Performance of Australian Commercial Concretes Modified with a Permeability Reducing Admixture

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ABSTRACT

A substantial research program was undertaken at the Australian Centre for Construction Innovation, University of New South Wales to evaluate and explore the potential efficiency of permeability reducing admixtures to enhance concrete durability in aggressive environments. This project used commercial concretes which contained conventional water reducing admixture, different types of supplementary cementitious materials and permeability reducing admixtures at various dose rates. For each type of concrete, a control batch was produced without permeability reducing admixture and other batches were produced with addition of permeability reducing admixtures at various dose rates. This paper outlines results of testing for compressive strength, drying shrinkage, sulphate resistance, chloride resistance, water absorption, and water permeability. Assessment of these test results indicates that, whilst concrete performance was influenced by cement type, these permeability reducing admixtures can also significantly improve the durability of concrete.

INTRODUCTION

An important consideration in modern concrete design is the durability of concrete in aggressive environments, such as chloride penetration marine environment, sulphate attack in sub-ground and sewerage structures and reinforcement corrosion. Permeability is one of the key parameters that determine the long term durability of concrete. A concrete of lower permeability normally has higher resistance to ingress of aggressive ions or gases as well as to corrosion of reinforcement and therefore it would be expected to have a longer service life. Concrete is generally considered to be porous due to existence of capillary pores, gel pores and porous cement-aggregate interface zones. The traditional means to improve concrete durability are through reduction of water/cement and/or increase of moist curing period, which alter porosity and in turn durability, which is strongly influenced by the nature and distribution of pores (1,2). More recently, partial replacement of portland cement with supplementary cementitious materials (SCMs), such as fly ash or ground granulated blast furnace (GGBF) slag, has frequently been adopted for concrete used in aggressive environments. The benefits and effects of using SCMs in concrete have been discussed widely in literature (3,4). While concrete of very low permeability can be made using very low water/cement incorporation of SCMs in the cement, practical difficulties may be encountered during construction with these types of concrete.

Permeability-reducing admixtures form a new class of chemical admixtures that can reduce the rate of transmission of moisture either in a liquid or vapour form through concrete. Several types of permeability-reducing admixtures are commercially available. Some of these are classified as hydrophobic admixtures due to presence of long chained fatty acids or vegetable oils (5,6,7,8,9), whereas some others are classified as microstructure modifiers which reduce concrete permeability through crystallisation activity in concrete pores (5). Most of these admixtures claim to have the ability to greatly reduce water penetration and also impart good resistance to chemical attack in concrete. A substantial research program was undertaken at the Australian Centre for Construction Innovation (ACCI) of the University of New South Wales to investigate a broad range of properties of various commercial concrete mixes modified with the latter type of permeability reducing admixture. The major aim of this investigation was to evaluate and explore compatibility of this mixture in a range of typical commercial concretes in order to assess durability performance. This paper outlines results obtained for compressive strength, drying shrinkage, sulphate resistance, chloride resistance, water absorption and AVPV and water permeability. Assessment of overall test results from the research project indicates that, whilst concrete performance was influenced by the type of cement, permeability reducing admixture can also significantly improve the durability of concrete in aggressive environments.

MATERIALS AND TEST METHODS

To minimise the difference in performance between “lab concrete” and “site concrete”, and

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to ensure relevance for construction applications, commercial concrete batches of two cubic metres each were used in this research. One of three types of cement were used in each concrete mixture, i.e. AS3972 Type-GP portland cement only, or AS3972 Type-GB fly ash blend (20% fine fly ash) or AS3972 Type-GB slag blend (38% slag). For each type of cement, a control concrete was produced without permeability reducing admixture and one or more concretes were produced with addition of a permeability reducing admixture at various dose rates recommended by the manufacturer. All concrete batches were supplied as a premixed concrete based on 32 MPa grade commercial concrete mixes. AS1478 Type-WR admixture was added as required to achieve a target slump of 80mm. The permeability reducing admixture (PRA) was added into selected concrete batches at the concrete supplier's plant according to manufacturer's specification and recommendations. The details of concrete mixture proportions are given in Table 1. Type-GP cement had a Blaine fineness of 340 m^2/kg, and the Type-GB cement (38% slag) had a Blaine fineness of 400 m^2/kg. However, the Blaine fineness of the Type-GB cement (20% fly ash) was not available. The fly ash used in the Type GB cement was low calcium AS3582.1 fine grade fly ash

The manufacturers of the specific crystal growth type of PRA used in this investigation claim it reacts with a broad range of hydration by-products which include various metal oxides and salts, including potassium, unhydrated and partially hydrated cement particulate as well as with calcium hydroxide regardless of the cement type or blend. The reaction products are claimed to be new crystalline minerals, which grow in voids, pores and cracks in concrete. To evaluate these claims the test program used concretes made with three different cement types. 32MPa strength grade concretes were chosen for this investigation because they are commonly used in structural applications, whilst still being sufficiently porous to demonstrate whether the addition of the crystal growth PRA influences key properties of the concretes. Concretes made with Type-GB cements of other compositions were included in the investigation, but because not all relevant properties were evaluated, those test data have not been reported in this paper.

