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The influence of reusing ‘Formtex’ controlled permeability formwork on strength and durability of concrete

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Abstract The effects of the reuse of ‘Formtex’ Controlled Permeability Formwork (CPF) liner on strength and durability properties of concrete were investigated at two different water-cement ratios and the results are reported in this paper. Test blocks were cast using the CPF on one side and impermeable formwork (IF) on the opposite side of the mould so that direct comparisons could be made between the two. The strength was assessed using the Limpet pull-off tester and both the air permeability and the water absorption (sorptivity) were measured using the Autoclam Permeability System. Both these instruments measured the ‘covercrete’ properties. In addition, cores cut from the test specimens were subjected to an accelerated carbonation test and a chloride exposure test. The results showed that the ‘Formtex’ CPF increases the surface strength and the durability of concrete compared to the IF. There was an almost complete elimination of blowholes. The permeability of concrete decreased and its resistance

to the ingress of both carbon dioxide and chlorides increased when CPF was used. The beneficial effects of the Formtex CPF were most evident in concrete of higher water-cement ratio. With the reuse of the Formtex liner twice, that is a total of three uses, the performance of the CPF to improve the properties of concrete remained almost the same. In this research the CPF liner was cleaned thoroughly between each use, which must be adhered to for site applications for reproducing the beneficial effects observed in the laboratory.

Keywords Formwork · Chloride ingress · Carbonation · Durability · Permeation · Concrete

1 Introduction

Controlled permeability formwork liners (CPF) are formwork systems for concrete which are permeable to air and water, but prevent the escape of cement particles. When concrete is placed and vibrated, air and water migrate to the interface of the concrete and the formwork and normally get trapped in conventional impermeable formwork (IF) (Fig. 1). However, with CPF the air and the excess water are removed. This results in a less permeable concrete surface which is virtually blow hole free.

Controlled permeability formwork has been used widely in the mid-eighties in Japan and, to a limited

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Fig. 1 The function of formwork liner in controlled permeability formwork

extent, in the late eighties in the UK, Sweden and Australia. Due to the developments in formwork which took place in Japan and, particularly in CPF, an Overseas Science and Technology Expert Mission to Japan was arranged with the support of the UK Department of Trade and Industry in 1989 [1]. Its members studied all aspects of formwork practice in Japan.

The principal Japanese CPF systems identified were The Kumagai Gumi Textile Form, The Kajima Silk Form, Shimizu CPF and Taisei Super Absorbed Polymer formwork. The Kumagai Gumi Textile Formwork was reported to be reused up to 33 times on one tunnel project, but the cleaning after each use was done with a high-pressure water jet. Other systems were also reported to be reused, but only a lesser number of times.

Parallel research carried out by DuPont has resulted in the development of a similar, but less expensive, polypropylene liner known as 'Zemdrain'. The principle of operation is similar to that of the Japanese liner mentioned above and both Japanese liner and Zemdrain systems have been shown, through laboratory investigations, to produce a highly durable near surface concrete [2–4]. Formtex, the CPF liner reported in this study, is manufactured by a Danish company called Fibertex. It is a flexible fabric made from polypropylene fibres and has two layers; one is a permeable layer allowing water and air to pass through and the other is a filter layer retaining concrete particles. The pore size of the filter layer has been designed to be slightly smaller than the size of the particles in the concrete [5]. Zemdrain is constructed of 100% polypropylene fibres and is thermally bonded.

Controlled permeability formwork, manufactured with different types of formwork liners, has been used for the construction of bridge piers, retaining walls, building structures, tunnels and dams. The principal benefits derived from CPF, as reported by the contractors, were surface finish with very few blow holes, textured surfaces giving good bond for tiles, render or plaster, and improved initial surface strength, allowing earlier formwork striking.

Limited research has been published on the performance of concrete made by using CPF. Sha'at et al. [4] investigated the effect of CPF with Zemdrain and reported that it generated a 10–20 mm deep surface layer with improved permeability and durability properties. Both Price [3] and Sha'at et al. [4] noted significant reductions in surface absorption in all concretes cast against CPF lined with Zemdrain. For the Zemdrain CPF, Price [3] reported, about 80–85% improvement in water absorption when used with both OPC and blended cement concretes. Sha'at [6] also has reported about 70–80% improvement in sorptivity when Zemdrain was used as the CPF liner for OPC concretes. He investigated a range of water-cement ratios and aggregate-cement ratios. The magnitude of the reduction in surface absorption caused by the CPF was much greater than that resulting from wet curing of conventionally cast concrete.

