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Comparison of permeability-reducing admixture and supplementary cementitious material for improved durability of concrete

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Abstract

As the focus of industry becomes increasingly concentrated on minimising life-cycle cost and environmental impacts, longevity of concrete structures becomes more important. Durability of concrete is a crucial factor in its performance over its expected lifespan. This study compares the effectiveness of a permeability-reducing admixture for hydrostatic conditions (PRAH) and fly ash as a supplementary cementitious material and filler, on the durability of concrete. The compressive strength, self-healing capabilities and various tests assessing durability were completed. The effect of curing conditions on PRAH and fly ash mixes were also evaluated. Concrete mixes incorporating fly ash performed better than Portland cement mixes in self-healing capability, oxygen permeability, and chloride conductivity. Some beneficial durability results were obtained from the combination of fly ash and PRAH. The inclusion of PRAH marginally reduced the depth of penetration of water under pressure for air-cured Portland cement mixes. Water-cured samples exhibited superior performance across all tests associated with durability.

Keywords: Permeability-reducing admixture (PRAH), Supplementary cementitious materials (SCM), Durability

1. INTRODUCTION

Society's insatiable appetite for concrete makes it the most widely employed construction material by volume [1]. To minimise the well documented environmental impact, consumption of energy and raw materials of concrete, it is crucial to maximise the lifespans of concrete structures. Long lasting structures are also more economic, especially if maintenance requirements are reduced. The durability of a material is associated with the resistance to deterioration over the required service life of the structure it forms part of. Concrete durability is therefore an important factor to ensure long lasting structures. Consequently, durability and sustainability are interdependent.

The deterioration mechanisms of concrete are related to its penetrability. Penetrability is defined as the degree to which concrete permits gases, liquids or ionic species to move through its pore structure [2]. Therefore, the intended application and exposure environment of concrete is important when evaluating concrete durability.

2. BACKGROUND

There are two main schools of thought on methods to achieve improved durability within concrete without lowering the water/cement ratio of a concrete mix design. The first, is a commonly used method to include supplementary cementitious materials (SCMs) such as fly ash. Due to the pozzolanic activity and improved packing density (filling effect) provided by SCMs the mechanical properties and durability of concrete are improved [3, 2]. The second method is the use of more recently developed permeability-reducing admixtures. Theoretically, permeability-reducing admixtures react with water and other concrete hydration products to form insoluble crystals which fill the pores and voids throughout the concrete matrix, thereby reducing permeability and so improving durability. In the absence of moisture, the active ingredients remain dormant. The curing conditions for concrete containing such admixtures can therefore not be ignored. However, literature reveals contradictory results and conclusions for 'permeability-reducing admixture for hydrostatic conditions' (PRAH). De Souza Oliveria et al. [4] reported a reduction in permeability with the use of PRAH. In 2021, Gojević et al. [3] concluded that permeability results were dependent on water-cement ratio, while Pazderka and Hájková [5] concluded that the effect of waterproofing admixture is negligible. With varying test methods, curing conditions and cement types, there is no definitive consensus on the reliability of waterproofing admixtures. There is also a lack of research into the use of PRAH along with SCM [6].

The purpose of this study was to compare the effectiveness of a commercially available PRAH and fly ash as a fine filler and pozzolanic material on the mechanical and durability properties of concrete. The effect of curing conditions on the aforementioned properties was also evaluated.

3. EXPERIMENTAL SETUP

3.1 Mix Design

A total of eight concrete mixes were cast to compare the effect of a PRAH and fly ash as a cement extender (SCM) and fine filler material, as well as curing conditions on the hardened properties of concrete. A water content of 220l/m³ was used to achieve adequate workability characterized by a 40mm slump measurement for the crushed aggregate used, as prescribed by Soutsos and Domone [7]. A CEM I 52.5R Portland cement (PC) reference mix with water-cement (w/c) ratio of 0.5 and a fly ash reference mix with a water-binder (w/b) ratio of 0.5 were considered. The w/c and w/b ratios of 0.5 were selected based on ratios given by the United States Bureau of Reclamation [8], for durability class concrete subject to exposure of extreme severity. The fly ash mix resembled the PC mix but with 25% of the cement and 50% of the fine aggregate portions replaced with unclassified fly ash (FA). The cement replacement yields a CEM II-B for the fly ash mixes (SANS 50197-1:2013) [9]. As per manufacturer recommendation, 1% by mass of cement PRAH was added to each reference mix to produce the applicable admixture samples. Each mix was placed either in a 25°C water bath or wrapped in plastic after casting and demoulding, to achieve water- and air-cured conditions. Locally available materials were used and a single source of cement, aggregate and unclassified fly ash were considered. Table 1 contains the dry materials and curing conditions of each mix.