Test Methods

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

Compressive Strength: Compressive strengths were tested with 100mm diameter cylinder samples after standard curing for 3, 7, and 28 days and were tested in accordance with AS1012.9.

Drying Shrinkage: Drying shrinkage samples were cast and cured according to AS1012.13. After initial moist curing for 7 days shrinkage was measured every 7 days until 56 day drying.

Length Change in Sulphate Solution: Mortar was sieved out of fresh concrete and samples were cast and cured according to AS2350.14. Expansions of the samples were measured using a comparator every 2 weeks after immersion in a sulphate solution. Final readings were taken after 16 weeks of immersion.
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Table. 1 Concrete Mixture Designs

Mix Code	W/C Ratio	Cement Type and Content (kg/m^3)	Permeability Reducing Admixture (% of Cement Content)	Total Fine Aggregate	Total Coarse Aggregate
PC1	0.55	GP (330)	Nil	42%	58%
PC2	0.55	GP (330)	0.8% PRA	42%	58%
PC3	0.55	GP (330)	1.2% PRA	42%	58%
FA1	0.50	20% Fly Ash (360)	Nil	41%	59%
FA2	0.50	20% Fly Ash (360)	0.8% PRA	41%	59%
FA3	0.50	20% Fly Ash (360)	1.2% PRA	41%	59%
SL1	0.55	38% Slag (330)	Nil	42%	58%
SL2	0.55	38% Slag (330)	0.8% PRA	42%	58%

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Nordtest: The Nordtest NT BUILD 443 is an accelerated bulk diffusion test method for assessment of chloride penetration into hardened concrete. It requires immersion of cylinder specimens in 16.5% NaCl solution for at least 35 days. The cylinder specimens 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 top surface for chloride content analysis and the chloride content results are used to determine chloride diffusion coefficient. In this program, the silver nitrate solution used in the ACCI cyclic chloride penetration test was also sprayed on the split concrete samples after the Nordtest to determine chloride penetration depths. The ACCI cyclic penetration test method is described in the publication of Concrete Institute of Australia (CIA) "Performance Criteria for Concrete in the Marine Environments".

Water Absorption and AVPV: Water absorption and apparent volume of permeable voids (AVPV) of concrete samples were measured in accordance with AS1012.21 after four different curing conditions. These were 7 days limewater curing followed by air-drying until age of 56 and 180 days, and 56 and 180 days continuous limewater curing.

Water Permeability Test: The ACCI test apparatus was modified from the Taywood water permeability test apparatus. An epoxy 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 the samples during the test period. Water leakage through the samples under the pressure was monitored and collected. The permeability coefficient was calculated using Darcy's equation.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Compressive Strength

The influence of the permeability reducing admixture on compressive strength of concretes made with Type-GP cement is shown in Fig.1. All concrete strengths increased with time at a similar rate as shown by testing at 3, 7, and 28 days. Concrete mixtures modified with the PRA (Mix-PC2 and Mix-PC3) generally had slightly higher strengths than control Mix-PC1 at the same age. At the age of 3 days, all the RPA modified mixtures had compressive strengths higher than control mixture by 8% to 14%. At ages of 7 and 28 days, PRA modified concrete mixtures recorded 4% to 8% higher strengths than control mixture.

Fig. 2 compares compressive strength results of the concrete mixtures containing 20% fly ash or 38% slag in the cement. Fly ash concretes (Mix-FA1, Mix-FA2 and Mix-FA3) had similar compressive strengths at each of 3 and 7 days, while PRA modified mixtures (Mix-FA2 and Mix-FA3) had 6% higher strengths at 28 days compared with Mix-FA1. PRA modified slag concrete Mix-SL2 had similar strength to control Mix-SL1 at 3 days and 5% to 13% higher strengths at later ages. It is probable that the early age strengths of the PRA modified concretes have been retarded by the extended setting time.

