An investigation into the Performance of Formtex Controlled Permeability Formwork and Effects of Its Reuse

Final Report

by

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Executive Summary

The effects of the reuse of Formtex Controlled Permeability Formwork (CPF) liner on properties of concrete related to strength and durability were investigated at two different water-cement ratios and the results are reported in this document. Concrete was cast using the CPF and impermeable formwork (IF) so that comparisons could be made between the two.

The strength was assessed using the Limpet pull-off tester and both the air permeability and 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 Formtex CPF increases the surface strength and durability of concrete compared to the impermeable formwork. There was an almost complete elimination of blowholes. The surface permeability of concrete cast using CPF was reduced and its resistance to ingress of both carbon dioxide and chlorides increased. The advantageous effect of Formtex CPF was most evident in concrete of higher water cement ratio. With the reuse of the Formtex liner once, that is a total of two uses, the performance of the CPF remained almost the same. However, it must be noted that there is a need to clean the CPF liner after each use.

1. Aims and Objectives

The aim of the test programme was to assess the effect of the reuse of Formtex controlled permeability formwork liner (CPF) on its performance in improving the strength, permeability and the durability of concrete. In order to study this, the following specific objectives were considered:

1. To compare strength, permeability and durability of concrete cast using Formtex CPF formwork to that cast using conventional impermeable formwork at different water-cement ratios.

2. To determine the effect of reusing the Formtex CPF on the above findings.

The scope of the work was limited to two OPC concrete mixes of different water cement ratios. The Formtex CPF was reused once and the findings are based on a laboratory investigation.

2. Formtex

Formtex is a CPF liner manufactured by a Danish company called Fibertex. It is a flexible fabric made from polypropylene fibres (Fig. 1). It is two-sided with a permeable side allowing water and air to pass through and a filter side retaining concrete particles. The pore size has been designed to be slightly smaller than the size of the particles in the concrete [1].

Fig. 1 Formtex CPF Liner

3. Experimental Programme

3.1 Experimental Variables

In order to satisfy the aims and objectives stated in section 1, three experimental variables were considered.

The first variable was the formwork used when casting the blocks. For each mix, concrete was cast on conventional impermeable formwork and on formwork covered in the permeable Formtex CPF membrane. The concrete surface cast using impermeable formwork will be referred to as the impermeable formwork face or IF face and the concrete surface cast using the Formtex CPF membrane will be referred to as the CPF face.

The second experimental variable was the water-cement ratio for the concrete mix. Two water-cement ratios were investigated, 0.45 and 0.5, in order to determine how the performance of Formtex CPF liner varied with water cement ratio.

Lastly, the Formtex CPF liner was reused once, for each water cement ratio, to establish how its effectiveness varied as it was reused.

All the tests detailed in section 4 are intended to determine how these variables affected the ability of Formtex CPF liner to improve the strength and durability related properties of concrete.

3.2 Layout of the Experimental Programme

Each use of the Formtex CPF membrane involved casting three blocks using the plywood moulds detailed in section 3.3. It was decided to cast three blocks in each mix so that there would be sufficient concrete to carry out all the tests required and ensure errors due to variability were minimised. Figure 2 shows the designation of concrete mixes and the related combination of the experimental variables. As for each mix three blocks were cast, altogether 12 blocks were cast.

3.3 Design of Formwork

Plywood formwork measuring 150x250x750mm was used. The 250x750mm surfaces were attached to the rest of the mould by wing-nuts to facilitate easy dismantling of the moulds and removal of the concrete blocks. One of these 250x750mm surfaces was covered on the inside with the Formtex CPF liner while the opposite surface was conventional impermeable formwork, consisting of oiled plywood (Fig. 3). Therefore, each block cast had opposite surfaces with one surface conventionally cast and the other cast using CPF, where concrete properties could be directly compared. The Formtex CPF liner was stretched taut over the plywood surface of the unassembled mould and firmly attached using a staple gun, as suggested by the manufacturer.

3.4 Concrete Mixes

The two water-cement ratios investigated, viz. 0.45 and 0.5, were designed to have cube strengths of 40 N/mm^2 and 30 N/mm^2 respectively. Initially a 0.4 water cement ratio mix was chosen to establish the effect the Formtex CPF would have on a dry mix. However, this was found to be unworkable so the water cement ratio was increased to 0.45. The 0.5 water cement ratio was chosen as it was considered to be a reasonably wet mix and would establish how well the CPF would perform in these conditions. The mixes were designed using the DoE method [2] and the proportions are shown in Table 1. A superplasticiser at a dosage of 1% of the weight of cement was added to the 0.45 water cement ratio mix to make it workable.

3.5 Casting

In order to control the water content of the mix, the aggregates used to manufacture the blocks were oven dried at 60°C for 4 days and allowed to cool for 24 hours so that they would be dry.

Extra water was then added when mixing to allow for absorption by the aggregates. This amounted to 1% of the weight of both the fine and the 10mm aggregates and 0.5% of the weight of the 20mm aggregates.

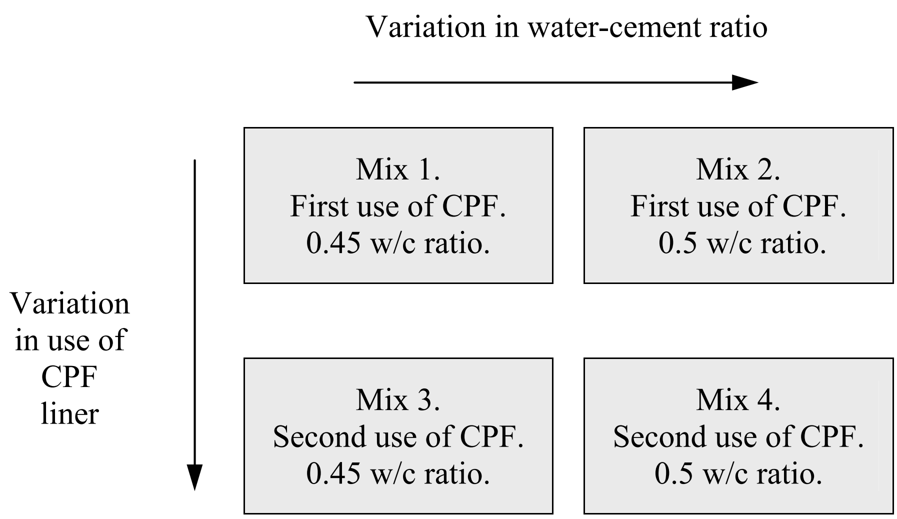

Fig. 2 Layout of the experimental programme

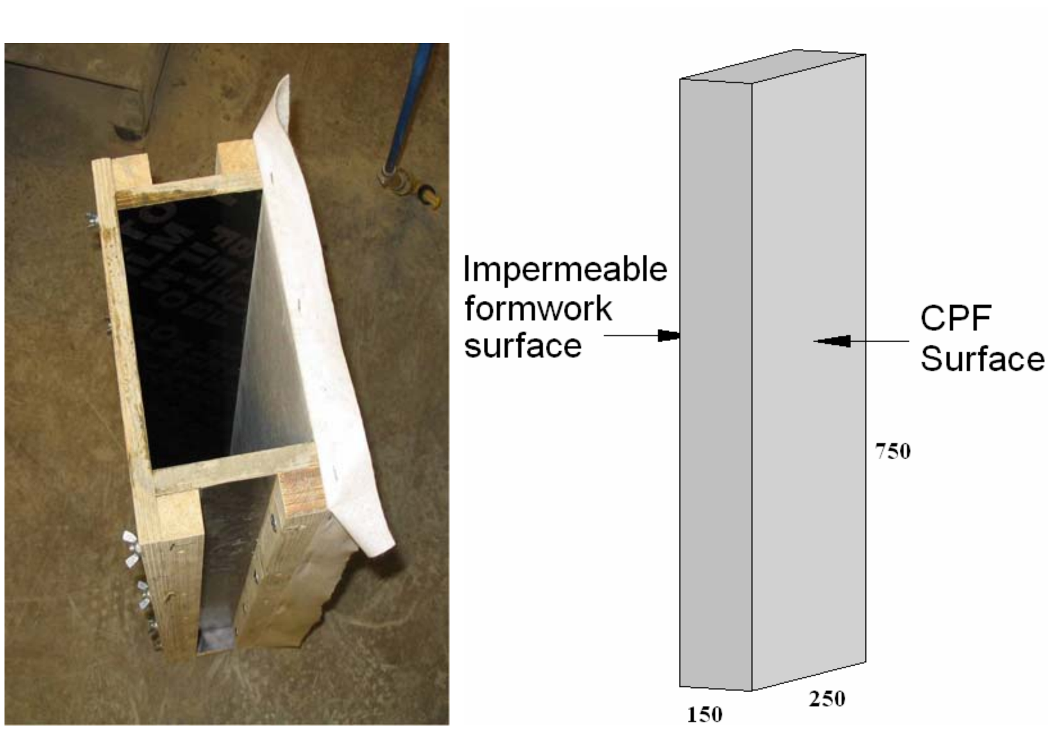

Fig. 3 Details of the mould and test specimens

Table 1 Concrete mix proportions in kg/m^3

Water-cement ratio	0.45	0.5
Cement (OPC)	445	450
20mm aggregate	855	840
10mm aggregate	425	420
Fine aggregate (natural sand)	525	515
Water	200	225
Superplasticiser	4.45	0

Before casting, the conventional plywood formwork was oiled to prevent the concrete sticking to it and it was then assembled. 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 100mm cubes were also cast in order to obtain the concrete compressive strength.

After 24 hours the formwork was stripped and the blocks removed from the moulds. The CPF liner 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. Figure 4 shows typical three concrete blocks manufactured each time for a mix.

