The effect of using controlled permeability formwork on the durability of concrete containing OPC and PFA *

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SUMMARY: *This paper presents a study to assess the effect of using the controlled permeability formwork (CPF) on the durability of ordinary Portland cement (OPC) and pulverised fuel ash (PFA) based concretes cured for different times. An experimental program has been undertaken in which trial specimens have been tested at various ages following different curing periods and regimes. Various tests were conducted and assessed using a range of destructive and non-destructive techniques such as Schmidt hammer, water permeability, sorptivity absorption, ultrasonic pulse velocity, and chloride diffusion and resistivity. The durability and strength test results during the period from 28 to 90 days are presented to compare the effects of using CPF with those of traditional (plywood) formwork on OPC and PFA concrete mixes, as specified on actual construction projects in Australia. The results indicate that CPF gave improved performance compared to the traditional formwork for surface properties of concrete. However, the effects are minimal on the bulk properties of the concrete.*

1 INTRODUCTION

The durability of reinforced concrete structures is a major issue worldwide with the corrosion of reinforcing steel due to the application of de-icing salts, from marine exposure or carbonation of the concrete, resulting in millions of dollars being spent annually on the repair and maintenance of structures (Soylev et al, 2007). The surface zone of the concrete has a significant influence on the durability of the structure, forming the first line of defence against either physical or chemical deterioration. Aggressive agents, such as chloride ions and carbon dioxide, penetrate the concrete through the surface zone, thus the transport properties of this zone control the rate of penetration into the bulk of the concrete. However, the surface of the concrete is more vulnerable to poor curing and compaction than the bulk of the concrete (Cairns, 1999). Therefore, for good durability, a well-compacted strong concrete surface zone is needed with low permeability, low diffusivity and no surface cracking.

Traditional approaches for improving the quality of the surface zone have been employed by improving the performance of the bulk concrete by materials selection and controlling mix proportions. Curing is also an important factor, but is quite difficult to control in practice. Controlled permeability formwork (CPF) has been shown to improve the durability of concrete (Coutinho, 2003; Nolan et al, 1995; Price, 2000). The CPF improves the quality of the surface zone of the concrete by allowing the bleed water and air to escape from the concrete surface while retaining the cement particles, resulting in a denser and less porous concrete surface. This technique reduces the near-surface water/binder ratio and reduces the sensitivity of concrete to poor site curing (Coutinho, 2003).

According to Price (2000), the CPF system has three basic elements (figure 1):

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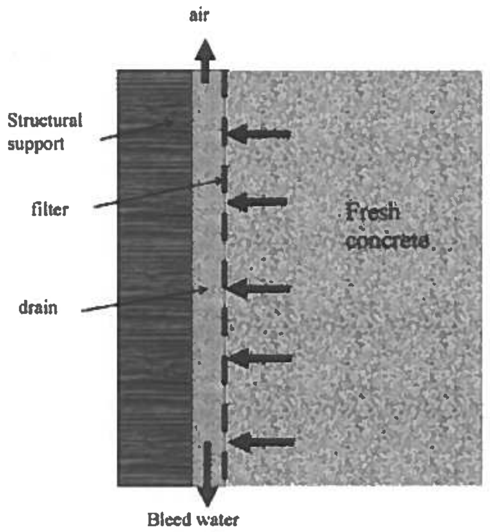

Figure 1: General elements of a CPF system (Price, 2000).

- A filter that allows the passage of air and water from the fresh concrete, but retains cement and other fine solids.
- A drainage system that transfers the air and water removed from the fresh concrete to outside the formwork.
- A structural support that supports the filter and drainage elements, and also maintains the required formwork profile and resists the concrete pressure.

The CPF material is produced in three general classifications:

- Type I – two-layer filter fabric systems that are fixed over a structural support and tensioned in-situ. These systems can be reused with careful cleaning between uses. Two CPF systems of this category are silk and textile form
- Type II – a single-layer filter fabric system that is fixed over a structural support and tensioned in-situ. These systems are generally single-use products.
- Type III – a two-layer system combining a filter fabric bonded to a backing grid. This type of CPF is fixed onto a structural support, but does not need tensioning. The filter fabric is pretensioned in the manufacturing process and tension is maintained by the backing grid. This type can be used more than once.