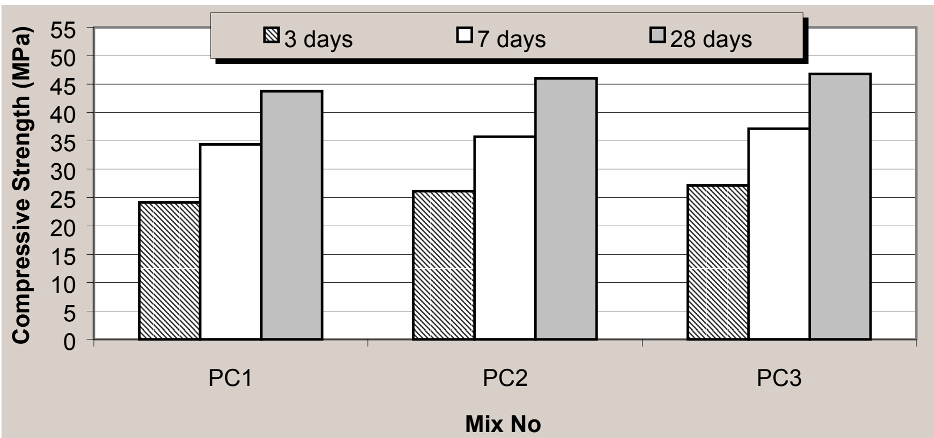

Fig 1. Compressive Strength of Type-GP concretes

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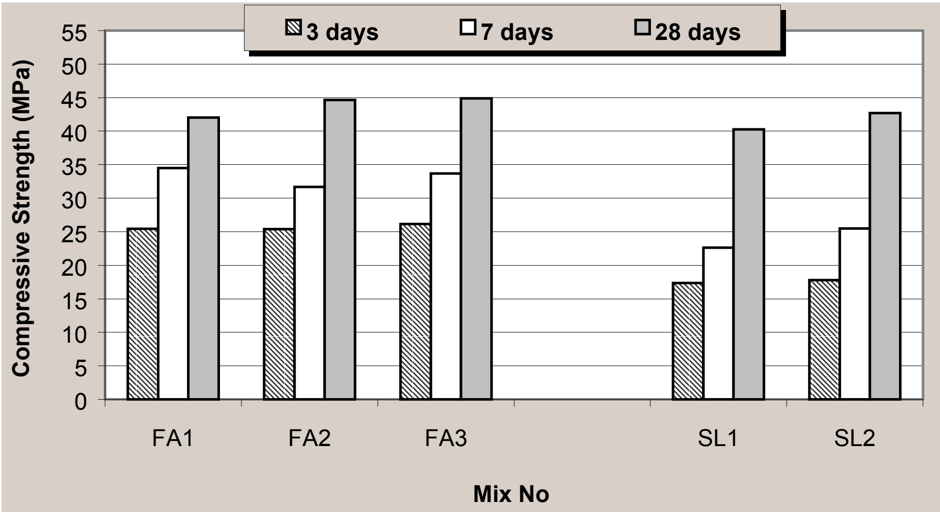

Fig 2. Compressive Strength of Fly Ash Concretes and Slag Concretes

Drying Shrinkage

The drying shrinkage results of four Type-GP cement concretes are shown in Fig 3. The concretes containing PRA (Mix-PC2 and Mix-PC3) had very similar drying shrinkage to the control concrete Mix-PC1. Fig 4 shows the drying shrinkage of 20% fly ash concretes (Mix-FA1, Mix-FA2 and Mix-FA3).

All flyash concretes had lower drying shrinkage compared with Type GP cement concretes and Type GB (38% slag) cement concretes. The PRA modified concretes Mix-FA2 and Mix-FA3 had lower drying shrinkages than the control concrete Mix-FA1 by 12% to 14% at 56 days.