Table 1 Dry material compositions [kg/m³] and curing conditions

Mix		Cement	FA SCM	PRAH	Fine Aggregate	FA Fine Aggregate	Coarse Aggregate	Curing Condition
PC	BW	440	-	-	907	-	911	Water
	BA	440	-	-	907	-	911	Air
	BPW	440	-	4.4	904	-	911	Water
	BPA	440	-	4.4	904	-	911	Air
FA	FW	330	110	-	434	332	911	Water
	FA	330	110	-	434	332	911	Air
	FPW	330	110	4.4	432	332	911	Water
	FPA	330	110	4.4	432	332	911	Air

3.2 Test Methods

Various tests were performed to evaluate the hardened properties of the mixes. Table 2 contains the properties tested, applicable standard followed and specimen dimensions.

Table 2 Testing procedures

Property	Standard	Specimen description
Compressive strength	SANS 5863:2006[10]	100 mm cubes
Self-healing effect	-	100 mm cubes
Hydration of matrix	-	100 mm cubes
Oxygen permeability	SANS 3001-CO3-2:2022[11]	70 mm disks described in SANS 3001-CO3-1:2015[12]
Water sorptivity	SANS 516-3:2009[13]	
Chloride conductivity	SANS 3001-CO3-3:2021[14]	
Depth of penetration of water under pressure	EN 12390-8:2019[15]	150 mm cubes

Coppola et al. [16] described self-healing as the ability of the material to restore mechanical characteristics and self-sealing as merely the ability to seal surface cracks. The seal-healing capacity of concrete can be considered as part of its durability. Retesting the compressive strength of the material is therefore a good measure of mechanical properties restored and an indicator of self-healing capability as opposed to measuring crack widths which only provide an indication of self-sealing on the surface of the material. As such, to assess the self-healing of each of the concrete mixes, the specimen which were tested for compressive strength at 7, 28 and 56 days were placed in water and retested 28 days after initial compressive strength testing.

The hydration of the concrete matrix was evaluated through mass gain/loss cycles. The mass gain/loss was determined by first leaving the samples in their allocated curing condition for a week, and then cycling the samples between a 50°C oven and 25°C water bath each week for 16 weeks. The samples were weighed between cycles and the mass gain/loss calculated as a percentage of initial mass after demoulding.

4. RESULTS AND DISCUSSION

4.1 Compressive Strength

The compressive strength of each mix was tested at 7, 28 and 56 days respectively. The results showed PRAH was inconsequential to compressive strength and the largest difference in strength was because of curing conditions. The air-cured samples were 13-20% weaker than water-cured samples at 28 days. The PC mixes' strength plateaued after 28 days, for both curing conditions. In contrast, the FA mixes showed continued strength increase over the testing period. This can be attributed to the spherically shaped fly ash particles which provided improved packing density of the concrete. This filler effect, along with fly ash's potential for pozzolanic reaction provided additional strength, which was noticeable when comparing the PC and FA mixes at as early as 28 days.

4.2 Self-healing Effect

The results of retesting the compressive strength of the samples originally tested at 7, 28 and 56 days are shown in Figure 1. The percentage of initial strength of the retested samples is also shown numerically on each bar.PRAH had no noticeable effect on the self-healing of the specimen. The fly ash mixes showed greater self-healing capacity than the PC mixes particularly at early age initial testing. The fly ash samples originally tested on 7 days all produced greater retested strengths. However, it should be noted that these specimens had the weakest initial strength and therefore present high percentages of initial strength on retesting. Nevertheless, the fly ash mixes performed at least 10% better, regardless of age and PRAH, when compared to the PC mixes. These results can be explained by the presence of microcracks in the samples after initial testing, which allowed water ingress while the samples were in the water bath. Hence, the unhydrated cement within the matrix had access to additional water to hydrate. These hydration products strengthen the matrix and simultaneously contribute to the pozzolanic reaction of the fly ash, further increasing strength.