This paper presents an experimental study to evaluate the durability properties of two ordinary Portland cement (OPC) mixes and one pulverised fuel ash (PFA) mix, each with and without CPF, and with different curing periods. A range of destructive and non-destructive tests were carried out to assess the strength, surface properties and the long-term durability performance for the mixes under different curing regimes.

2 MATERIALS, MIX PROPORTION, SPECIMEN DETAILS, CURING REGIMES

A total of three different mixes were used in the study, two with OPC and one with 30% PFA replacement. OPC-A mix is a normal concrete mix used in the laboratory based on the British method published by Department of the Environment (Teychenne et al, 1988), while OPC-B and the 30% PFA were typical mixes specified on construction projects in Australia, provided by GHD Australia. All mixes are aimed to achieve 80 mm slump.

The mix proportions are given in table 1. General purpose (GP) cement, supplied by Cement Australia in accordance to AS3972 (Standards Australia, 1997), was used for preparing the mixes for this study. The coarse sand used was natural river gravel with 10 mm maximum size, and the fine sand was natural river sand with 80% passing from 600 µm sieve. The aggregates were prepared in accordance with AS2758.1 (Standards Australia, 1998). The PFA was a class F fly ash from Gladstone quarry. Two admixture used in OPC-B and PFA mix were WRDA-GWR, a water reducing admixture, and Daracem 100, a superplasticizer, both manufactured by Grace Construction Australia.

The CPF liner adopted was a Type II liner. The physical properties of the liner are shown in table 2.

Two concrete blocks of size 200 × 600 × 600 mm as shown in figure 2 were cast for this study. The CPF liner was attached on the 600 × 600 surfaces for one block and the traditional timber formwork surface is used for the second block. The mixing was performed in accordance with AS1012.2 (Standards Australia, 1994) using a pan mixer. After pouring, poker vibration was applied.

Table 1: Mix proportions (for 1 m^3 of mix).

	OPC-A (kg)	OPC-B (kg)	PFA (kg)
Sand – coarse	523	370	370
Sand – fine		275	264
Aggregate – 20 mm	838	550	550
Aggregate – 14 mm		350	350
Aggregate – 10 mm	419	280	280
GP cement	402	400	280
PFA			120
Water	193	159	159
WRDA-GWR		1.2	1.2
Daracem 100		1	0.56

Table 2: Characteristics of permeability formwork.

Physical properties	Unit	Value
Pore size	µm	<30
Weight	gm^{-2}	250
Air permeability at 800 Pa	s^{-1}m^{-2}	250
Tear strength machine direction	N	250
Tear strength cross direction	N	200
Thickness at 2 kPa	Mm	1.2
Composition	100% polypropylene	

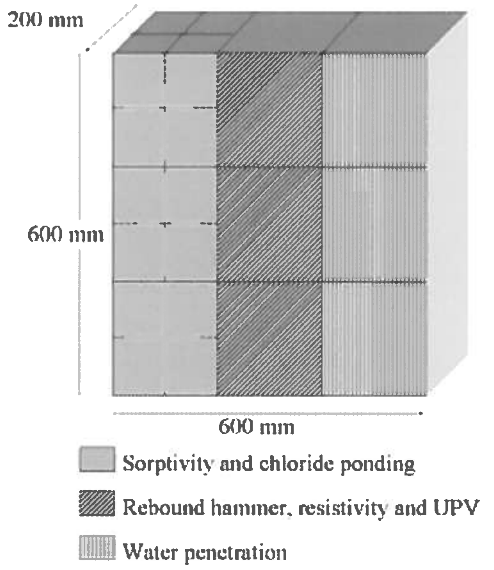

Figure 2: Dimensions and cutting positions of a concrete block and test types.

The concrete blocks were demoulded after 24 hours from casting and then cured with wet hessian for different curing time (table 3). The 14-day curing period was adopted to replicate the curing specification applied in hot/humid conditions encountered in northern Australia. The 1-day curing period was used to evaluate the effectiveness of the CPF in reducing the curing period. After the period of curing, the concrete blocks were exposed to the laboratory environment (26 °C and 40% RH).