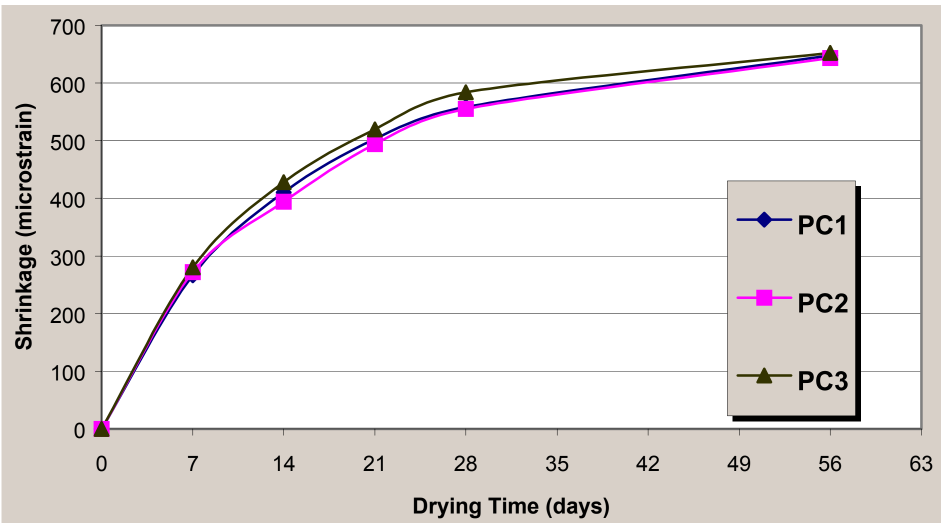

Fig 3. Drying Shrinkages of Type-GP Concretes

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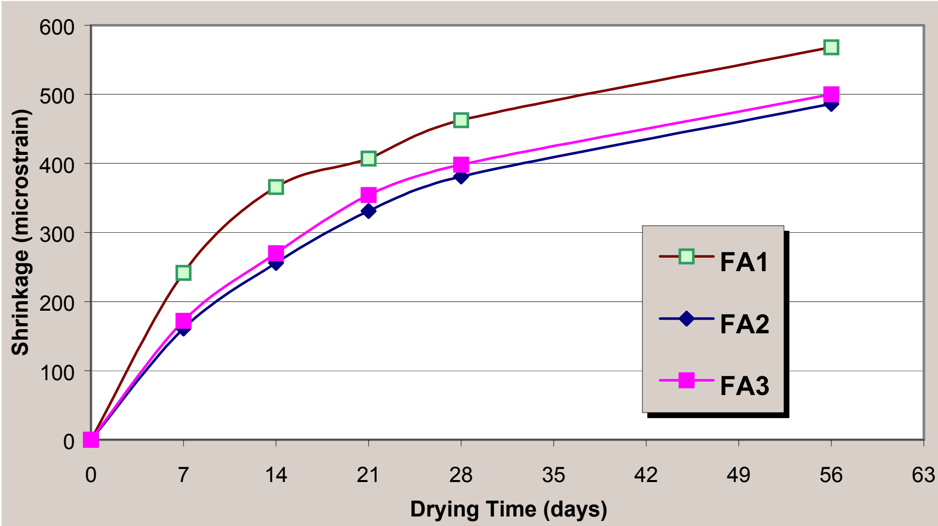

Fig 4. Drying Shrinkages of Fly Ash Concretes

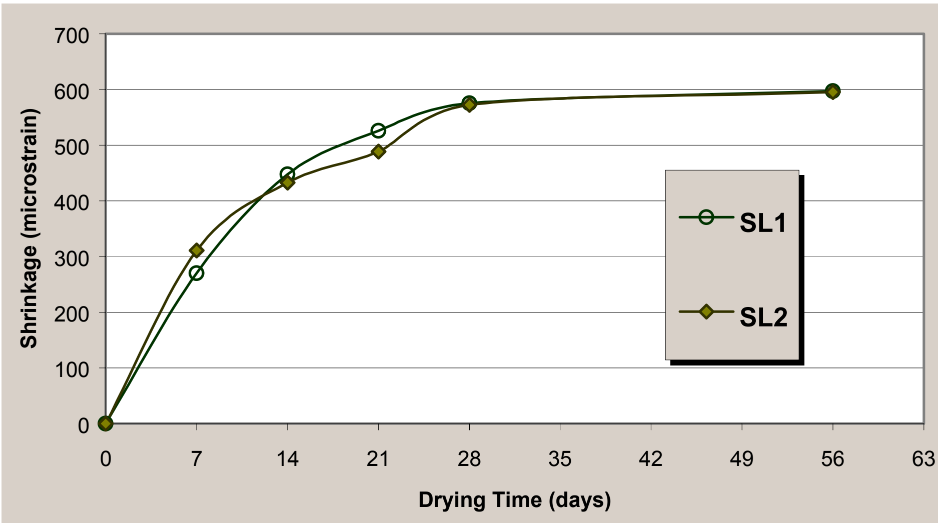

Fig 5. Drying Shrinkages of Slag Cement Concretes

Fig-5 shows the drying shrinkage results of 38% slag cement concretes (Mix-SL1 and Mix-SL2). The shrinkage of concrete Mix-SL2 was very similar to that of the control concrete Mix-SL1. In general, the test results show that PRA modified concretes have similar or modestly lower drying shrinkages compared to the control concretes.

Sulphate Expansion

Potential expansion of concretes in sulphate environments was assessed in accordance with AS2350.14 by immersing samples in a sulphate solution over 16 weeks. Fig. 6 presents length changes of mortar samples of Type-GP concretes and measured according to AS2350.14. Whilst the PRA modified concrete Mix-PC2 and control concrete Mix-PC1 showed similar expansion, the PRA modified concrete Mix-PC3 had lower expansion than the control concrete Mix-PC1 at each age.