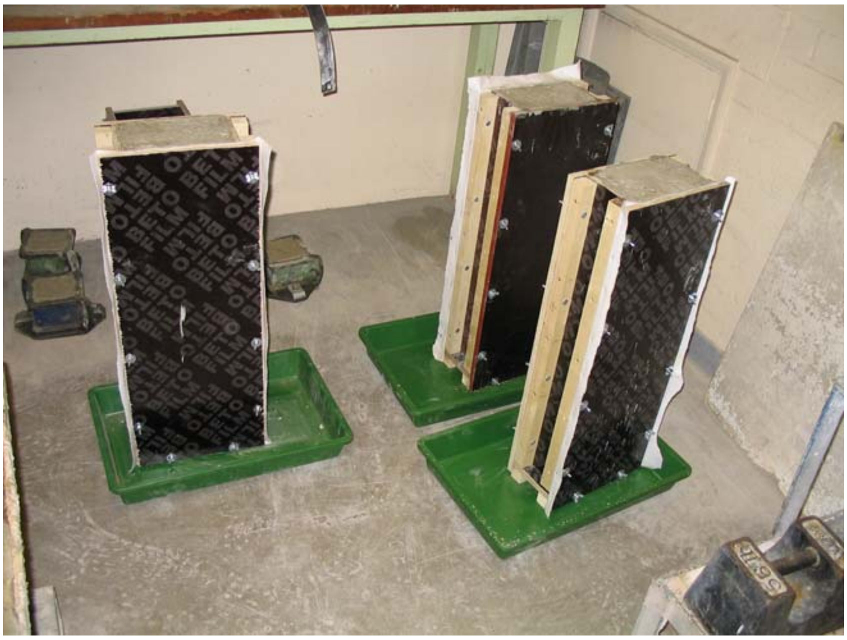

Fig. 4 The concrete blocks just after casting

3.6 Coring

The 150x250x750mm blocks cast were used for pull-off tests, air permeability tests and sorptivity tests as detailed in section 4. When these tests were completed two cores of 100mm diameter were removed from each block, to be used for carbonation and chloride ingress tests. The cores were drilled through the 250x750mm face so that the test surfaces were on each end of the cores.

4 Test Programme

4.1 Introduction

A number of tests were carried out on the concrete blocks to assess their strength and durability properties. All the tests were carried out on the 250x750mm surfaces which were cast using either conventional formwork or Formtex CPF liner. The tests completed were as follows.

- Pull-off tests
- Air permeability tests
- Water absorption tests
- Carbonation tests
- Chloride ingress tests

In addition, compressive strength was determined using standard cubes at the age of 28 days.

4.2 Compressive Strength Testing

The cubes were cured in a water bath at 20°C (±1^0C) for 28 days and crushed to determine the compressive strength.

4.3 Pull-Off Strength Testing

Pull-off tests were completed on the specimens after 28 days. These tests are used to indicate the strength of the concrete in the near-surface zone of the blocks. As the Formtex CPF is meant to lower the water-cement ratio of the near-surface zone, these tests are particularly relevant. Direct comparison of the CPF formed and conventional formwork formed surfaces can be easily made.

Pull-off testing was carried out using Limpet, a pull-off test instrument developed by Queen's University Belfast [3]. This is a partially destructive test used to find the surface strength of the concrete. The test involves bonding a circular steel probe of 50mm diameter to the surface of the concrete using an epoxy resin adhesive that is stronger in tension than the concrete surface (Fig. 5a). An increasing tensile force is applied, using the Limpet (Fig. 5b), until the concrete fails (Fig. 6). The force required for failure is displayed on a display on the Limpet and a nominal tensile strength can be calculated by dividing the pull-off force with the area of the probe. This strength can be converted to an equivalent compressive strength using calibration tables.

Pull-off probes were attached to each test surface using Febset epoxy resin adhesive. Two probes were used on each surface so that six results could be averaged for each mix and thereby experimental errors minimised. The total number of pull-off tests completed was 48, as there were 2 probes on each test surface, 2 test surfaces per block, 3 blocks per mix and 4 mixes. The probes were attached 200mm from each end of the blocks and allowed to set for 48 hours. They were then pulled off using the Limpet and the required force was recorded.

Fig. 5a Pull-off probe

Fig. 5b Limpet Pull-off Tester

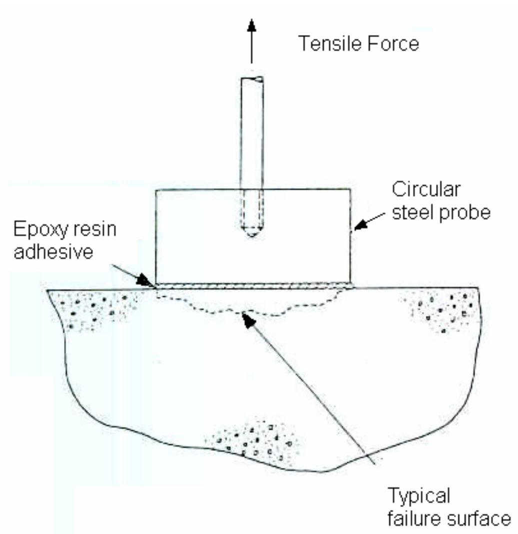

Fig. 6a Principle of Pull-off test

Fig. 6b Concrete surface after a pull-off test

4.4 Air Permeability Testing

Permeability is an important property of concrete related to durability. If concrete is too permeable aggressive substances will easily penetrate and weaken it. Two types of permeability tests were performed on the specimens, viz air permeability and water absorption (sorptivity) tests. These tests were performed on the blocks after they had been oven dried at 50°C and 20% relative humidity for two weeks. The blocks were placed in the oven immediately after the pull-off tests were completed.

Autoclam Permeability System (Fig. 7), an instrument developed by Queen's University Belfast [4], was used to measure the air permeability of the concretes. The Autoclam applies an air pressure to the surface of the concrete and measures the rate of pressure dissipation.

One air permeability test was performed on each test surface so that an average of three tests could be obtained for each mix. Therefore, altogether 24 tests were completed. In order to perform the test, a rubber ring was placed centrally at the test location and a circular metal plate (base ring) was clamped on top. The Autoclam apparatus was bolted onto the base ring. The air pressure applied to the concrete within the rubber ring was increased to 0.5 bars by means of a syringe. The decay of pressure was monitored over a 15 minute period, the pressure being noted every minute for the duration of the test.

The air permeability index is given by [5]:

$$K_a = \text{Ln}\,(P_0 / P_1) / t$$

where P_0 is the initial pressure, P_1 is the final pressure and t is the time interval. To calculate K_a, a graph of $\log_e$(pressure) versus time was plotted for each Autoclam test. The negative of the slope of each graph was obtained and reported as K_a.

Fig. 7 The Autoclam Permeability System attached to the test block

4.5 Water Absorption (Sorptivity) Test

This test also was carried out using the Autoclam Permeability System and gives the sorptivity index. This is a measure of the capillary suction of the concrete. A high sorptivity index indicates increased capillary suction and therefore increased susceptibility to water-borne salts and other aggressive liquids. The test involves bringing water into contact with the concrete surface and applying a nominal pressure of 0.02 bar and measuring the rate of water absorbed [4].

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 3 test results for each mix. In order to carry out the test, a rubber ring was placed centrally at the test location and a circular metal plate (base ring) was clamped on top. The Autoclam apparatus was bolted onto the base ring. The chamber between the concrete and Autoclam was filled with water and the pressure was increased to 0.02 bar. The volume of water absorbed was measured every minute for 15 minutes.

The Sorptivity index is given by [5]:

$S = V / T^{½}$

where V is the quantity of water that has entered into the concrete and T is the corresponding time.

The relationship between water absorbed and square root of the time is linear, so the sorptivity index is obtained by plotting V versus $T^{½}$ and calculating the gradient of the best fit line [5].

4.6 Carbonation Test

Carbonation tests were conducted to determine the effectiveness of Formtex CPF liner at improving the resistance of concrete to carbonation. 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 a 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 on 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 two weeks to redistribute the remaining moisture so as to get a uniform internal relative humidity of approximately 65%.

Testing the resistance to carbonation in normal atmospheric conditions would take a long time because the concentration of carbon dioxide in the atmosphere is about 0.03%. In order to complete the tests within a reasonable time, an accelerated carbonation test was carried out using a carbonation chamber at a carbon dioxide concentration of 5%. The cores were placed in the carbonation chamber at 20°C (±0.5°C)and 65% (±1%) relative humidity for six weeks to allow accelerated ingress of carbon dioxide.

After the cores were removed from the carbonation chamber they were split along its length and sprayed with phenolphthalein indicator solution (Fig. 8). 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 end of each core.

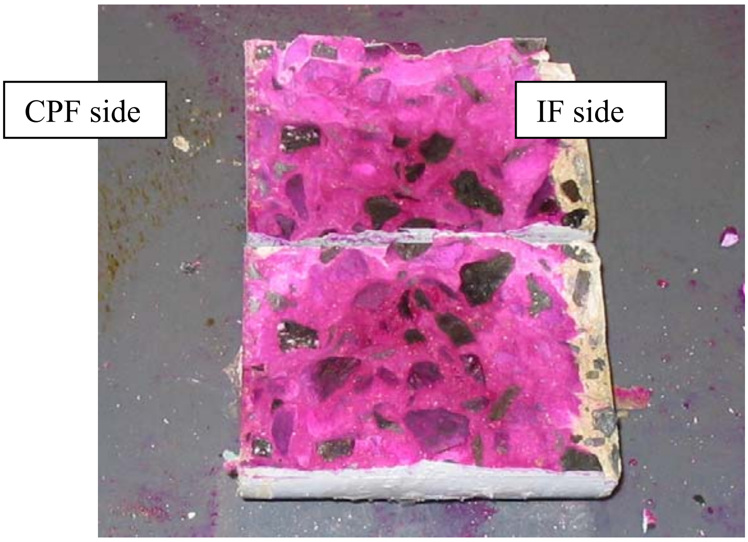

Fig. 8 Cores split into two halves sprayed with phenolphthalein indicator solution

4.7 Chloride Ingress

To establish the effectiveness of Formtex CPF liner at improving the resistance of concrete to ingress of chloride ions, the concrete was subject to chloride penetration tests. One core from each block was used for the tests so as to test three cores for each test condition. As with the carbonation testing, the cores were immersed in water for 3 days to ensure that they all had a 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 on each end of the cores. The cores were then placed in a 0.55 molar salt solution. The solution was replaced weekly to ensure that its concentration remained reasonably constant throughout the test. Chloride ions can migrate into concrete by absorption and diffusion, but in this test the primary transport mechanism was diffusion because the cores were saturated before the testing began and remained saturated for the duration of the test.