At the age of 28 days, the concrete blocks were cut using a diamond saw. The blocks were cut into three different sizes – 200 × 200 × 200 mm, 200 × 200 × 100 mm and 100 × 100 × 100 mm. Identical tests were undertaken on the top, middle and bottom sections.

Table 3: Curing regimes.

Mix	Curing times		
	1-day wet curing	14-day wet curing	
	CPF	CPF	Plywood
OPC-A	Yes	Yes	Yes
OPC-B	No	Yes	Yes
30% PFA	No	Yes	Yes

The cut specimens were then left in the laboratory environment until testing. The type, number and the date of each test are given in table 4.

3 TEST PROGRAM

3.1 Sorptivity

The sorptivity tests were undertaken in accordance with DIN 52617 (DIN, 1987). The sides of the specimens were coated with epoxy to allow free water movement only through the bottom face (unidirectional flow). The results were plotted against the square root of the time to obtain a slope of the best fit straight line. According to Hall (1989), the penetration of water under capillary action can be modelled by:

$$I = A + St^{1/2} \tag{1}$$

where *I* is the cumulative absorbed volume after time *t* per unit area of inflow surface. *I* = *Dw*/*ar*, *Dw* being the increase in weight, *a* the cross-sectional area and *r* the density of water. *A* is the constant, and *S* is the slope of the strait line representing the sorptivity.

3.2 Water penetration

The depth of water penetration was assessed in accordance with DIN 1048 (Deutsches Institut für Normung, 1990) using a concrete permeability apparatus (as shown figure 3). The cubes were placed inside the permeability cells and a water pressure of 100 kPa was applied to the samples for two days, followed by 300 and 700 kPa for one day each. At the end of this period, the test samples were removed from the cells, surface dried and split in half in the perpendicular direction of the injection face. The average depth of penetration was measured and the average value was used as an indication of the permeability of the concrete.

3.3 Surface hardness

Surface hardness was measured using a Schmidt Rebound Hammer in accordance with BS 1881 (BSI, 1986). Twelve individual readings were taken on each block. The average of 10 readings was taken. Readings that differed by more than six units were

Table 4: Test program.

Specimen size (mm)	OPC-A			OPC-B			30% PFA		
	Test	No.	Day	Test	No.	Day	Test	No.	Day
100 × 100 × 100	Sorptivity	6	28	Sorptivity	6	56	Sorptivity	6	56
200 × 200 × 200	Water penetration	6	28	Water penetration	6	56	Water penetration	6	56
200 × 200 × 100	Rebound hammer	6	28	Rebound hammer	6	56	Rebound hammer	6	56
200 × 200 × 100				Resistivity	6	28 90	Resistivity	6	28 90
200 × 200 × 100				UPV	6	28 90	UPV	6	28 90
100 × 100 × 100				Chloride ponding	1	28	Chloride ponding	1	28

Table 5: Typical rate of corrosion ranges.

Resistance meter reading (Ω)	Ω.cm	Rate of corrosion
0-160	0-5000	Very high
160-640	5000-20,000	High
640-1600	20,000-50,000	Low
1600+	50,000+	Negligible

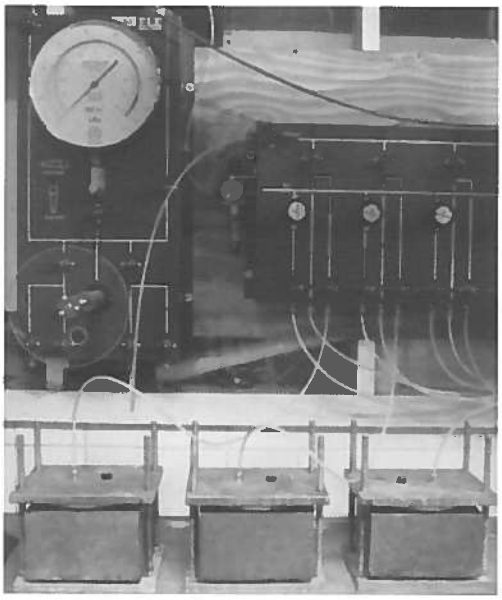

Figure 3: Concrete permeability apparatus.

discarded, and if more than two readings differed from the average by six units, the entire set was discarded and readings from a new location were taken.