Length changes of samples of fly ash concrete and slag concrete in sulphate solution when tested to AS2350.14 are shown in Fig. 7. Comparing the two slag concrete mixes, PRA modified slag concrete Mix-SL2 had 58% lower expansion than the control Mix-S1. While both 20% fly ash concrete mixes recorded excellent sulphate resistance, the PRA modified concrete Mix-FA2 had 7% reduction in expansion compared to the control concrete Mix-FA1.

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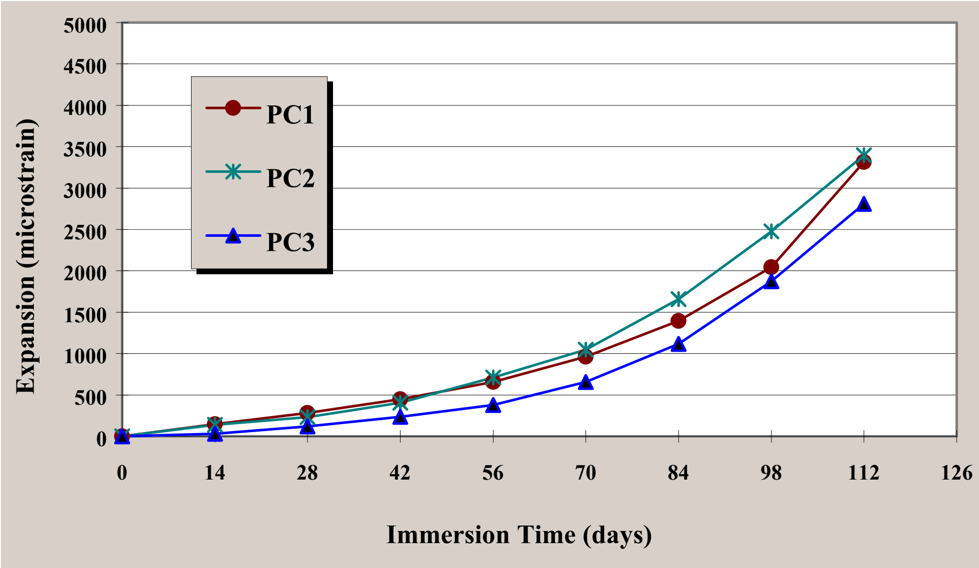

Fig. 6 Length Changes of Samples in Sulphate Solution for Type-GP Concretes

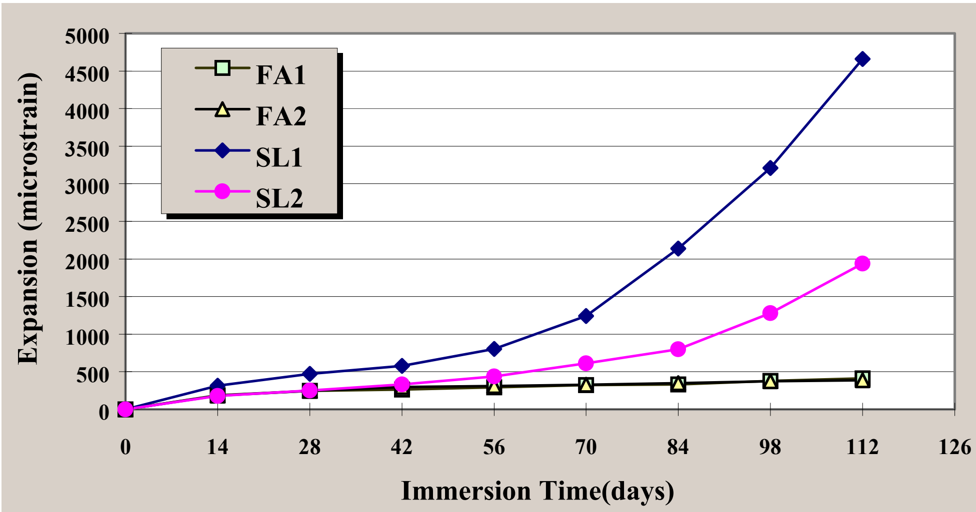

Fig. 7 Length Changes in Sulphate Solution for Fly Ash and Slag Concretes

Chloride Penetration by NordTest Method

All three Type-GP cement concretes, two fly ash concretes and two slag concretes in this program were tested by Nordtest method. Fig. 8 shows chloride penetration depth of all concretes in this test. For each of the three types of concrete, PRA modified mixes had lower chloride penetration depth than respective control concretes. For Type-GP cement concrete, chloride penetration depths in PRA modified Mix-PC2 and Mix-PC3 were 10% and 32% lower than that in control Mix-PC1. Chloride penetration depth in PRA modified fly ash concrete Mix-FA2 was significantly lower (by 38%) than that in control Mix-FA1. PRA modified slag concrete Mix-SL2 had a marginally lower chloride penetration than control Mix-SL1.