Sha'at [6] reported about 80–85% improvement (reduction) in air permeability when Zemdrain CPF was used for OPC concretes. This result was noted to a range of water-cement ratios and aggregate-cement ratios used in his investigation. In their study, Sha'at et al. [4] also showed that the surface strength, measured using the pull-off test, increased by up to three times when CPF with Zemdrain was used instead of the normal IF.

In his study with Zemdrain CPF, Price [3] reported, for both OPC concrete and blended cement concrete that the carbonation depths were about 80–85% more for IF concrete than the CPF concrete. Sha'at [6] reported, about 40–55% deeper carbonation for IF concrete than Zemdrain concrete, for a range of curing regimes applied to OPC concretes. Price [7] also concluded from his carbonation study that the carbonation resistance of all the concretes studied were significantly increased by casting against the Zemdrain CPF. The improvement was particularly noticeable for concrete containing PFA

or a high proportion of GGBFS. All these results indicate that the surface improvement of concrete due to the use of CPF liners reflects on the carbon dioxide ingress as well, for both OPC and blended cement concretes.

Price [3] reported the effect of using CPF with Zemdrain for concretes containing additive materials such as Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS) on their durability. He concluded that the penetration of chlorides into concrete and their build-up at the level of reinforcement were significantly reduced by using the CPF for all the concretes examined. Basheer et al. [8] noted dramatic reduction in chloride ingress for concrete surfaces manufactured with CPF compared to normal concrete surfaces, irrespective of the curing conditions or mix proportions. A similar good performance of Zemdrain CPF concrete was reported by Coutinho [9] in her laboratory study with concretes made with cement partially replaced with Portuguese Rise Husk Ash. Her study included strength, absorption by capillary action and chloride ion penetration. McCarthy and Giannakou [10] confirm this performance for in situ CPF concrete in the splash zone and inter-tidal regions in marine environment. Price [7] has carried out a laboratory based investigation to understand the effect of environmental condition in hot climates on the resistance of CPF to chloride salt spray cycles. Samples, after an age of 7 months were exposed to a salt spray cycle of 4 h spray and 20 h drying. This was repeated 75 times. He concluded that concrete surfaces cast against CPF exhibit less chloride penetration depth. Similar results were reported by Sha'at [6] from his study with Zemdrain CPF. He observed 90–95% reduction in chloride diffusion when Zemdrain CPF was used with OPC concrete.

As reported above, the CPF liner used by Price [3, 7] and Sha'at et al. [4, 8] was Zemdrain manufactured by Dupont. Not much published information is available on Formtex CPF, especially on its reuse. Therefore, a study was conducted using Formtex to assess the effect of reuse of Formtex CPF on its performance in improving strength, permeability and durability of concrete. This paper reports the findings of this investigation. The scope of the work was limited to two OPC concrete mixes of two water-cement ratios and the CPF was reused twice. The findings are based on a laboratory investigation.

2 Experimental programme

2.1 Variables

The effect of the reuse of Formtex CPF was investigated by using the same CPF for three times, as illustrated in the layout of the investigation in Table 1. Two water-cement ratios were investigated, 0.45 and 0.5, in order to determine how the performance varied with water-cement ratio. These two water-cement ratios represented two grades of concrete viz. C40 and C30, respectively. The mixes were designed using the DoE method [11] for a slump of 60–90 mm and the proportions are shown in Table 2. For each mix, the test blocks were made using both conventional IF and CPF made of Formtex membrane. The concrete surface obtained using IF is referred to as the Impermeable Formwork face or IF face and that obtained using the Formtex CPF is referred to as the CPF face in this paper.

2.2 Materials

Ordinary Portland cement, medium sand and 20 mm well graded basalt aggregate were used to cast the test blocks. In order to control the water-cement ratio of the mixes, dried aggregate was used. However, a pre-determined quantity of water to take account of the aggregate absorption was added to the mix water at

Table 1 Layout of experimental programme

Variables	W/C					
	0.45			0.5		
Number of use of CPF	1	2	3	1	2	3

Table 2 Concrete mix proportions in kg/m³

Mix ingredient	W/C	
	0.45	0.5
Cement (OPC)	445	450
20 mm aggregate	855	840
10 mm aggregate	425	420
Fine aggregate (natural sand)	525	515
Water	200	225
Superplasticiser	4.45	0

the time of manufacturing the concrete. A naphthalene formaldehyde super-plasticiser was added to the 0.45 water-cement ratio mix in order to achieve the intended slump.