3.4 Resistivity

Resistivity was measured using a Wenner probe. The test was undertaken using four probes 50 mm apart. Four holes were drilled to a depth of no more than 5 mm, corresponding to a maximum of 1/8 of the electrode spacing. A smear of electrical conductive paste was applied to each hole and the resistivity was recorded when the signal value reached 100%. Typical resistivity values are shown in table 5.

3.5 Ultrasonic pulse velocity (UPV)

UPV measurements were taken using an ultrasonic transmitter and a receiver (CH-8034-Z). Pulses of longitudinal stress waves generated by the electro-acoustical transducer at one surface of the concrete were received by the second transducer at the opposite surface. The transit time, *T*, was measured and the pulse velocity, *V*, was calculated.

3.6 Chloride ponding

The chloride ponding test was performed in accordance with AASHTO T259 (AASHTO, 1997). The specimens, one from each level, were ponded 28 days after casting. All faces, other than the top face, were painted with epoxy to prevent chloride ingress. The chloride analysis was undertaken at a NATA accredited laboratory. The results were modelled using Fick's second law of diffusion to provide a surface chloride concentration, C_s, and effective chloride diffusion coefficient, D_{eff}.

4 RESULTS

The results of the tests are presented in figures 4 to 12 and in tables 6 to 12. A two character notation is adopted to denote the specimen types for each mix. The first character: C for CPF and P for plywood formwork. The second character (number and letter): 1d for 1-day curing and 14d for 14-days curing with wet hessian.

4.1 Surface appearance

When the concrete block cast with CPF was demoulded, the surface was observed to be damp, indicating that moisture was being retained at the surface (figure 4), while the equivalent plywood cast blocks were dry (figure 5). After the 14-day curing period, the appearance of the concrete block cast with the CPF was found to be textured and dark in colour, whereas it was dustier and lighter for the concrete block cast with ordinary formwork. In terms of blowholes, only a few were observed in the CPF concrete block (near the top), while many blowholes appeared throughout the surface of the block cast with the traditional formwork (figure 6).

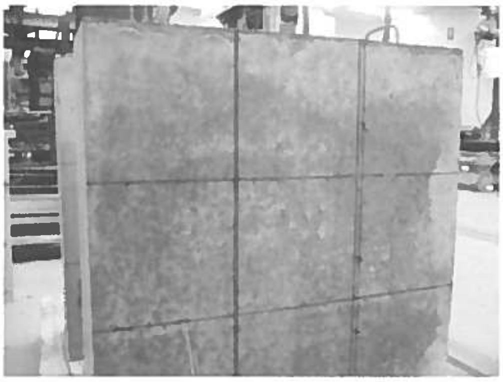

Figure 4: CPF concrete block after demoulding.

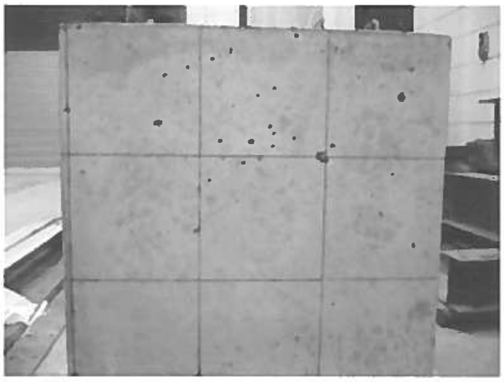

Figure 5: Plywood concrete block after demoulding.

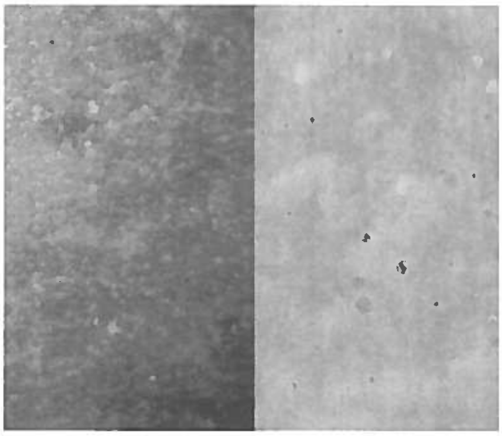

Figure 6: Surface appearance of concrete cast with CPF (left) and plywood formwork (right).