After the completion of the Nordtest, powder samples were extracted at different depths from the top surface of the cylinder specimens for chloride content analysis and the results were used to determine the chloride diffusion coefficients. Fig 9. (a), (b) and (c) show the chloride penetration profiles in three types of concrete.

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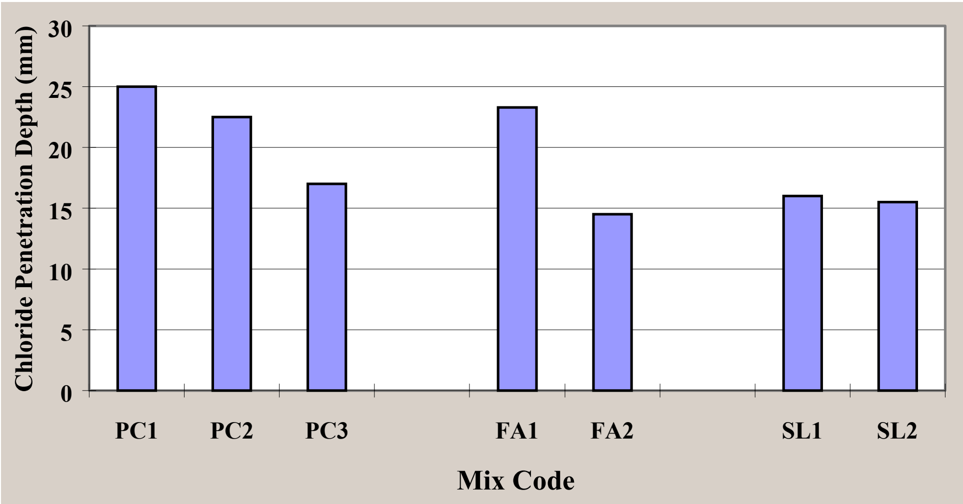

Fig. 8 Chloride Penetration Depths by Nordtest after 35 Days Immersion

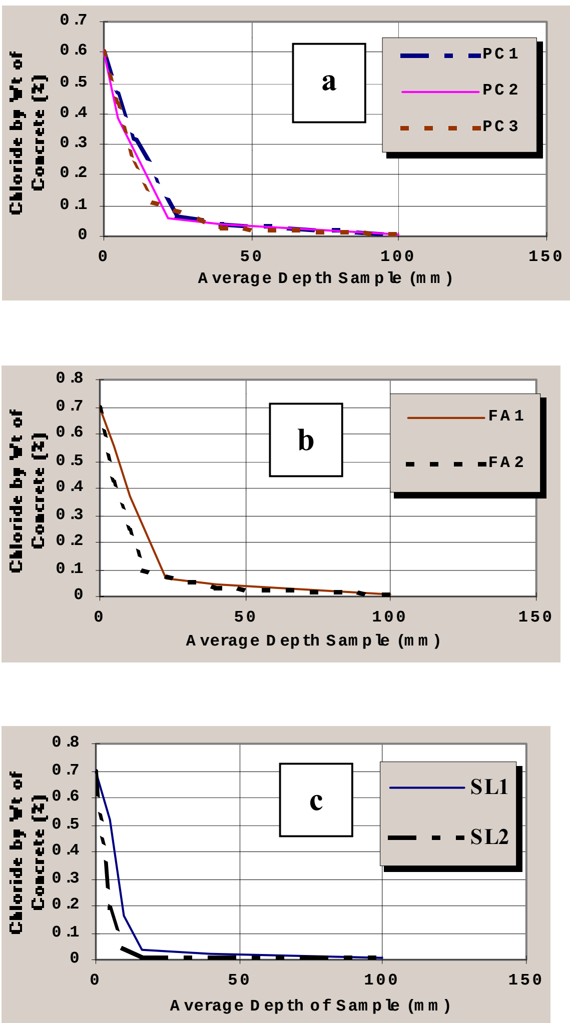

Fig.9 a), b) and c) Chloride Penetration Profiles by Nordtest

d	Chloride Ion Diffusion Coefficient ($10^{-12}m^2/s$)
PC1	35
PC2	25
PC3	24
FA1	30
FA2	15
SL1	12
SL2	4

Fig. 9 d) Chloride Ion Diffusion Coefficients for All Concretes

Chloride ion contents in concretes modified with PRA decreased more rapidly with distance from exposure surface than that in the control concretes. Fig 9(d) shows calculated chloride diffusion coefficients using Fick's law. The chloride ion diffusion coefficients show similar trends to chloride profiles. Mix-PC2 and Mix-PC3 had a 30% reduction in chloride diffusion coefficient whereas Mix-FA2 had 50% and Mix-SL2 had 66% reduction in chloride diffusion coefficient when compared to their respective control concrete