After the cores were removed from the salt solution at two different exposure periods, the depth of penetration of chloride ions was determined. This was done in two different ways, one was to spray the concrete with silver nitrate and the other was to carry out profile grinding of the concrete.

4.7.1 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 (Fig. 9). The depth of penetration was measured, to the nearest millimetre, at seven equally spaced locations along the chloride penetration line. These values were averaged to give a depth of penetration for each end of each core.

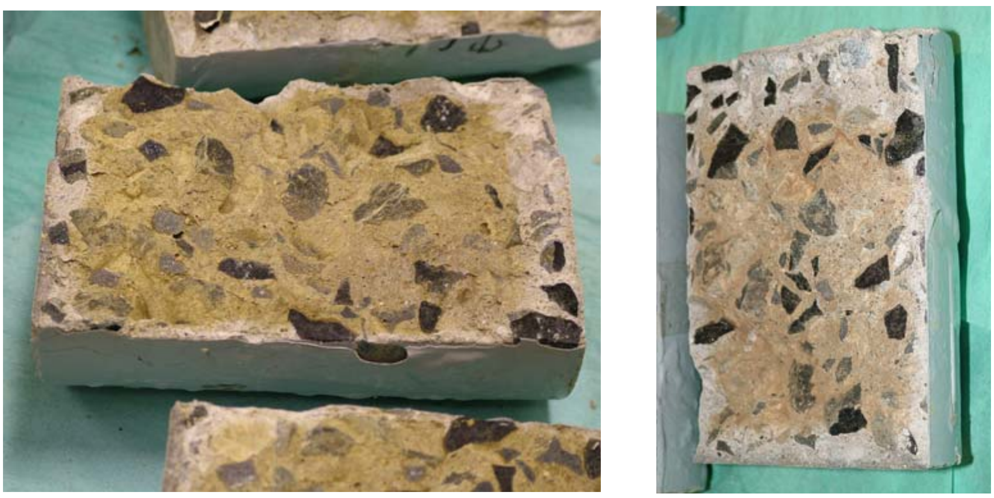

Fig. 9 Silver nitrate test showing depth of penetration of chloride ions

4.7.2 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 (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 [6] at 2 or 3mm depth increments to a maximum depth of 25mm from the concrete test surface and the dust samples were collected and placed in plastic sample bags. Figure 10 shows a core after the dust samples were collected. These dust samples were then analysed in the laboratory to determine the chloride content, as described below.

The chloride ions in the concrete dust were extracted using an acid extraction method according to BS 1881: 124 [7]. The procedure was as follows:

1. Approximately 1 gram of dust sample was accurately weighed into a conical flask.
2. 50ml of deionised water and 10ml of 1 N nitric acid was added to the conical flask to disperse the sample
3. The sample was stirred and boiled for 5 minutes.
4. During boiling of the sample 50 ml of hot deionised water was added to the solution.
5. After being allowed to cool, the sample was filtered to remove the dust.
6. The sample was titrated using a Metrohm automatic potentiometric titrator (Fig. 11) to determine the chloride content.

The chloride content was expressed as a percentage of the concrete mass.

Fig. 10 Core after dust samples were removed.

Fig. 11 Metrohm Titrator

The chloride content was plotted against depth from surface of the cores to give the chloride profile (Fig. 12). Finally, the apparent diffusion coefficient (D_a) was calculated. This is a measure of the concrete's ability to resist ingress of chloride ions. It was calculated using a non linear regression curve fitting and its derivation, as given below [8]:

The chloride profiles were modified using non-linear curve fitting method (NT-BUILD 443). The values of surface chloride concentration (C_s) and apparent diffusion coefficient (D_a) were determined by fitting equation (1) to the measured chloride profile by means of a non-linear regression analysis.

$$C_C(x,t) = C_s - (C_s - C_i).erf\,(x / \sqrt{4.D_a.t}) \qquad \text{Eq. (1)}$$

where,

$C_c(x,t)$ is the chloride concentration expressed in percentage weight of concrete, measured at the depth x at the exposure time, t
C_s is the boundary condition at the exposed surface (surface chloride concentration)
C_i is the initial chloride concentration measured
x is the depth below the exposed surface (mm)
D_{app} is the apparent diffusion coefficient
t is the exposure time in seconds.
erf is the error function.

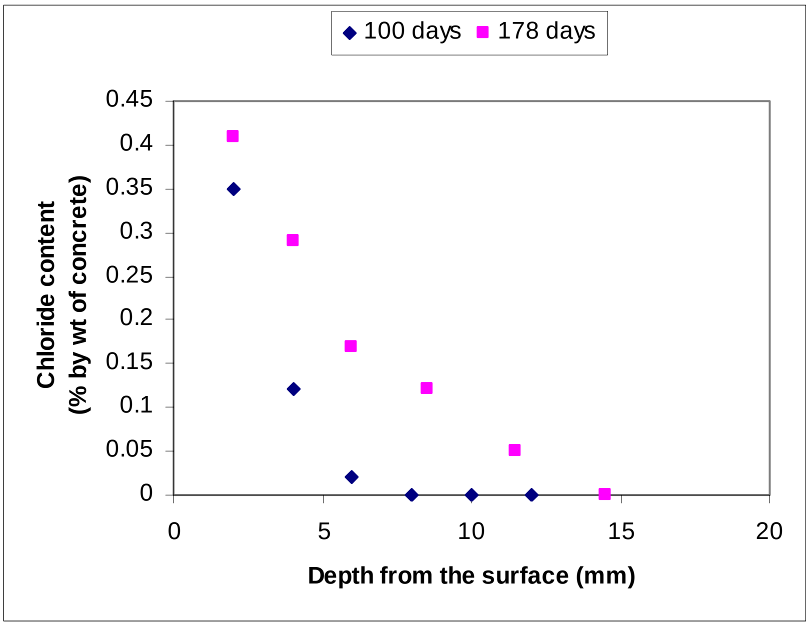

Fig. 12 Typical chloride profiles for Formtex CPF at 0.45 w/c

The curve fitting of Eq. (1) was done in accordance with the method of least square, Eq. (2)..

$$S = \sum_{n=1}^{N} \Delta C^2(n) = \sum_{n=1}^{N} (C_m(n) - C_c(n))^2 \qquad \text{Eq. (2)}$$

where,

S is the sum of squares to be minimised
N is the number of concrete layers used in the curve fitting
$\Delta C(n)$ is the difference between the measured and the calculated chloride concentration of the nth concrete layer
$C_m(n)$ is the measured chloride concentration of the nth concrete layer
$C_c(n)$ is the calculated chloride concentration in the middle of the nth concrete layer

5. Results and Discussion

5.1 Introduction

All test data obtained are reported in the Appendix. The results were averaged for each test surface (i.e. Formtex CPF surface and impermeable formwork surface) of each mix and discussed in this section. This reduces experimental variations and improves the clarity of the results as it is more easily seen how the results differ with each experimental variable (type of formwork used, reuse of CPF and water-cement ratio).

5.2 Visual Observation

When the formwork was removed from the blocks 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 that 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 (Figs. 13 and 14). This darkening indicates a denser concrete and that the water-cement ratio of the surface layer of the blocks cast using the CPF liner was lowered.

Fig. 13 Concrete cast using IF

Fig. 14 Concrete cast using Formtex CPF

5.3 Compressive Strength Test Results

The two mixes cast with water-cement ratios 0.45 and 0.5 were meant to have cube strengths of 40 N/mm^2 and 30 N/mm^2 respectively. Figure 15 shows the average compressive strength of the concrete used to manufacture the test blocks. The results of the compressive strength tests show that the two water-cement ratio mixes have compressive strengths of around 50 N/mm^2 and 40 N/mm^2 respectively. These results are higher than expected, but the results demonstrate that the two batches of concrete used to study the effect of the reuse of CPF had reasonably consistent strengths.

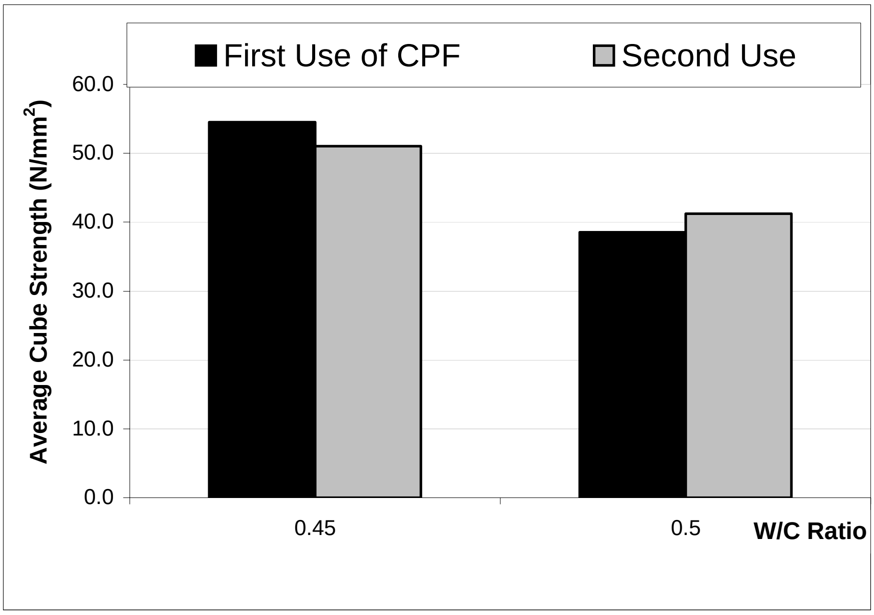

Fig. 15 Average cube strength of each batch of concrete

5.4 Pull-Off Test Results

The average pull-off test result for each test condition is presented in Fig. 16. The results clearly show that the Formtex CPF cast surfaces had higher surface strengths than the IF cast surfaces. The results also demonstrate that the effect of Formtex was evident at both water-cement ratios, but the 0.5 w/c mix showed a slightly higher increase in strength (33% compared to 30% for the 0.45 w/c mix). The overall average increase in surface strength due to the use of the Formtex CPF was 31%.