4.2 Sorptivity

The results of the sorptivity (water absorption by capillarity) tests are presented in table 6 and figure 7. The sorptivity test results for all concrete mixes cured for different periods has shown that the CPF specimens have consistently lower values of sorpitivity than that of the corresponding plywood specimens. The use of CPF reduced the sorpitivity by between (40% to 45%) when concrete is cured for the same period. The results also show that the bottom levels experience a significant reduction in sorptivity compared to the middle and the top levels. This effect is due to the higher hydrostatic pressure at the bottom driving more bleed water compared to the top and middle level.

4.3 Water penetration

The depth of water penetration test results are given in table 7 and figure 8. The water penetration data shows that the CPF cured specimens reduced the level of water penetration for all mixes. These results are in agreement with the water absorption data. The results also show that 1-day curing with CPF had lower water penetration than that of 14-day plywood cured concrete specimens. The results suggest that the CPF improves the surface characteristics and performance of the concrete, both for the OPC mixes and the PFA mix.

4.4 Surface hardness

The results of the Schmidt Hammer tests are presented in table 8 and figure 9. The surface hardness data show no clear trends, either regarding curing regime or casting level. The hardness values of the plywood cured specimens are lower than that of CPF cured specimens, but the difference is marginal. This is more noticeable for OPC-A mix specimens,

Table 6: Sorptivity data.

Mix	Sorptivity (mm.min$^{-0.5}$)					
	28 days			56 days		
	Top	Middle	Bottom	Top	Middle	Bottom
OPC-A/C1d	0.157	0.145	0.120			
OPC-A/C14d	0.132	0.129	0.113			
OPC-A/P14d	0.214	0.208	0.200			
OPC-B/C14d				0.060	0.064	0.046
OPC-B/P14d				0.102	0.101	0.088
PFA/C14d				0.092	0.077	0.065
PFA/P14d				0.148	0.138	0.142

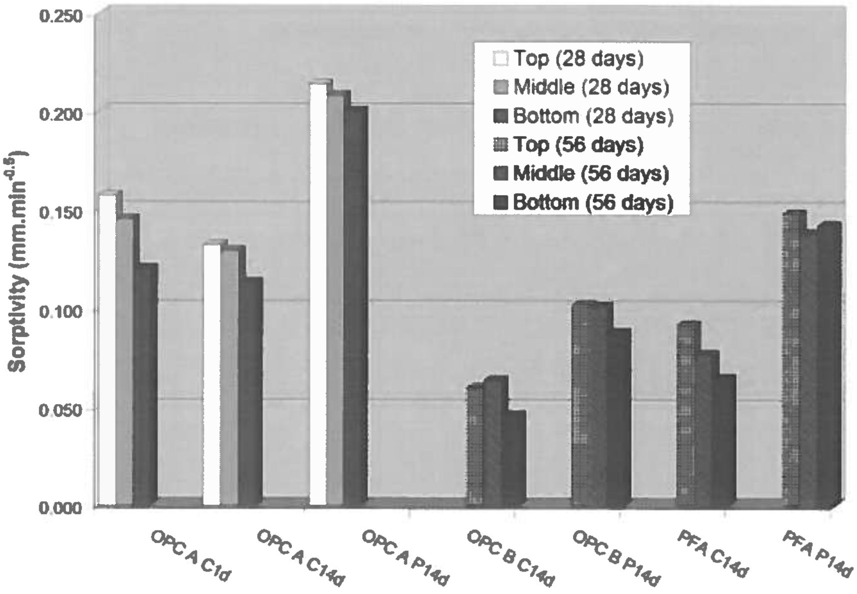

Figure 7: Sorptivity of concrete cast with CPF and plywood formwork for different curing periods.

Table 7: Water penetration test results.