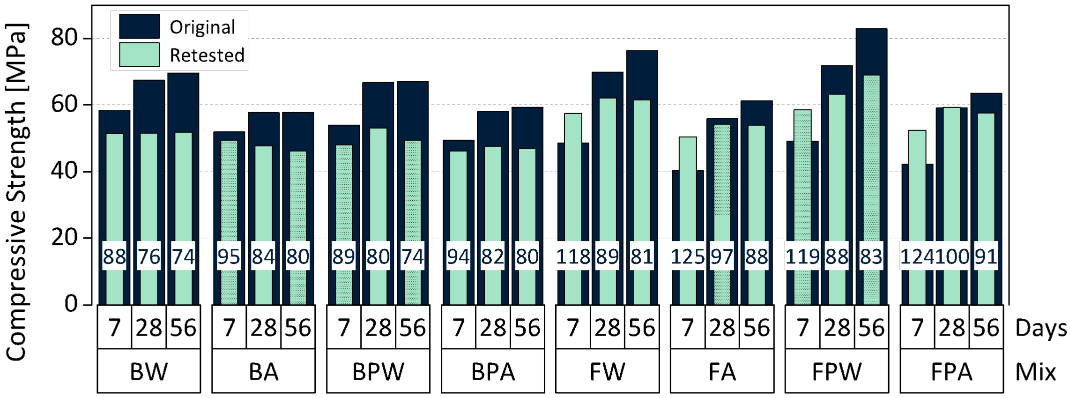

Figure 1 Self-healing effects in terms of compressive strength

4.3 Hydration of Concrete Matrix

The purpose of the mass gain/loss testing was to evaluate the continued development of hydration products or crystal growth within the concrete matrix over time. The results over the 16-week testing period are shown in Figure 2.The different mixes experienced similar mass gain/loss for the first 28 days after which distinction between the fly ash and PC mixes become increasingly evident. The mass lost with each drying cycle significantly decreased after the 4th week for the fly ash mixes. This corresponded to the generally accepted principle that the pozzolanic reaction of fly ash only starts after a few weeks and therefore the concrete matrix would contain more hydration products [17]. There was no clear indication of increasing mass because of crystal growth resulting from the addition of PRAH. The PC mixes showed marginal increase in mass because of further hydration of the cement but were much closer to plateau than the FA mixes. This is because CEM I cement hydrates and gains strength faster than CEM II-B, cement but the reaction slows down sooner as a result. This trend correlated to the results presented for compressive strength and self-healing effects in terms of cement hydration and pozzolanic reaction.

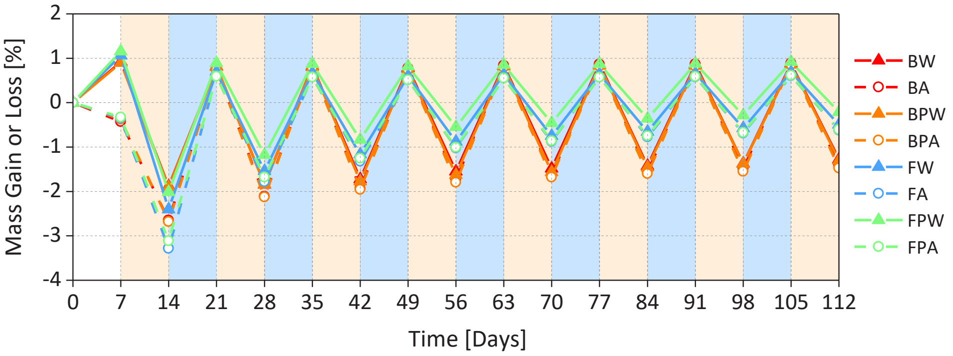

Figure 2 Mass gain/loss with water and oven cycling

4.4 Durability According to SANS3001-CO3

The results of the oxygen permeability and chloride conductivity are presented in Figure 3 and Figure 4. The durability class ranges according to Alexander et al.[18] are shown on the right side of each graph.

The oxygen permeability test is an assessment of the gas permeability of concrete which is generally accepted as a durability-related property of concrete. The overall micro and macro-structure of the concrete is evaluated through this test and it is useful to assess the interconnectedness of the pore structure [2]. The oxygen permeability index (OPI) calculated by this test method is plotted on a log scale and small differences are therefore significant. Torrent and Fernández Luco [19] stated that OPI detected the difference between binder types as well as curing conditions. All the tested samples can be rated as 'Excellent' according to the durability classifications suggested by Alexander et al. [18]. The difference between curing conditions is evident as all water-cured samples performed better than their air-cured counterparts. The fly ash samples yielded higher OPI values than the PC samples, a result also found by Heiyantuduwa [20]. Gas permeability is not commonly used to assess PRAH and therefore literature on their performance is lacking. According to Figure 3, the effect of PRAH can be marginally beneficial when combined with fly ash.

The South African chloride conductivity test is an accelerated diffusion test related to chloride ingress into concrete. The penetration of chloride provides favourable conditions for the corrosion of reinforcement bars. Therefore, chloride ion penetration is recognised as the main cause of long-term deterioration of reinforced concrete structures [21]. From Figure 4 it is apparent that the fly ash samples produced much lower chloride conductivity than the PC samples, a finding supported by multiple authors [2, 20, 22]. Air-cured samples showed an increase in conductivity compared to water-cured samples. The effect of PRAH was slightly advantageous when used along with fly ash. The water sorptivity test is a measure of rate of absorption of the concrete. The results found in this study were variable with no clear trend regarding binder or inclusion of PRAH. Results from literature on absorption of PRAH mixes also vary and are contradictory [3, 4, 21, 23].