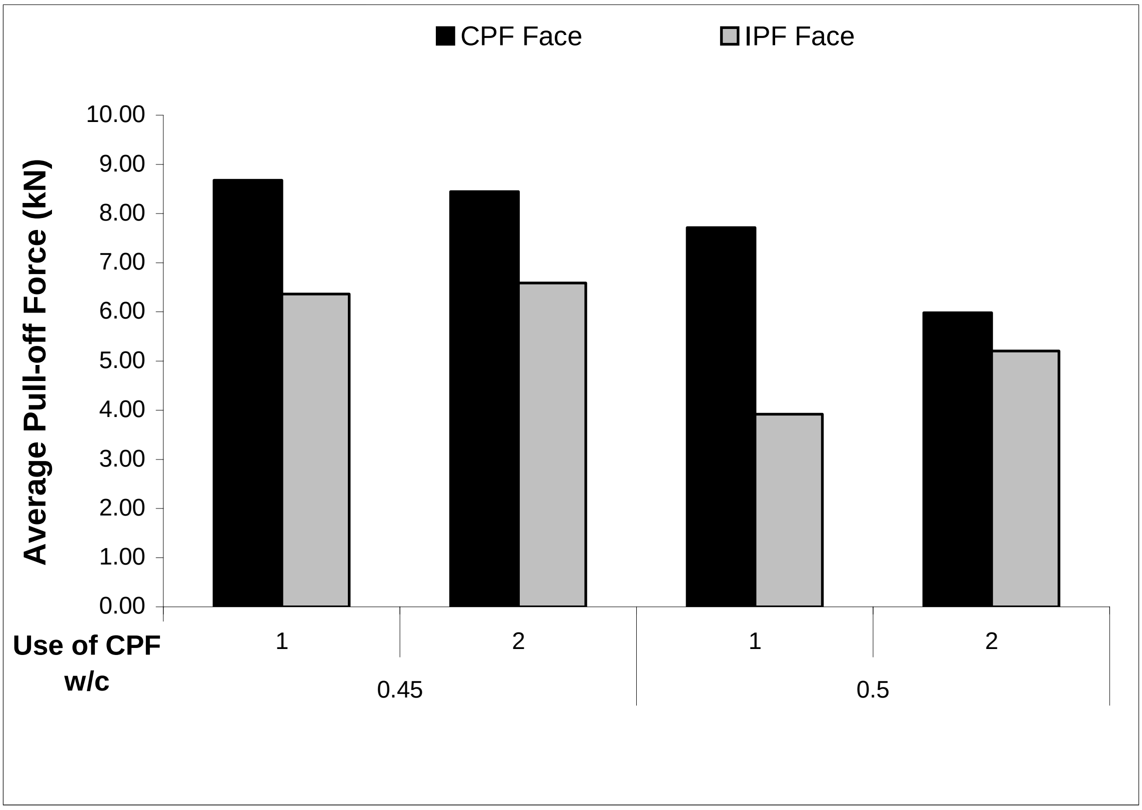

Fig. 16 Average pull-off force for each test condition

Figure 16 shows that, except for the experimental variability, there was no difference between the first use and second use of the Formtex CPF liner on the pull-off strength, suggesting that the effectiveness of the liner was present during its use two times. This was surprising as it was presumed that the pores of the liner 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 w/c was similar to that cast using impermeable formwork at 0.45 w/c.

5.5 Air Permeability Test Results

The air permeability results in Fig. 17 show that the air permeability index, K_a, is higher for the near surface concrete cast using impermeable formwork. 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 CPF was found to improve at 0.45 w/c and no detrimental effect was observed at 0.50 w/c.

The results show a variation in the air permeability index between the two w/c. The surfaces cast using impermeable formwork of the 0.5 w/c ratio mixes have much higher permeability than the CPF cast surfaces of the 0.5 w/c ratio mixes. The K_a values for the concrete cast using impermeable formwork in this case are 64% greater than the corresponding CPF face. In the case of 0.45 w/c ratio mix this reduction is approximately 56%. This shows that the CPF is more effective at reducing K_a values of high w/c mixes. In other words the effect of the CPF is more pronounced in the 0.5 w/c mix.

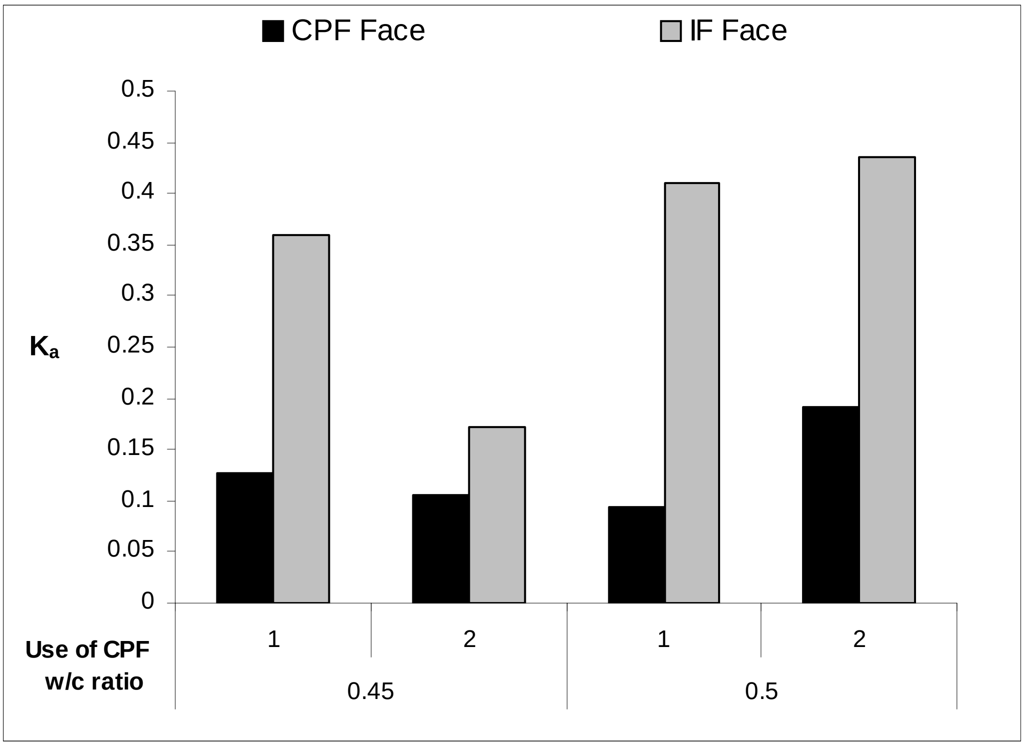

Fig. 17 Air Permeability Index (K_a)

5.6 Sorptivity Test Results

Figure 18 shows that the sorptivity index decreased with the use of Formtex CPF at both water-cement ratios. The degree of improvement was 29% for 0.45 w/c and 43% for 0.5 w/c. When the Formtex liner was reused, it did not result in any noticeable change in the sorptivity values, suggesting that Formtex can be used once without detrimentally affecting its desirable properties, viz drainage of water and air from the covercrete. 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 CPF. Once again, it may be noted that the sorptivity index of 0.45 w/c concrete made with IF is similar to that of 0.5 w/c concrete made with the CPF.

5.7 Carbonation Results

The depth of carbonation in Fig. 19 show a very significant reduction from the conventionally cast concrete to that cast using CPF. In the case of concrete cast with IF, carbonation progressed to about 9mm in 0.45 w/c concrete and approximately 13mm in 0.5 w/c concrete. This was reduced to almost zero for both water-cement ratios when Formtex CPF was used, resulting in percentage improvements of 94% and 97% for the 0.45 w/c and 0.5 w/c mixes respectively. The average depth of carbonation in 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 water-cement ratio.