Mix	Water penetration (mm)					
	28 days			56 days		
	Top	Middle	Bottom	Top	Middle	Bottom
OPC-A/C1d	70	60	130			
OPC-A/C14d	60	50	105			
OPC-A/P14d	130	45	90			
OPC-B/C14d				50	37	31
OPC-B/P14d				80	77	49
PFA/C14d				36	32	28
PFA/P14d				90	85	83

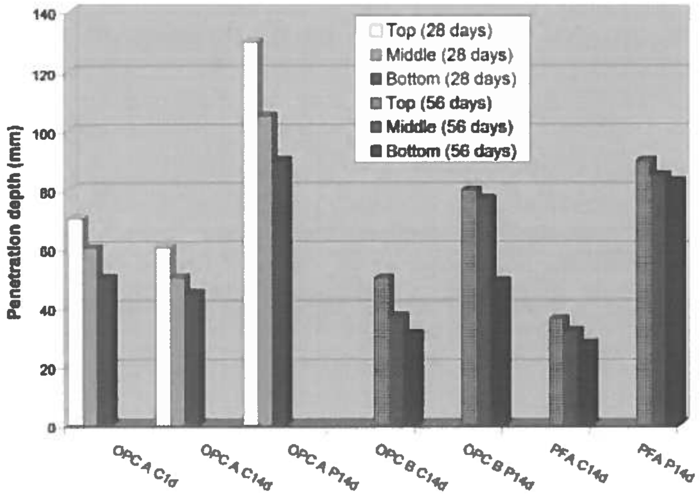

Figure 8: Permeability as water penetration depth of concrete cast with CPF and plywood formwork for different curing periods.

Table 8: Surface hardness test results.

Mix	Surface hardness (rebound number)					
	28 days			56 days		
	Top	Middle	Bottom	Top	Middle	Bottom
OPC-A/C1d	36.5	39.0	40.4			
OPC-A/C14d	46.6	49.8	50.4			
OPC-A/P14d	32.8	33.6	32.4			
OPC-B/C14d				25.0	27.0	28.0
OPC-B/P14d				28.0	25.0	27.0
PFA/C14d				25.7	30.8	29.7
PFA/P14d				26.7	26.4	29.1

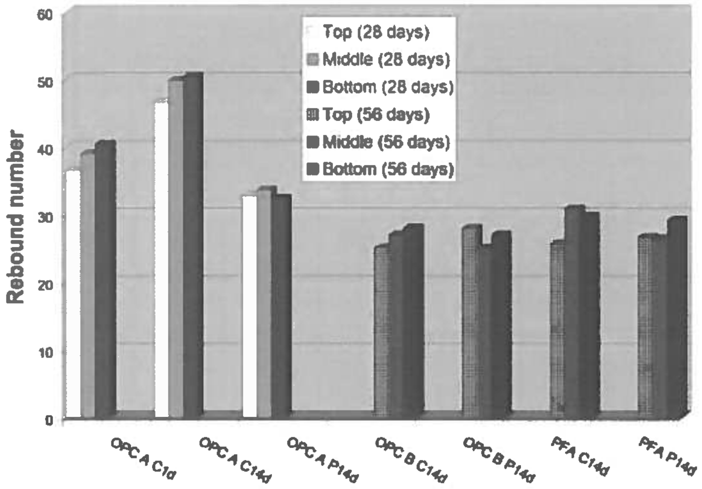

Figure 9: Surface hardness of concrete cast with CPF and plywood formwork with different curing periods.

while the OPC-B and PFA mixes are almost identical. This can be explained by the Schmidt Hammer test being a measure of the strength of the bulk concrete, rather than just the surface. As has been previously discussed, the CPF affects 20-30 mm of the concrete surface. Thus any measure of the bulk concrete, rather than the surface layer, is not expected to show any significant difference in results.

4.5 Resistivity

The resistivity test results are presented in table 9 and figure 10. The resistivity results show a significant increase in resistivity with time. Indeed the PFA results at 90 days were all greater than 100 kΩ.cm, the top of the range for the resistivity meter. The OPC concrete specimens showed an approximately 30% increase in resistivity with time. No variation was observed between the CPF and plywood cured specimens at 56 days, but at 90 days the CPF cured OPC specimens displayed an approximately 25% higher resistivity than the plywood cured specimens. No data was available to compare the PFA specimens at 56 and 90 days. The resistivity tests are specifically designed to measure the bulk value rather than the surface value, and as such similar data would be expected for both curing regimes as the CPF only affects the surface layers. It may be that the different surface qualities have resulted in different rates of drying, thus resulting in the observed variation in resistivity. However, resistivity measurements have been shown to be subject to misleading results (Bungey et al, 2006), which could also be a contributing factor.