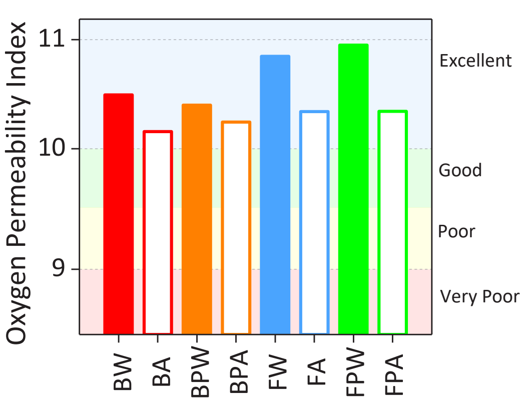

Figure 3 Oxygen permeability index

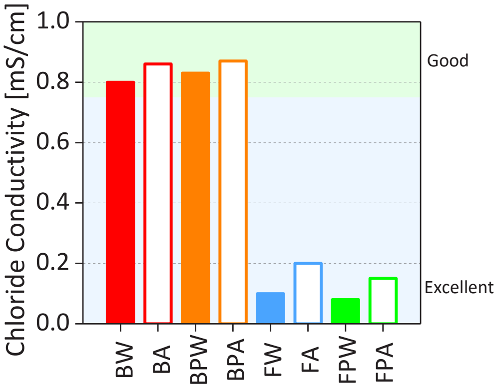

Figure 4 Chloride conductivity index

4.5 Water Depth Penetration

Water depth penetration under pressure is another test method associated with durability. The average depth of penetration was determined for each mix based on EN 12390-8:2019[15], however the test was conducted on mature samples - older than 80 days. This was to permit sufficient time for any crystal growth due to inclusion of PRAH and comparatively further cement hydration or pozzolanic reaction of the reference samples, to occur. A similar approach was adopted by García Calvo et al. [24]. Figure 5 presents the average depth of penetration for each mix. The most notable difference in penetration depth derives from the different curing conditions as all air-cured samples showed significantly larger penetration depths compared to their water-cured counterparts. It should be noted that for reinforced concrete structures with cover of 30 mm or less, the results for air cured samples are detrimental. The performance of the water-cured samples underlines the necessity of implementing adequate curing conditions for concrete. The inclusion of PRAH had no significant effect on the penetration depths of the water-cured samples but reduced the penetration depths of the PC air-cured samples to a small extent. The inclusion of fly ash produced improved results for the air-cured samples, regardless of the presence of PRAH. Literature reports various findings for depth of penetration for concrete with PRAH. Coppola et al. [16] reported improved watertightness with PRAH but stated that the effects were more prominent in poor quality concretes (w/c=0.6) and also concluded that the effectiveness of the admixture in water-cured samples was reduced. Gojević et al. [3] also reported reduced water penetration with PRAH but for high w/c ratios. Conversely, Cappellesso et al. [23] found PRAH increased water penetration. In this study the inclusion of PRAH marginally reduced the depth of water penetration for PC air-cured samples, but the incorporation of fly ash reduced depth of penetration to a greater extent. Neither fly ash nor admixture equalled results obtained from water curing.

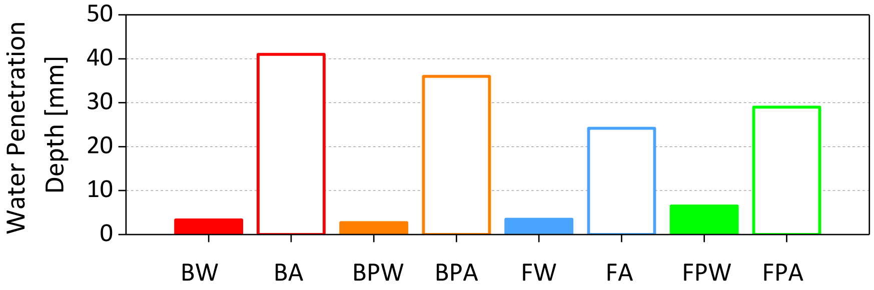

Figure 5 Average depth of water penetration

5. CONCLUSION

The conclusions of this study are as follows:

1) The pozzolanic reactions and filler effect supplied by the fly ash in concrete had more advantageous effects on the compressive strength, self-healing, hydration products within the concrete matrix, oxygen permeability and chloride conductivity when compared to concrete containing PRAH.
2) The inclusion of fly ash was more effective in reducing depth of water penetration of concrete when compared to PRAH for air-cured samples.
3) The effects of curing conditions were clearly seen in strength and durability testing. Water-curing produced superior results compared to air-curing.

The conclusions of this study indicated that improved durability for gaseous and ionic environments can be achieved through the inclusion of fly ash as SCM and fine filler. However, the best durability results derive from adequate water curing.

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