Water Absorption & AVPV Test

The water absorption and AVPV (Apparent Volume of Permeable Voids) of concretes were determined in accordance with the Australian Standard AS1012.21. The tests were conducted under four different curing conditions in order to understand the effects of air or limewater curing and the curing time on water absorption and

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AVPV of different concretes. These curing conditions were A) 7 days limewater curing followed by air curing at 23 °C until 56 days; B) 7 days limewater curing followed by air curing at 23 °C until 180 days; C) 56 days continuous limewater curing; and d) 180 days continuous limewater curing.

Table 2 summarises the water absorption test results for all concretes under the four curing conditions. In general, the PRA modified concretes had lower water absorption than the respective control concretes under all curing conditions. The most significant reduction in water absorption of 14% was found with the PRA modified fly ash concretes Mix-FA2 compared with the control Mix-FA1 at the age of 180 days. All concretes recorded lower water absorption values under continuous limewater curing to 56 or 180 days compared to that under 7 days limewater curing followed by air curing to 56 or 180 days. The reduction in water absorption under continuous limewater curing was more significant in the concretes using blended cements. The PRA modified concretes also benefited more from limewater curing than the respective control concretes.

Table 2 also shows the effect of increased curing time on water absorption test results under either air curing or limewater curing conditions. The increase in curing time either in air or limewater resulted in decreased water absorption in all concretes. The increase in air curing from 56 days to 180 days resulted in reduction of water absorption by 2.6% to 4.5% in PRA modified concretes. The most significant reduction in water absorption due to prolonged limewater curing was found with fly ash concrete Mix-FA2 which had 20% lower water absorption when limewater curing was extended from 56 to 180 days. It appeared that prolonged limewater curing promoted the chemical reactions in the PRA concrete and hence reduced the water absorption.

Table 3 summarises the test results for AVPV (Apparent Volume of Permeable Voids). In general, the AVPV results showed similar trends to the water absorption results. The PRA modified concretes had lower AVPV values than the respective control mixes under all curing conditions. The reductions in AVPV were found for concrete Mix-PC3 with 9% lower AVPV than the control Mix-PC1 after 56 days limewater curing and with 13% lower AVPV after 180 days limewater curing. The PRA modified fly ash concretes and Type-GP concretes have benefited from prolonged limewater curing and show more significant reductions in AVPV than the control mixes. Ongoing chemical reactions between PRA and cement by-products could be promoted by good curing conditions, which have resulted in reduced volumes of permeable voids. The PRA modified slag concretes show no significant improvement in AVPV compared with the control slag concrete except after 7 days limewater curing and 49 days in air.

VicRoads (VIC) has a specification for concrete work based on AVPV value at 28 days. For grade 32MPa concrete, it requires the AVPV value not to be greater than 14%.

Table. 2 Summary of Water Absorption Test Results

Mix No	7d Lime + 49d Air	7d Lime + 173d Air	56 days Limewater	180 days Limewater
	Water Absorption (%)			
Type-GP (SL)				
PC1	5.89	5.82	5.69	5.19
PC2	5.85	5.70	5.49	5.20
PC3	5.77	5.59	5.06	4.94
Type-GB (20% Fly Ash, Type-F)				
FA1	5.46	5.89	5.13	4.63
FA2	5.37	5.13	5.01	3.98
Type-GB (38% Slag)				
SL1	6.96	6.5	4.96	4.59
SL2	6.51	6.38	5.01	4.49

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Table 3. Summary of AVPV Test Results

AVPV %				
Mix No	**7d Lime + 49d Air**	**7d Lime + 173d Air**	**56 days Limewater**	**180 days Limewater**
Type-GP (SL)				
PC1	14.17	13.7	13.17	13.35
PC2	13.96	13.54	12.54	12.74
PC3	13.47	13.18	11.99	11.59
Type-GB (20% Fly Ash)				
FA1	13.06	12.95	12.71	10.75
FA2	12.65	12.05	12.2	9.87
Type-GB (38% Slag)				
SL1	16.22	15.15	11.37	10.5
SL2	15.06	14.97	12.37	10.79

In Table 3, all the concrete cured in limewater for 56 and 180 days had lower AVPV values than 14%. For concrete specimens cured 7 days in limewater followed by air curing to 56 and 180 days, control concretes had AVPV close to 14%. However, the PRA modified concretes had AVPV values considerably lower than 14%.