The results do show that the bottom cast material has a marginally higher resistivity than the top level. This is again attributed to the compaction. The more the concrete is compacted, the lower the porosity and the less pore water, and hence fewer free ions, to pass the charge – leading to a higher resistivity.

4.6 Ultrasonic pulse velocity

The ultrasonic pulse test is a technique that measures the bulk property of the concrete. The UPV test results are presented in table 10 and figure 11. It is obvious that no clear variation in results when the CPF and plywood cured specimens are compared.

Table 9: Resistivity test results.

Mix	Resistivity (kΩ.cm)					
	56 days			90 days		
	Top	Middle	Bottom	Top	Middle	Bottom
OPC-B/C14d	26	24	26	42	40	41
OPC-B/P14d	20	24	23	29	31	33
PFA/C14d	69	74	78	>100	>100	>100
PFA/P14d	65	75	78	>100	>100	>100

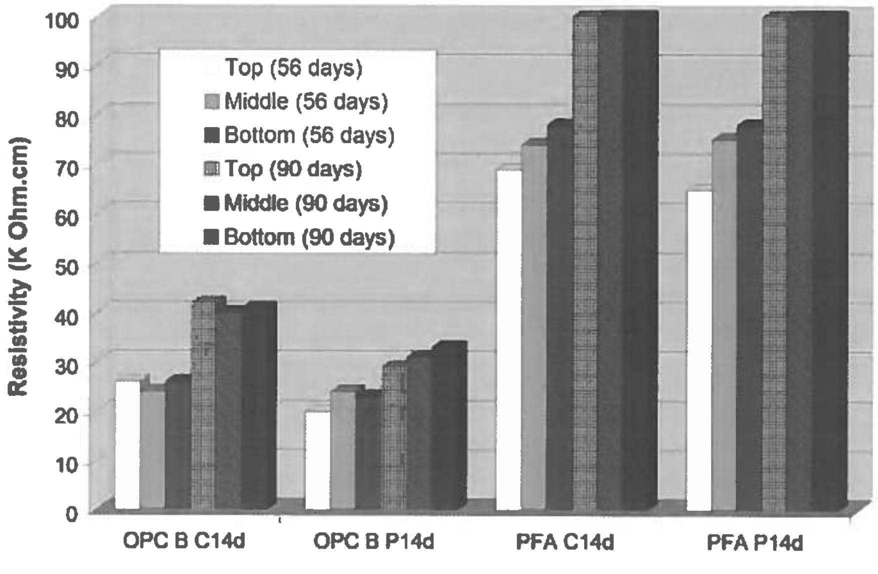

Figure 10: Resistivity of concrete cast with CPF and plywood formwork for different curing periods.

Table 10: UPV test results.

Mix	Pulse velocity (m.s^{-1})					
	56 days			90 days		
	Top	Middle	Bottom	Top	Middle	Bottom
OPC-B/C14d	4510	4820	4760	4570	4750	4780
OPC-B/P14d	4630	4790	4810	4360	4610	4620
PFA/C14d	4730	4620	4960	4830	4710	4720
PFA/P14d	4610	4790	4600	4710	4720	4670