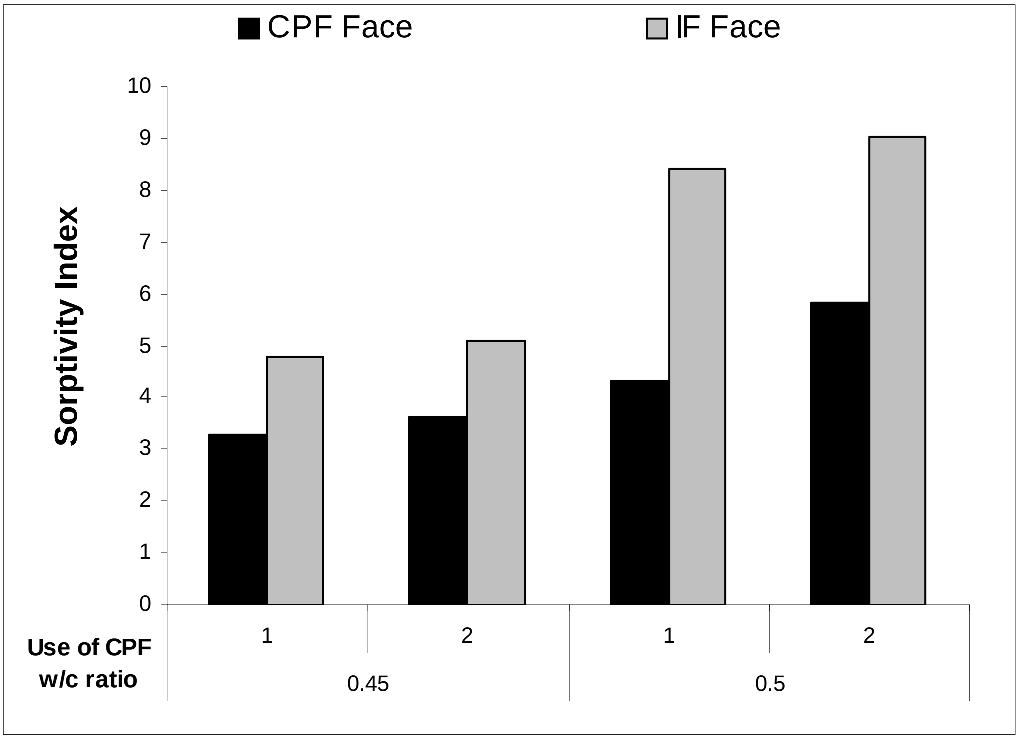

Fig. 18 Sorptivity Index

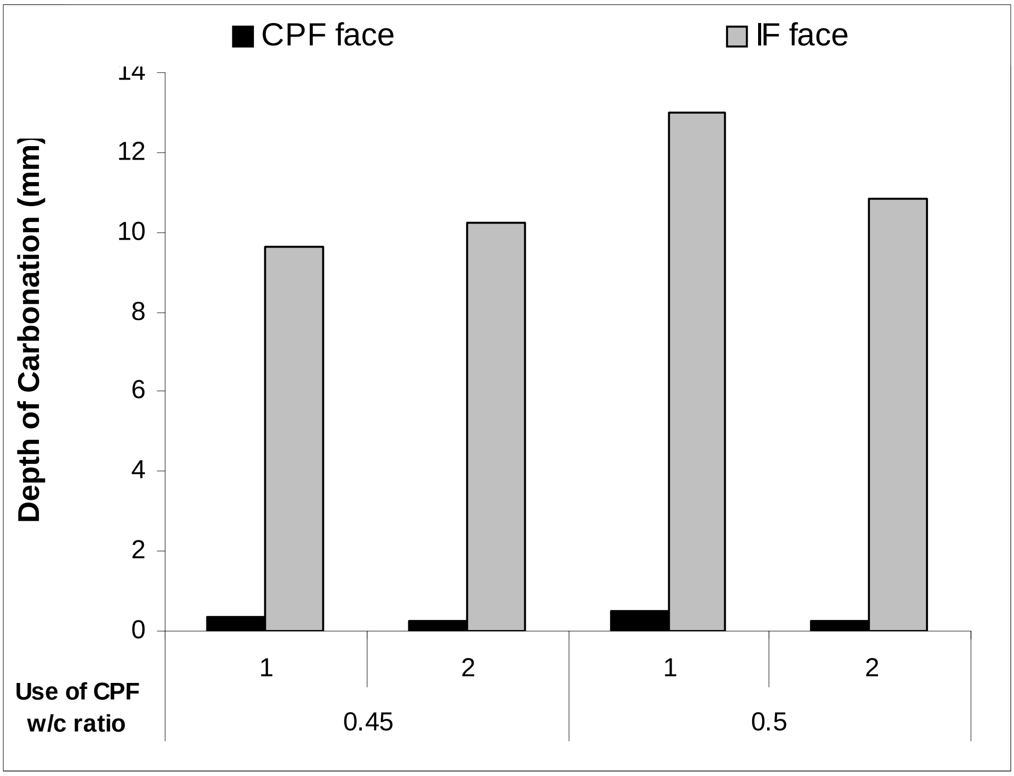

Fig. 19 Depth of Carbonation

The effect of reusing the Formtex CPF liner on the depth of carbonation in Fig. 19 would clearly indicate that its effectiveness was not detrimentally affected at both water-cement ratios.

5.8 Chloride Ingress Results

5.8.1 Silver Nitrate Test

The depth of chloride ingress after 100 days of chloride ponding is presented in Fig. 20. 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 the test duration. In the case of IF cast concretes, the chloride ions were able to penetrate up to an average depth of 24.7mm in the case of 0.5 w/c concrete and about 20mm in the case of 0.45 w/c concrete. All of the concrete cast using Formtex CPF had depth of chloride penetration slightly under 15mm, irrespective of the w/c. That is, Formtex CPF was able to produce concrete with uniform chloride ion penetration resistance at both these water-cement ratios.

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 once 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.

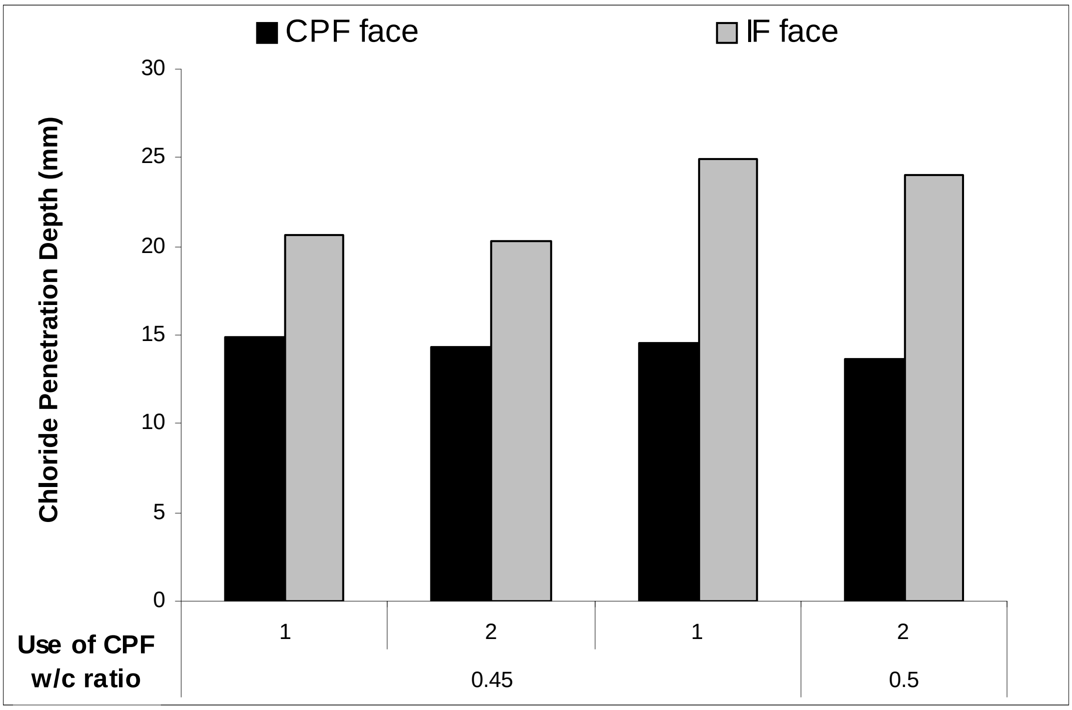

Fig. 20 Chloride penetration depth after 100 days of chloride ponding

5.8.2 Chloride Profiles

The effect of the reuse of Formtex on chloride ion penetration is presented in the form of chloride profiles in Figs. 21 and 22 for 100 days and 178 days of exposure respectively. These profiles were used to calculate the corresponding apparent chloride diffusion coefficients, as described in section 4.7.2, which are presented in Figs. 23 and 25 for the two duration of exposure.

Figure 21(b) compares the two different uses of the CPF liner at both 0.45 and 0.5 water-cement ratios after 100 days of exposure to 0.55 molar sodium chloride solution. The corresponding results for IF are presented in Fig. 21(a) 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 w/c concrete that the second use of the CPF resulted in a deeper penetration of chloride ions. However, a comparison with their counterparts for the IF would suggest that this variation is the effect of the concrete itself because there was deeper penetration of chloride ions in block 2 compared to block 1 in the case of IF. The results of 0.5 w/c clearly illustrate that there was no detrimental effect on the performance of the CPF with reuses of the Formtex liner.

