate Resistance of Concrete"; Waste Management, Vol. 16, Nos 1-3, pp145-149, 1996.
2. Philipose, K.E., "Durability Prediction from Rate of Diffusion Testing of Normal Portland Cement, Fly Ash, and Slag Concrete", Durability of Concrete-2nd International Conference, Montreal, Canada, Vol. 2, 1991, pp335-354.
3. Polder, R. B., "Laboratory Testing of Five Concrete Types for Durability in a Marine Environment", Corrosion of Reinforcement in Concrete Construction, 1996, pp115-123.
4. Lefave, J.M., "Using Mineral and Chemical Durability-Enhancing Admixtures in Structural Concrete", Concrete International, August, 2002, pp71-78.
5. Standards Australia, "Chemical Admixtures for Concrete, Mortar and Grout; Part 1: Admixtures for Concrete", Australian Standard™ 1478.1, Sydney, 2000
6. Kao, G, Chang, Z.T., Munn, R., "Performance of Xypex Admix Modified Australian Commercial Concretes", AusIndustry START Graduate Program, University of New South Wales, Australia, 2003.
7. R.L. Munn, G. Kao, Z.T. Chang, "Performance and Compatibility of Permeability Reducing and other Chemical Admixtures in Australian Concretes", 7th CANMET/ACI International Conference on Superplasticiser and other Chemical Admixtures in Concrete, Berlin, Germany, October, 2003.
8. R.L. Munn, G. Kao, Z.T. Chang, "Performance of Australian Commercial Concretes Modified with Permeability Reducing Admixture", NZCS, Wairakei New Zealand, October, 2003.
9. R.L. Munn, G. Kao, Z.T. Chang, "Resistance to Sulphate and Chloride Attack of Concretes Modified with Permeability Reducing Admixture", The 21ST Biennial of The Concrete Institute of Australia, Brisbane, Australia, July, 2003, pp221-231.
10. Nordtest Method: Accelerated Chloride Penetration and Hardened Concrete, Nordtest NT Build 443, ESPO, Finland, 1995.
11. Thomas, M.D.A. and Bamforth, P.B., "Modelling Chloride Diffusion in Concrete Effect of Fly Ash and Slag", Cement and Concrete Research, 29, 1999, pp487-495.

12. Boddy, A., Bentz. E., “An Overview and Sensitivity Study of a Multimechanistic Chloride Transport Model”, Cement and Concrete Research, 29, 1999, pp827-837.
13. Stanish. K, Thomas. M, “The Use of Bulk Diffusion Tests to Establish Time-Dependent Concrete Chloride Diffusion Coefficients”, Cement and Concrete Research, 33, 2003, pp.55-62.