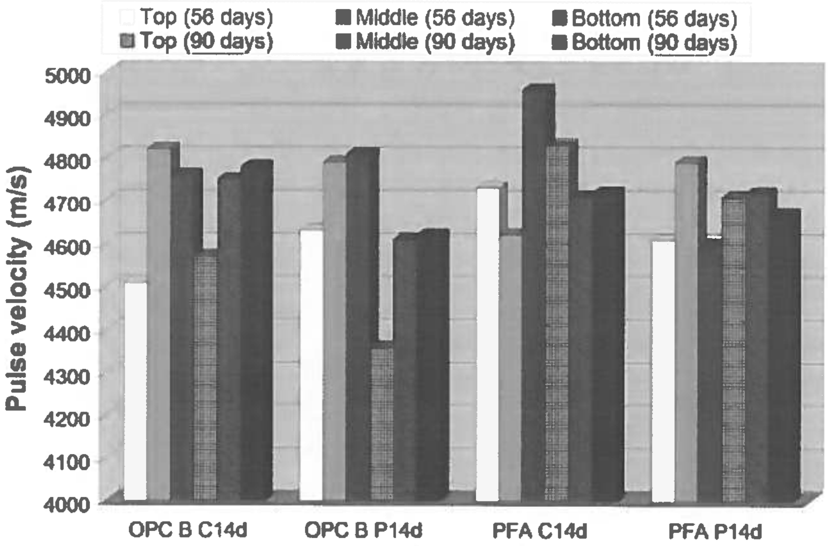

Figure 11: UPV of concrete cast with CPF and plywood formwork for different curing periods.

The measured UPV data has similar values for both cast position (top, middle or bottom) and for ages (56 and 90 days).

4.7 Chloride ponding

The results of chloride ponding tests conducted on concrete specimens were analysed for chloride content at three depth increments – 0-25, 25-50 and 50-75 mm – as shown in table 11. The chloride profiles were then plotted and the best fit curve fitted using Fick's 2nd Law of Diffusion (Crank, 1975), to determine the chloride diffusion coefficients as shown in figure 12. The chloride diffusion coefficients are calculated and presented in table 12.

The results show that the chloride diffusion coefficient of OPC concrete was reduced significantly from 4.12 × 10^{-13} to 2.70 × 10^{-13} cm^{2}s^{-1} when CPF is used. This is a clear indication that the CPF has improved the durability of OPC concrete. However, no similar improvement is observed for the PFA concrete. In fact a small increase in the chloride diffusion coefficient is observed, from 3.01 to 3.17 × 10^{-13} cm^{2}s^{-1} for the CPF cured specimen, though this is such a small variation

Table 11: Percentage chloride by weight of sample.

Mix	Percentage chloride by weight of sample		
	0-25 mm	25-50 mm	50-75 mm
OPC-B/C14d	0.0710	0.0155	0.0050
OPC-B/P14d	0.1025	0.0120	0.0115
PFA/C14d	0.0695	0.0160	0.0075
PFA/P14d	0.0730	0.0110	0.0060

Table 12: Chloride diffusion coefficients.

Mix	Chloride diffusion coefficient (10^{-13} m^{2}s^{-1})
OPC-B/C14d	2.70
OPC-B/P14d	4.12
PFA/C14d	3.17
PFA/P14d	3.01

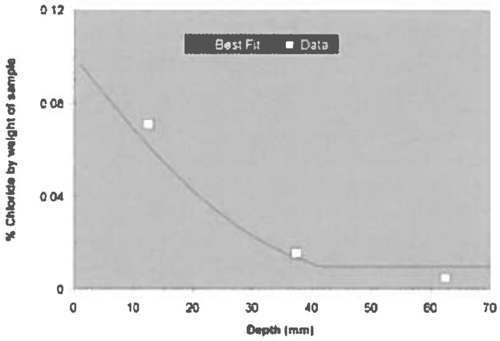

Figure 12: Best fit curve to calculate chloride diffusion coefficient using Fick's 2nd law of diffusion.

as to be encompassed by the experimental variation. Similar results have been observed by other authors (Bai et al, 2003) and are attributed to the material properties of the PFA, which is known to improve its diffusion characteristics with time compared to OPC concrete. Due to the PFA chloride diffusion improving with time, it may be that the use of CPF may show some improvement with additional time.

5 CONCLUSION

The durability tests undertaken on OPC and PFA concretes show the significant effects on improving the surface properties of concretes when the CPF is used. However, the effects are minimal on the bulk properties of the concrete (resistivity, UPV and surface hardness).

The casting position (top, middle and bottom) has an effect on the materials durability, with bottom cast concrete having the best durability properties, followed by the middle and then the top level. This is attributed to the increase in compaction level with the increase of concrete depth. The effect of using the CPF was found to improve the properties of the bottom cast concrete where the pressure level is high, while the effect is less at the top level.

The CPF provides an improvement in the water absorption and water permeability performance for both the OPC and PFA concrete. The CPF does not, however, show any improvement in the chloride diffusion coefficient for the PFA at the time of casting.

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