(a) Impermeable formwork (b) Formtex CPF

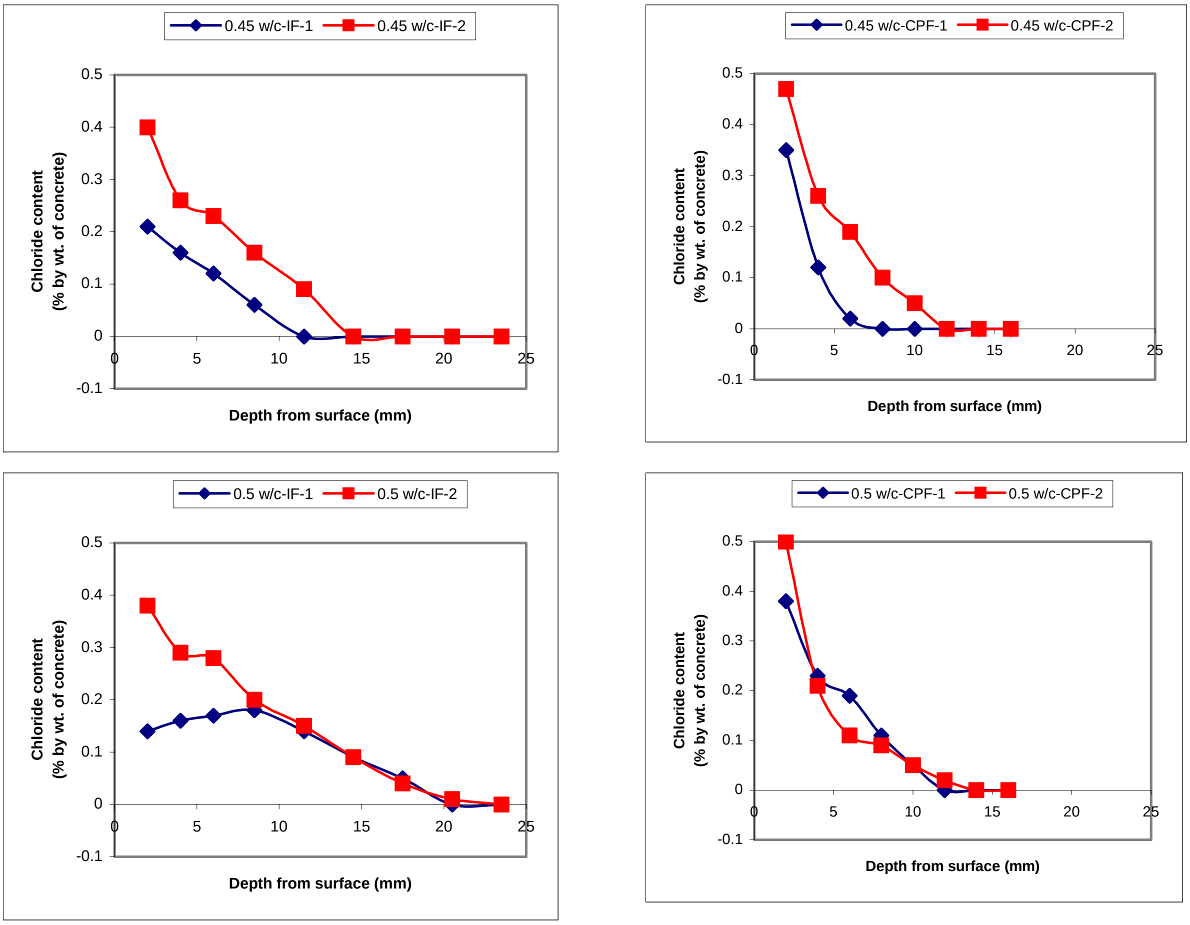

Fig. 21 Chloride profiles after 100 days of exposure

A comparison between the two sets of figures would suggest that there was more build up of chlorides near the surface for CPF formed concretes. This, however, has not accompanied by a deeper penetration of chloride ions. Therefore, the finer pore structure obtained with the CPF acted as a physical barrier to the penetration of chloride ions. There was no penetration of chlorides beyond 12mm from the surface for the CPF, but this depended on the water-cement ratio for the IF. Nevertheless, it was considered to be essential to investigate profiles for a longer period of exposure in order to check if chloride ions are withheld in the zone of concrete very close to the surface for CPF. These profiles are presented in Fig. 22.

In Fig. 22, there was a small increase in the depth of penetration of chloride ions with the reuse of the Formtex liner. An almost similar trends in profiles were obtained with the two uses of the Formtex liner at both water-cement ratios, with the 0.5 w/c concretes indicating a slightly deeper penetration of chloride ions. It can be noted that whilst the surface chloride content remained almost constant at the 100 days of exposure levels for both w/c in the case of CPF concretes, it slightly increased from 100 days to 178 days, with associated deeper penetration of chloride ions, for the IF concretes. At both w/c, the CPF concretes performed better than the IF concretes in resisting deeper penetration of chloride ions.

(a) Impermeable formwork (b) Formtex CPF

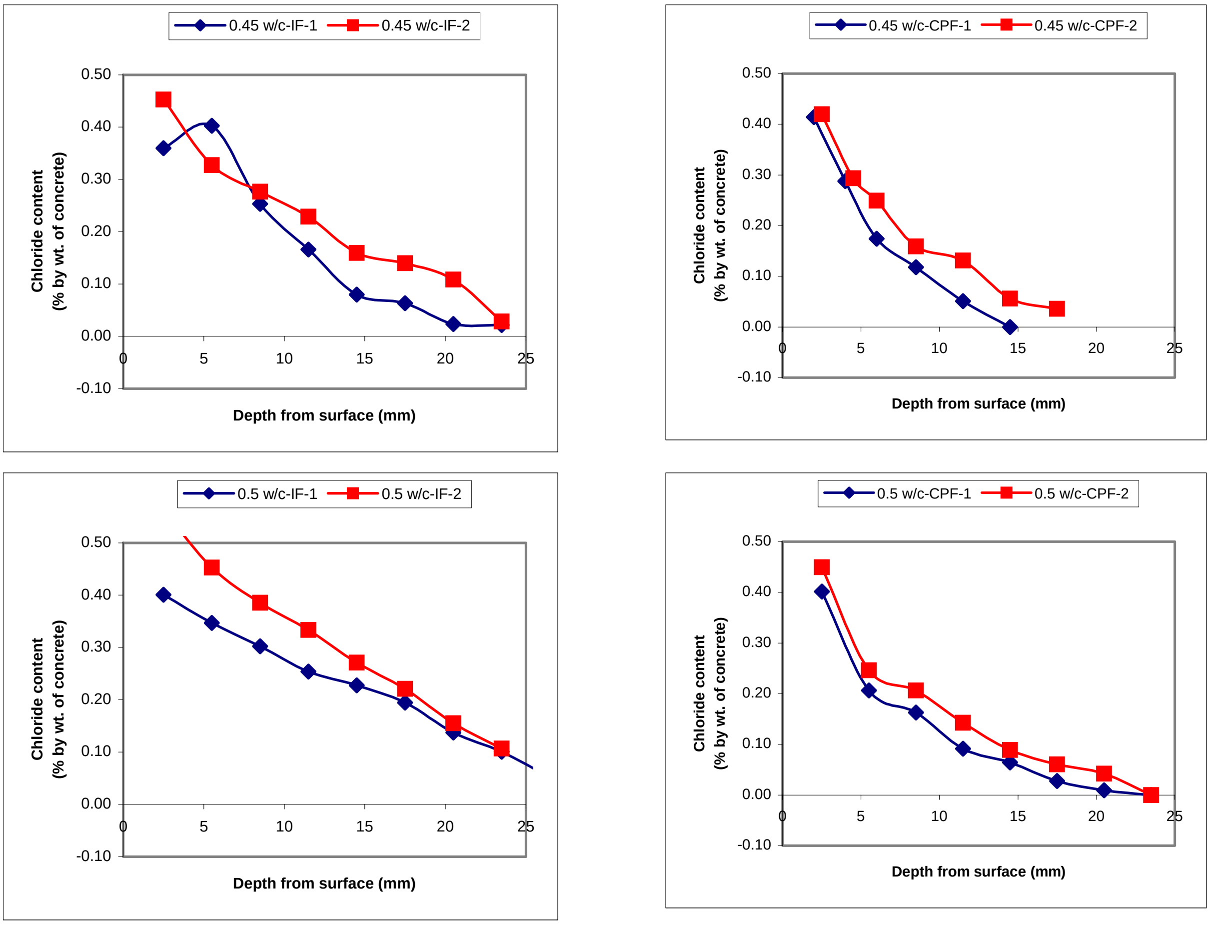

Fig. 22 Chloride profiles after 178 days of exposure

The apparent diffusion coefficient calculated based on the above two sets of profiles is presented in Figs. 23 and 24 respectively for the 100 days and the 178 days of exposure. As with all the previous results, these results show that the concrete cast using Formtex CPF was of better quality than that cast using conventional formwork. Using the CPF yielded an average improvement of 55% for the 0.45 w/c concrete and a 66% for the 0.5 w/c concrete.

Further to the trends of profiles in Figs. 21 and 22, the apparent chloride diffusion coefficients in Figs. 23 and 24 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 0.5 w/c 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 a small increase in D_a could be seen for the IF concrete as well. Nevertheless, the protective capability was evident in comparison to the IF in all cases.

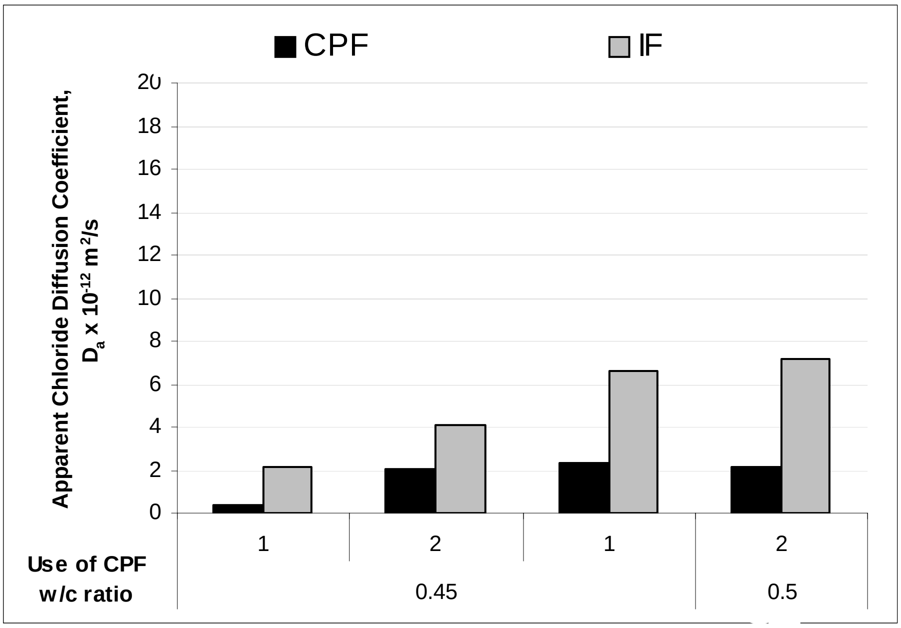

Fig. 23 Apparent Chloride Diffusion Coefficient (100 days of exposure)