2.3 Manufacturing test specimens

Test conditions used for the study are given in Table 1. Three samples of each variable were prepared and altogether 18 blocks were cast. The test blocks were of size $150 \times 250 \times 750 \text{ mm}^3$. One of the $250 \times 750 \text{ mm}^2$ surfaces was cast with the CPF formwork and all other surfaces were cast with an impermeable plywood formwork (Fig. 2). Therefore, each block had its opposite surfaces of size $250 \times 750 \text{ mm}^2$ cast against the conventional formwork and the other cast using the CPF. In order to prepare the CPF, the Formtex liner was stretched taut over the plywood surface of the unassembled mould and firmly attached using a staple gun, as suggested by the manufacturer.

Before assembling the mould, the conventional plywood formwork was oiled to prevent the concrete sticking to it. The part of the mould containing the Formtex CPF liner was left unattached until just prior to casting so that the oil from the plywood would not touch the CPF liner and block its pores.

The concrete was prepared in a rotary mixer and immediately after the mix was ready a standard slump test was carried out. The moulds were then filled with the concrete and compacted using a poker vibrator. Three standard 100 mm cubes were also cast in order to obtain the compressive strength of the concrete.

Fig. 2 Details of the mould and test specimens

After 24 h the formwork was stripped and the blocks removed from the moulds. Where the CPF liner was reused, it was lightly brushed and the moulds cleaned and reassembled so as to be ready for the next mix. The blocks were air cured for 28 days at 20°C and 75% relative humidity. The cubes were cured in a water bath at 20°C for 28 days.

2.4 Test methods

The following tests were carried out on the concrete blocks to assess their strength and durability properties.

- Pull-off test
- Air permeability test
- Water absorption test
- Accelerated Carbonation test
- Chloride ingress test

All these tests were carried out on the $250 \times 750 \text{ mm}^2$ surfaces which were cast using either the conventional formwork or the Formtex CPF liner. In addition, compressive strength was determined using standard cubes at the age of 28 days.

When the pull-off test, air permeability test and the sorptivity test were completed two cores of 100 mm diameter were removed from each block, which were used for the carbonation and the chloride ingress tests. The cores were drilled through the $250 \times 750 \text{ mm}^2$ face so that the test surfaces were on each end of the cores.

2.4.1 Compressive strength testing

The cubes were cured in a water bath at $20^\circ\text{C} (\pm 1^\circ\text{C})$ for 28 days and crushed to determine the compressive strength.

2.4.2 Pull-off strength testing

The Pull-off test was carried out on the specimens after 28 days using the Limpet. This instrument was developed in the Queen's University Belfast [12] and is a partially destructive test used to find the strength of the cover concrete. As the Formtex CPF is meant

to lower the water-cement ratio of the near-surface zone, this test is particularly relevant. A direct comparison of the CPF formed and conventional formwork formed surfaces can be easily made using the pull-off strength.

Two test locations were used on each surface so that six results could be averaged for each experimental condition and thereby experimental errors minimised. In order to carry out the test a 50 mm diameter steel disc was bonded to the test surface by means of an epoxy resin adhesive. When the adhesive was cured, the Limpet was fastened to the disc. By means of a mechanical system, the disc was pulled off by applying a gradually increasing tensile force to the disc. The disc came off by breaking the concrete surface and the load required to pull the disc off the concrete was noted on a digital display unit. By knowing the surface area of the disc and the force applied at failure, the tensile strength of the near surface concrete was calculated.

2.4.3 Air permeability and sorptivity tests

Two types of permeation tests were performed on the specimens, viz air permeability and water absorption (sorptivity) tests. Both these tests were carried out using the Autoclam Permeability System, an instrument developed at Queen's University Belfast [13]. The tests were performed on the blocks after they had been dried at 40°C and 20% relative humidity for 2 weeks. Tests were carried out on three test locations for each test condition so that an average can be used as test result.

To carry out the air permeability test, an air pressure was applied to the surface of the concrete through a test ring attached to the surface of the concrete and the rate of pressure decay was measured. From the data thus collected, an air permeability index was calculated, as described in reference 13. One air permeability test was performed on each test surface so that an average of three tests could be obtained for each experimental condition.