Water Permeability Test

Both PRA modified and control concretes made with Type-GP and Type-GB cements (20% fly ash) were tested for water permeability by the ACCI method under water pressure up to 10 bars. The concrete specimens were cured in limewater for 90 days before testing for water permeability and Table 4 shows the permeability coefficients calculated following testing.

Concrete specimens of PRA modified Type-GP concrete Mix-PC3 showed no signs of water penetration under a 100-metres head water pressure. However, water penetration was measured for the specimens of the Type-GP control Mix-PC1 under a 60-metres head water pressure and lower water penetration was measured for the specimens of PRA modified Type GP concrete Mix-PC2. The calculated water permeability coefficient for Mix-PC2 was significantly lower than the control Mix-PC1, even though the absorption values shown in the Table 2 were similar to control.

Table 4. Water Permeability Coefficients

Mix No	**PC1**	**PC2**	**PC3**	**FA1**	**FA2**
Water Permeability Coefficient (m/s)	$1.76 X 10^{-12}$	$0.98 X 10^{-12}$	Nil	Nil	Nil

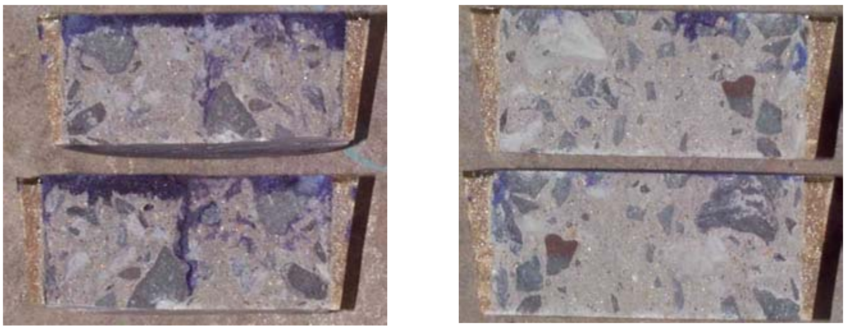

Fig.10 Water Penetration Depths in Water Permeability Test Specimens Mix-FA1 (left) & Mix-FA2 (right)

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No water transmission was measured for the three Type-GB cement (20% fly ash) concretes, including PRA modified concrete Mix-FA2 and the control concrete Mix-FA1. Because the water permeability was negligible for fly ash concretes another method was used to examine water penetration depth by using the methylene blue indicator technique used in the RTA sorptivity test. Mix-FA1 had an average of water penetration depth of 8mm whereas Mix-FA2 showed no water penetration when tested using this method, as shown in Fig 10.

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 $1x10^{-10}$ to $1x10^{-12}$ m/sec have acceptable quality, while concretes with permeability coefficient greater than $1x10^{-10}$ m/s have poor quality. Concretes with permeability coefficients less than $1x10^{-12}$ m/s are regarded as very good concretes for use in severe environments. According to these criteria all PRA modified concretes are ranked as good quality concretes suitable for severe environments

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 32MPa. The selected test results and conclusions are summarised with respect to cement type as follow:

For Type-GP cement concretes, mixtures modified with the PRA admixtures have shown from modest to significant improvements in hardened state properties. Early age strengths were generally improved. PRA modified concretes show equivalent or lower drying shrinkage and sulphate expansion. The PRA modified concretes show lower penetration and chloride diffusion rates in the Nordtest, compared with control concrete. Similar to lower water absorption and AVPV in Type-GP mixes under all curing conditions. PRA modified concretes show significant lower water permeability at dosage rate of 0.8% even though water absorption values were similar to control. No visible water leakage was observed under water pressures up to 10 bars at dosage rate of 1.2%.

For Type-GB cement concretes (20% fly ash), mixtures modified with PRA admixture have shown small to significant improvements in hardened state properties. Later age strength has increased slightly and drying shrinkage and sulphate expansion have been reduced modestly with introduction of the PRA. The PRA modified fly ash concretes show lower penetration and chloride diffusion rates in the Nordtest and lower water absorption and AVPV values under all curing conditions. No water penetration was measured in PRA modified flyash concretes.

For Type-GB cement concrete (38% slag), mixtures modified with PRA admixture have shown small to significant improvements in hardened state properties. Strengths at all ages were modestly improved whilst drying shrinkage was similar to the control concrete. Sulphate expansion and chloride diffusion rates were significantly reduced in the PRA modified concrete.

The test results confirmed that this PRA is compatible with both portland and blended cement concretes which also contained a typical water reducing admixture. The inclusion of this permeability reducing admixture in these concretes has resulted in a significant improvement for some key durability related properties. Further research is required to confirm its performance in concretes of higher strength grades typically used in severe durability applications.

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