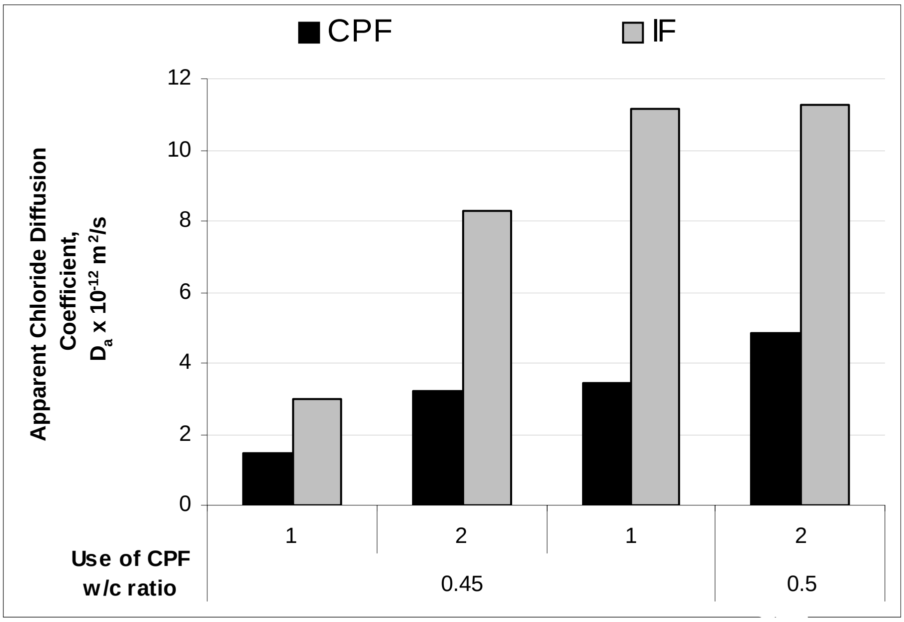

Fig. 24 Apparent Chloride Diffusion Coefficient (178 days of exposure)

5.9 Summary

In each test completed, concrete cast using Formtex CPF liner showed better strength and durability properties than the same concrete cast using conventional impermeable formwork. The performance was better at the higher water-cement ratio. The percentage improvement in test results from using Formtex CPF in comparison to the conventional impermeable formwork is summarised in Table 2. Overall, there was no marked change in performance of the Formtex CPF with reusing it once at both 0.45 and 0.5 water-cement ratios.

Table 2. Percentage improvement in test results from using Formtex CPF liner.

Tests Completed	0.45 w/c	0.5 w/c	Average
Pull-Off Test	30	33	28
Air Permeability Test	56	64	60
Sorptivity (Water Absorption) Test	29	43	36
Carbonation Depth	94	97	96
Chloride Penetration Depth	27	43	36
Chloride Diffusion Coefficient (100 days)	57	70	67
Chloride Diffusion Coefficient (178 days)	53	62	58

6. Conclusions

On the basis of tests carried out, it can be concluded that the use of Formtex CPF produces concrete of higher quality, with significantly higher strength and durability properties than concrete that is cast using conventional impermeable formwork. The durability enhancing effect of Formtex CPF is more pronounced when concrete of higher water-cement ratio is used. The Formtex CPF had little decrease in its performance after being reused once.

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2. Building Research Establishment, Design of normal concrete mixes, DoE, BR 106, 1988, 42 pp.

3. Long, A.E., Murry, A.McC., "*The Pull-Off partially destructive test for concrete*", Queen's University of Belfast.

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Appendix

A. Compressive Strength Results

A1. 0.45 water cement ratio

1st use of Formtex CPF liner.

Block no.	1	2	3
Force (kN)	547	519	569
Stress (N/mm^2)	54.7	51.9	56.9

2nd use of Formtex CPF liner.

Block no.	1	2	3
Force (kN)	480.9	497.8	552
Stress (N/mm^2)	48.09	49.78	55.2

A2. 0.5 water cement ratio

1st use of Formtex CPF liner.

Block no.	1	2	3
Force (kN)	394.6	355.4	405.3
Stress (N/mm^2)	39.46	35.54	40.53

2nd use of Formtex CPF liner.

Block no.	1	2	3
Force (kN)	406.3	409.1	420.7
Stress (N/mm^2)	40.63	40.91	42.07

B. Pull-Off Test Results

B1. 0.45 water cement ratio

1st use of Formtex CPF liner				
Face	**Block No.**	**Disk**	**Force (kN)**	**Ave Force (kN)**
CPF	1	1 2	7.60 8.64	8.12
	2	1 2	9.15 9.50	9.33
	3	1 2	9.45 7.72	8.59
IF	1	1 2	6.70 6.13	6.42
	2	1 2	7.40 5.80	6.60
	3	1 2	6.64 5.50	6.07

2nd use of Formtex CPF liner				
Face	**Block No.**	**Disk**	**Force (kN)**	**Ave Force (kN)**
CPF	1	1 2	6.79 8.68	7.74
	2	1 2	7.60 9.46	8.53
	3	1 2	7.89 10.26	9.08
IF	1	1 2	7.37 7.52	7.45
	2	1 2	5.44 5.73	5.59
	3	1 2	7.37 6.08	6.73

B2. 0.5 water cement ratio

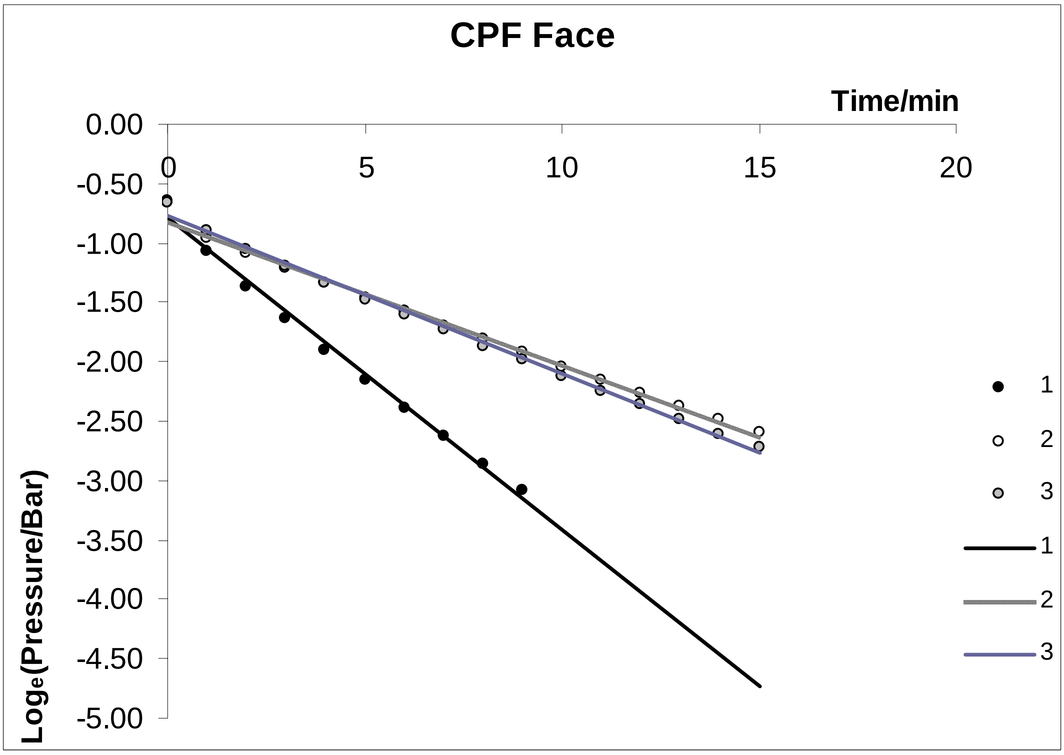
1st use of Formtex CPF liner				
Face	**Block No.**	**Disk**	**Force (kN)**	**Ave Force (kN)**
CPF	4	1 2	5.40 5.98	5.69
	5	1 2	10.15 8.73	9.44
	6	1 2	8.17 7.81	7.99
IF	4	1 2	3.83 2.62	3.23
	5	1 2	3.13 5.45	4.29
	6	1 2	3.71 4.80	4.26

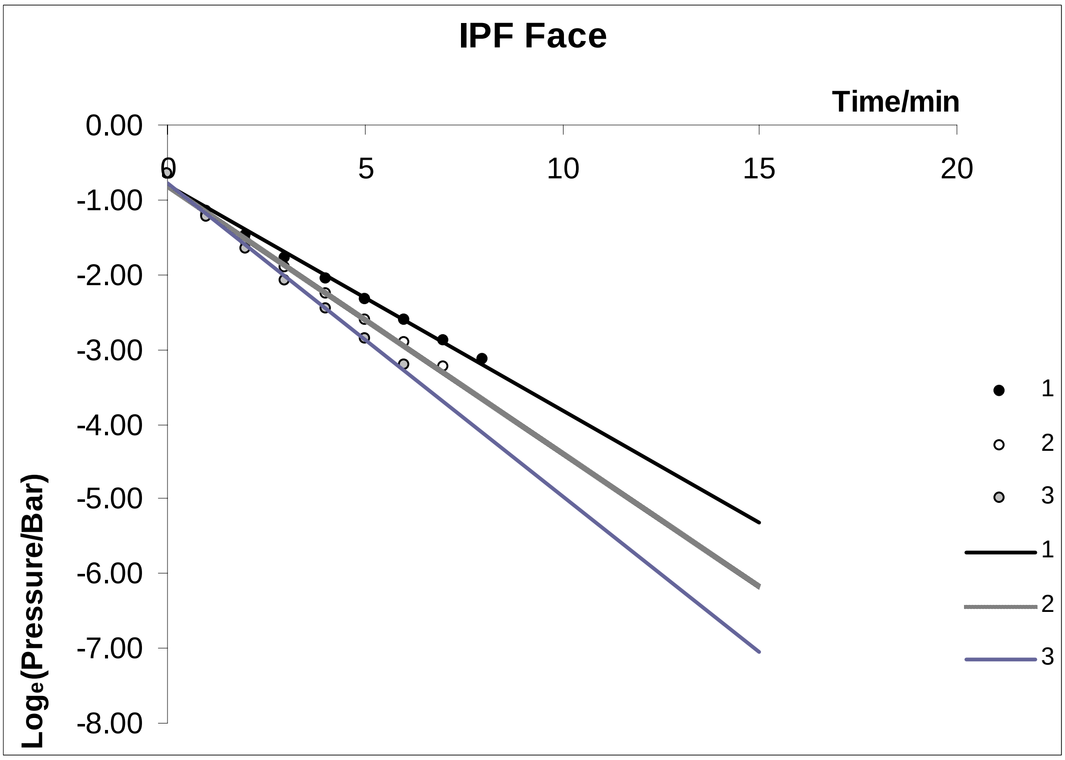
2nd use of Formtex CPF liner				
Face	**Block No.**	**Disk**	**Force (kN)**	**Ave Force (kN)**
CPF	4	1 2	5.44 4.95	5.20
	5	1 2	4.89 7.03	5.96
	6	1 2	6.47 7.08	6.78
IF	4	1 2	5.36 5.01	5.19
	5	1 2	5.54 4.71	5.13
	6	1 2	5.34 5.22	5.28