The Autoclam Sorptivity test involved bringing water into contact with the concrete surface and applying a nominal pressure of 0.02 bar and measuring the rate of water absorbed [13]. From the data thus obtained a sorptivity index was calculated, as described in reference 12. As in the case of the air

permeability test, one water absorption test was performed on each test surface so as to get an average of three test results for each experimental condition.

2.4.4 Accelerated carbonation test

One core from each block was used for the carbonation tests so as to get an average of three test results for each test condition. These cores were immersed in water for 3 days to ensure that they all had similar initial moisture content. They were then coated on their circumferential face with an epoxy emulsion to ensure that the ingress of carbon dioxide into the concrete could occur only through the test surfaces at each end of the cores. The cores were then oven dried at 50°C and 20% relative humidity for a week to remove moisture from them. Finally they were wrapped in cling film and conditioned at 70°C for 2 weeks to redistribute the remaining moisture so as to get a uniform internal relative humidity of ~65%.

The carbonation tests were carried out in an accelerated carbonation chamber and the specimens were exposed to a carbon dioxide concentration of 5% for 6 weeks to allow accelerated ingress of carbon dioxide at 20°C ($\pm 0.5^\circ\text{C}$) and 65% ($\pm 1\%$) relative humidity. At the end of 6 weeks, the cores were removed from the carbonation chamber, split along their length and the freshly broken surfaces sprayed with a 1% phenolphthalein indicator solution. The depth of carbonation, highlighted by the area that is clear, was measured to the nearest millimetre at seven equally spaced locations along the interface line. These values were averaged to give a depth of carbonation for each type of formwork for each core.

2.4.5 Chloride ingress

As with the carbonation testing, the cores were immersed in water for 3 days until the weight increase was stabilised. This was to ensure that all the samples had similar initial moisture content. They were then coated on their circumferential face with an epoxy emulsion to ensure that the ingress of chloride ions into the concrete could only occur

through the test surfaces at each end of the cores. The cores were then immersed in a 0.55 molar sodium chloride solution. The solution was replaced weekly to ensure that its concentration remained reasonably constant throughout the test. Because of the high moisture condition of the samples at the time of exposure to chloride, the primary transport mechanism by which chloride ingress took place was diffusion.

After the cores were removed from the salt solution at two different exposure periods, 100 and 178 days, the depth of penetration of chloride ions was determined (the details of the test samples are given in Table 3). This was done in two different ways, one was by spraying the concrete with silver

nitrate solution and the other was by carrying out profile grinding of the concrete [14]. Both these procedures are described below.

2.4.5.1 Silver nitrate test In order to carry out this test, one of the cores for each testing condition was removed from the 0.55 molar salt solution after 100 days. They were then split along their length and sprayed with a 0.1 molar silver nitrate solution. The concrete turned into a slightly lighter shade (lighter grey) where chloride ions were present and turned slightly darker where there was none. The depth of discolouration was measured, to the nearest millimetre at seven equally spaced locations along

Table 3 Test sample details for chloride test (0.45 and 0.5 w/c)

Exposure period (days)	Number of samples							
	Total	Form work		Use of form work			Test	
		CPF	IF	1	2	3	Diffusion	Spray ^a
100	12	6	–	2	–	–	1	–
				–	2	–	–	1
				–	–	–	1	–
				–	–	2	1	–
				–	–	–	–	1
				–	–	–	–	1
		–	6	2	–	–	1	–
				–	2	–	–	1
				–	–	–	1	–
				–	–	2	1	–
				–	–	–	–	1
				–	–	–	–	1
180	12	6	–	2	–	–	1	–
				–	2	–	–	1
				–	–	–	1	–
				–	–	2	1	–
				–	–	–	–	1
				–	–	–	–	1
		–	6	2	–	–	1	–
				–	2	–	–	1
				–	–	–	1	–
				–	–	2	1	–
				–	–	–	–	1
				–	–	–	–	1

^a Sprayed with silver nitrate to determine the depth of penetration of chloride

the chloride penetration line. These values were averaged to give a depth of penetration of chloride for each type of formwork for each core.

2.4.5.2 Profile grinding This test is more accurate than the silver nitrate test and was used to determine the chloride profile after both 100 and 178 days of exposure. A chloride profile shows how the amount of chloride ions (expressed as a percentage of the weight of concrete) vary, with depth, into the concrete.

Dust samples of the concrete were obtained using a profile grinder at 2 or 3 mm depth increments to a maximum depth of 25 mm from the concrete test surface and they were placed in plastic sampling bags. The chloride ions in the concrete dust were extracted using an acid extraction method, according to BS 1881: 124 [15]. The chloride content was then determined by carrying out the potentiometric titration. These values expressed as a percentage of the concrete mass were plotted against depth from surface of the cores to give chloride profiles (Fig. 3). Finally, an apparent diffusion coefficient (D_a) was calculated using a non-linear regression curve fitting [15]. The values of surface chloride concentration (C_s) and apparent diffusion coefficient (D_a) were determined for the measured chloride profiles by means of a non-linear regression analysis [15]. The curve fitting to the analytical solution of second Fick's law was done in accordance with the method of least square.

Fig. 3 Typical chloride profiles for Formtex CPF at 0.45 w/c

3 Results and discussion

3.1 Introduction

The results were averaged for each test surface (i.e. Formtex CPF surface and IF surface) of each mix so that the effect of experimental variations could be minimised. This also improved the clarity of the results and, hence, it was easier to see how the results differed with each experimental variable (type of formwork used, reuse of CPF and water-cement ratio). Due to the large number of variables for chloride test, only one test sample could be used.

3.2 Visual observation

When the blocks were removed from the formwork, a significant difference between the CPF and IF cast surfaces was evident. The CPF cast surfaces were completely free of blow holes, with the exception of a couple of blocks which had a very small number of blow holes. In contrast there was a significant number of blow holes in the conventionally cast surfaces. The CPF cast surfaces were darker and had a coarser texture than the conventionally cast surfaces. This darkening indicates a denser concrete and that the water-cement ratio of the surface layer of the blocks cast using the CPF liner has been lowered due to the combined effect of an increase in cement content and a decrease in water and air content [3, 7].

3.3 Compressive strength of the different batches of concrete

The effect of reusing the CPF liner was studied by manufacturing test blocks from three different batches of concrete for each water-cement ratio. The variability between the three batches was studied by determining the compressive strength of the concrete. Figure 4, which shows the average 28-day cube compressive strength of the three batches of concretes with 0.45 and 0.5 water-cement ratios, demonstrates that there was no significant variation between the three batches of concrete. The average compressive strength was around 50 and 40 N/mm², respectively, for the 0.45 and the 0.5 water-cement ratio.

Fig. 4 Average cube strength of each batch of concrete

Fig. 5 Average pull-off force for each test condition

3.4 Pull-off tensile strength

The average pull-off tensile strength for each test condition is presented in Fig. 5. The results clearly show that the CPF cast surfaces had higher surface tensile strengths than the IF cast surfaces. The results also demonstrate that the effect of the CPF was evident at both water-cement ratios, but the 0.5 water-cement ratio mix showed a slightly higher increase in strength (33% compared to 30% for the 0.45 water-cement ratio mix). The overall average increase in surface strength due to the use of the Formtex CPF was 31%.

Figure 6 also shows that, if the variability between the three batches of concrete can be accounted in terms of experimental variables, there was no difference between the first use and two subsequent uses of the Formtex CPF liner on the pull-off tensile strength. This suggests that the effectiveness of the liner was present during its use three times. This was not expected as it was presumed that the pores of the liner

Fig. 6 Air permeability index

would become blocked after the first use and, hence, its ability to drain off excess water and air would decrease. It is interesting to observe that the strength of concrete cast using Formtex CPF at 0.5 water-cement ratio was similar to (or better than) that cast using IF at 0.45 water-cement ratio.

3.5 Air permeability index

The results in Fig. 6 show that the air permeability index, K_a , is higher for the near surface concrete cast using IF. This means that these surfaces are much more permeable than those cast using the Formtex CPF. With the reuse of the liner, the performance of the Formtex CPF was slightly varying for both water-cement ratios. The average improvement (reduction) in air permeability due to reuse was around 56% for 0.45 water-cement ratio. However, for 0.5 water-cement ratio concrete the permeability increased for the second use. Because the effect of reuse of CPF was not consistent for the two water-cement ratios in this study, further investigation is required to verify this for a range of water-cement ratios.

3.6 Sorptivity index

Figure 7 shows that when the Formtex liner was reused twice, it did not result in any noticeable change in the sorptivity values. This suggests that Formtex can be used three times without detrimentally affecting its sorptivity. It can also be seen that the sorptivity index decreased with the use of the

Fig. 7 Sorptivity index

Formtex CPF at both water-cement ratios. The degree of improvement was 29% for 0.45 water-cement ratio and 43% for 0.5 water-cement ratio. As this test is a measure of the absorption of the concrete, it can be concluded that the intake of aggressive substances by capillary suction is likely to be reduced with the use of the Formtex CPF. Once again, it may be noted that the sorptivity index of 0.45 water-cement ratio concrete made with IF is similar to that of 0.5 water-cement ratio concrete made with the Formtex CPF.

3.7 Depth of carbonation

Figure 8 indicates a very significant reduction in depth of carbonation for concretes cast using the Formtex CPF compared to the conventionally cast concrete. In the case of the concrete cast with IF,

Fig. 8 Depth of carbonation

carbonation progressed to about 9 mm in 0.45 water-cement ratio concrete and ~13 mm in 0.5 water-cement ratio concrete. This was reduced to almost zero for both water-cement ratios when the Formtex CPF was used, resulting in a percentage improvement of 94 and 97% for the 0.45 water-cement ratio and the 0.5 water-cement ratio mixes, respectively. The average depth of carbonation in Formtex CPF cast concrete was about the same for both water-cement ratios, suggesting that the Formtex CPF was capable of preventing the ingress of carbon dioxide regardless of the water-cement ratios investigated in this work.

The effect of reusing the Formtex CPF liner twice on the depth of carbonation can also be seen in Fig. 8. Clearly the effectiveness of the CPF was not detrimentally affected when it was used three times at both water-cement ratios. The small increase in depth of carbonation with the third use of the Formtex CPF at 0.45 water-cement ratio is considered to be due to experimental variability because no such effect was observed at 0.5 water-cement ratio. However, this will have to be verified with more tests.

3.8 Chloride penetration resistance

3.8.1 Silver nitrate test

The depth of chloride ingress after 100 days of chloride ponding determined using the Silver Nitrate spray test is presented in Fig. 9. These results show how far chloride ions of a 0.55 molar salt solution were able to penetrate into the concrete at the end of

Fig. 9 Chloride penetration depth after 100 days of chloride ponding

the test regime. In the case of IF cast concretes, chloride ions were able to penetrate up to an average depth of 20 and 24.7 mm, respectively, for 0.45 and 0.5 water-cement ratios. All the concretes cast using the Formtex CPF had a depth of chloride penetration slightly under 15 mm, irrespective of the water-cement ratio. That is, the Formtex CPF was able to produce concrete with uniform chloride ion penetration resistance at both these water-cement ratios and the percentage reduction was about 25 and 40% for 0.45 and 0.5 water-cement ratio.

Figure 9 also demonstrates that the effectiveness of the CPF at reducing the depth of penetration of chloride ions did not change as the CPF liner was reused. Therefore, it can be concluded that Formtex can be used three times whilst retaining its beneficial effect in reducing the chloride ion ingress. However, it must be realised that the silver nitrate test is a qualitative test and hence these results must be used with caution. A better comparison of the different experimental variables is possible with the use of the apparent chloride diffusion coefficient, which is discussed in the next section.

3.8.2 Chloride profiles

The effect of the reuse of Formtex on chloride ion penetration is presented in the form of chloride profiles in Figs. 10 and 11 for 100 days and 178 days of exposure, respectively. These profiles were used to calculate the corresponding apparent chloride diffusion coefficients, which are presented in Figs. 12 and 13 for the two duration of exposure.

Figure 10b compares the three different uses of the CPF liner at both 0.45 and 0.5 water-cement ratios after 100 days of exposure to a 0.55 molar sodium chloride solution. The corresponding results for the IF are presented in Fig. 10a so that comparisons could be made of the two sets of data and the effect of the CPF identified. It would appear for the 0.45 water-cement ratio concrete that the second and third use of the CPF resulted in a slightly deeper penetration of chloride ions. However, a comparison with their counterparts for the IF would suggest that this variation was due to the effect of the concrete itself because there was deeper penetration of chloride ions in blocks 2 and 3 compared to block 1 in the case of

Fig. 10 Chloride profiles after 100 days of exposure

Fig. 11 Chloride profiles after 178 days of exposure

the IF. However, this will have to be verified with more tests. The results of the 0.5 water-cement ratio clearly illustrate that there was no detrimental effect on the performance of the CPF with two reuses of the Formtex liner.

The results in Fig. 10 provide an opportunity to validate the usefulness of the silver nitrate spray test. A close examination of the depths from the silver nitrate test in Fig. 9 and the corresponding profiles in Fig. 10 would indicate that the chloride content was almost negligible at depths highlighted by the silver nitrate spray test. Therefore, it can be concluded that this test is a very useful and conservative test to identify the resistance of OPC concretes to the penetration of chlorides.

A comparison between the two sets of data in Fig. 10 (i.e. Fig. 10a vs Fig. 10b) would suggest that there was more build up of chlorides near the surface for CPF formed concretes. Price [3] reported that the use of CPF results in an increased cement content and decreased water content (i.e. decreased water-cement ratio) nearer to the surface. Associated with these

changes, the chloride binding capacity of the matrix improves which explains the increased chloride build up in Fig. 10b nearest to the surface for CPF concrete can be expected. This, however, was not accompanied by a deeper penetration of chloride ions. That is, the finer pore structure obtained with the CPF acted as a physical barrier to the penetration of chloride ions. There was no penetration of chloride ions beyond 12 mm from the surface for the CPF, and in the case of the IF this depended on the water-cement ratio. Nevertheless, it was considered to be essential to investigate if deeper chloride penetration occurs with longer periods of exposure in the case of the CPF formed concretes. Therefore, profiles were obtained after 178 days of chloride exposure (Fig. 11).

When the corresponding profiles in Figs. 10 and 11 are compared, the following observations can be made.

1. For the IF, both the surface and the inner chloride content increased with the increased duration of exposure. Clearly there was greater penetration of chlorides at the higher water-cement ratio.

- In the case of CPF, the surface chloride content remained almost constant at both water-cement ratios between 100 and 178 days of exposure. However, the increased duration of exposure was accompanied by an increased depth of chloride ingress and this was higher at 0.5 water-cement ratio.
- The reuse of CPF had a slight detrimental effect on 0.45 water-cement ratio concrete. However, this was not noted for 0.5 water-cement ratio concrete.

Naturally the above results are alarming because the protection provided by the CPF could depend on the duration of exposure. However, it must be noted that the chloride content at deeper parts is smaller in the case of CPF cast concrete compared to the IF cast concrete. Therefore, CPF is likely to provide a longer service life.

The apparent diffusion coefficients calculated based on the above two sets of profiles for the 100 and the 178 days of exposure are presented in Figs. 12 and 13, respectively. As with all the previous results, these results show that the concrete cast using the Formtex CPF was of better quality than cast using the conventional formwork. Using the CPF yielded an average improvement of 55% for the 0.45 water-cement ratio concrete and 66% for the 0.5 water-cement ratio concrete.

Further to the trends of profiles in Figs. 10 and 11, the apparent chloride diffusion coefficients in Figs. 12 and 13 would highlight that there was a gradual but modest decrease in performance of the Formtex liner with each subsequent use, with the exception of the

Fig. 12 Apparent chloride diffusion coefficient (100 days of exposure)

Fig. 13 Apparent chloride diffusion coefficient (178 days of exposure)

0.5 water-cement ratio mixes exposed to chlorides for 100 days. A closer examination of the results would suggest that the increase in apparent chloride diffusion coefficient could be related to the quality of the concrete itself because an increase in D_a could be seen for the IF concrete as well. However, the effect of reuse on lower water-cement ratio concretes will have to be further investigated.

4 Conclusions

On the basis of tests carried out, it can be concluded that the use of Formtex CPF produces concrete surfaces of higher quality, with significantly higher strength and durability properties than concrete that is cast using conventional IF.

The performance of the Formtex CPF was better at the higher water-cement ratio. The percentage improvement in test results from using the Formtex CPF in comparison to the conventional IF is summarised in Table 4.

Table 4 Percentage improvement in test results from using Formtex CPF liner

Measured property	0.45 w/c	0.5 w/c
Tensile strength	30	33
Air Permeability	56	64
Sorptivity (water absorption)	29	43
Carbonation depth	94	97
Chloride penetration depth	27	43
Chloride diffusion coefficient (100 days)	57	70
Chloride diffusion coefficient (178 days)	53	62

The effect of reusing the Formtex was not clear from this study. Mostly, in the case of higher water-cement ratio concrete, there was no clear reduction in quality of concrete. However, this was not the same in the case of lower water-cement ratio concrete. This will have to be investigated further.

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