C. Air Permeability Test Results

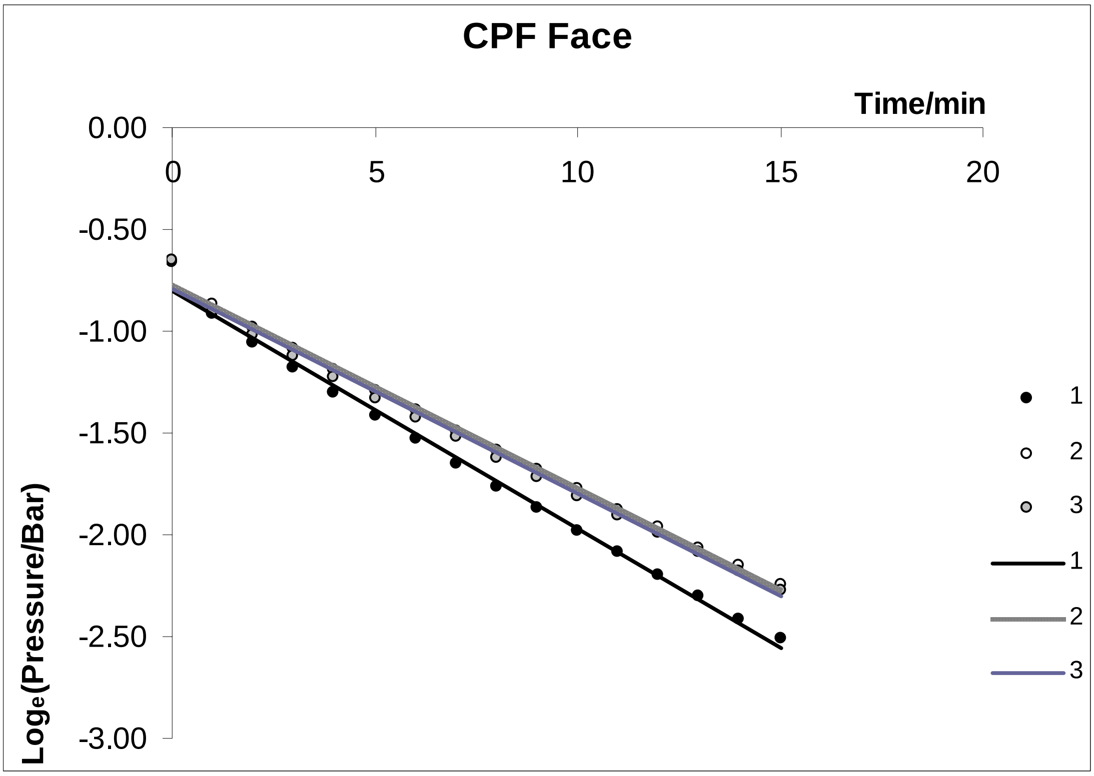
C1. 0.45 water cement ratio

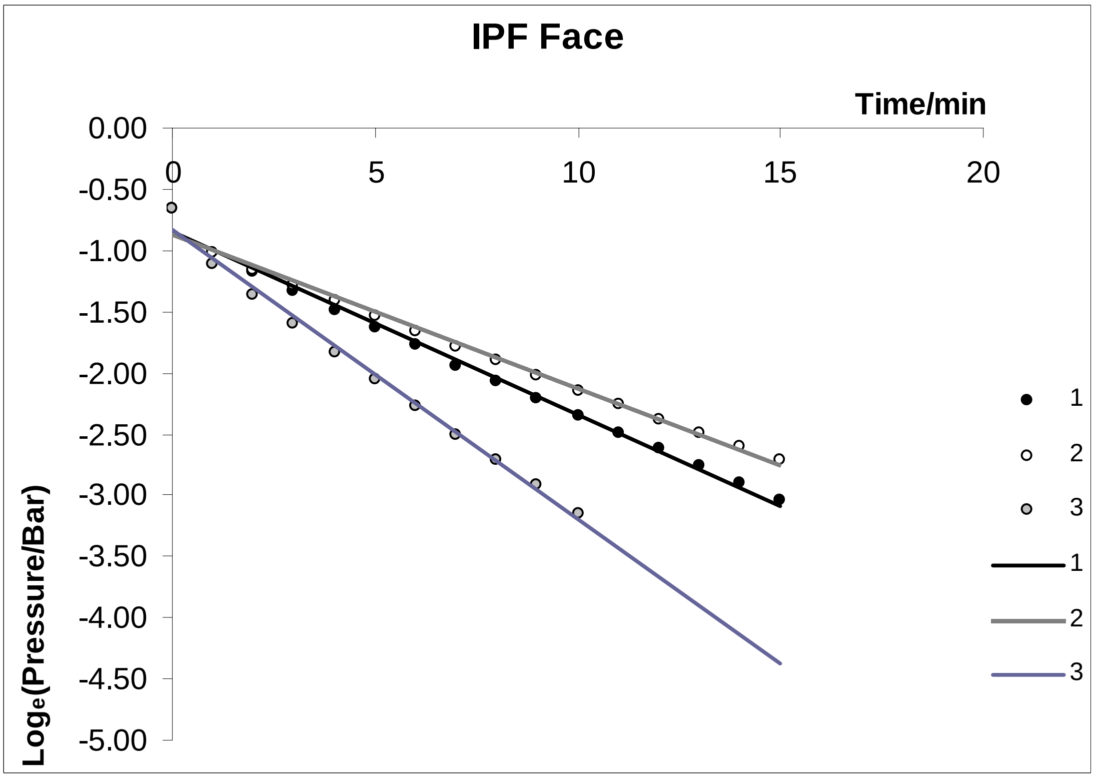
1st use of Formtex CPF liner





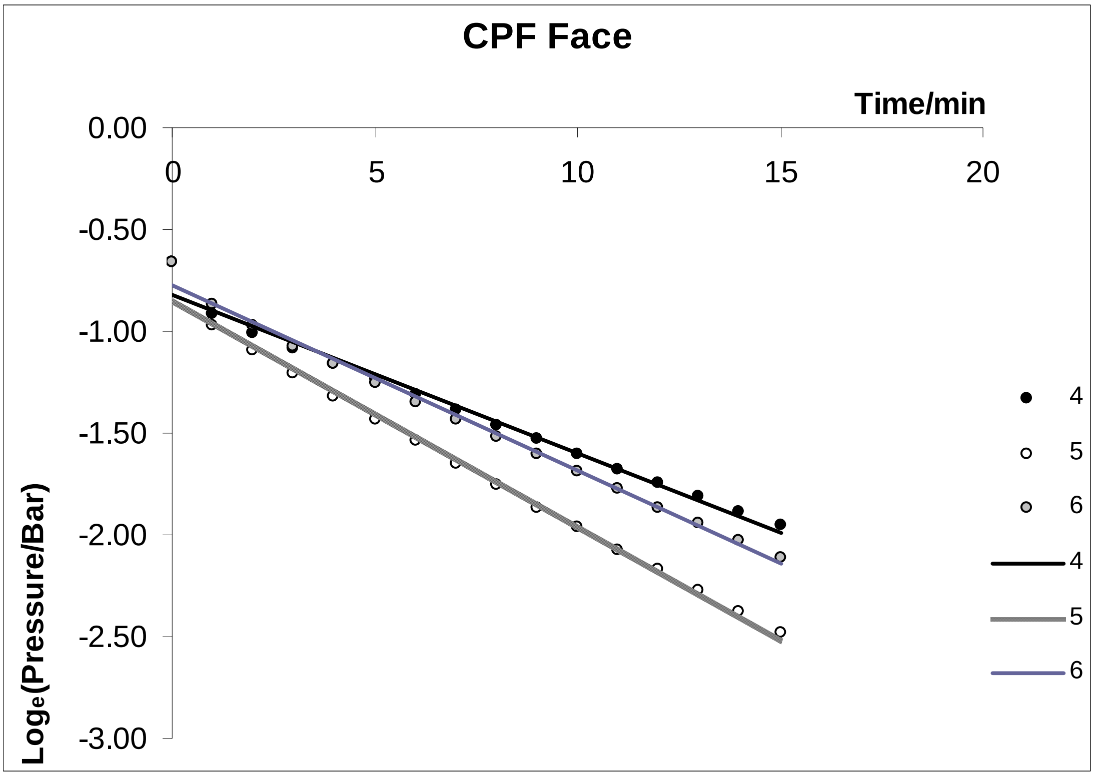
2nd use of Formtex CPF liner

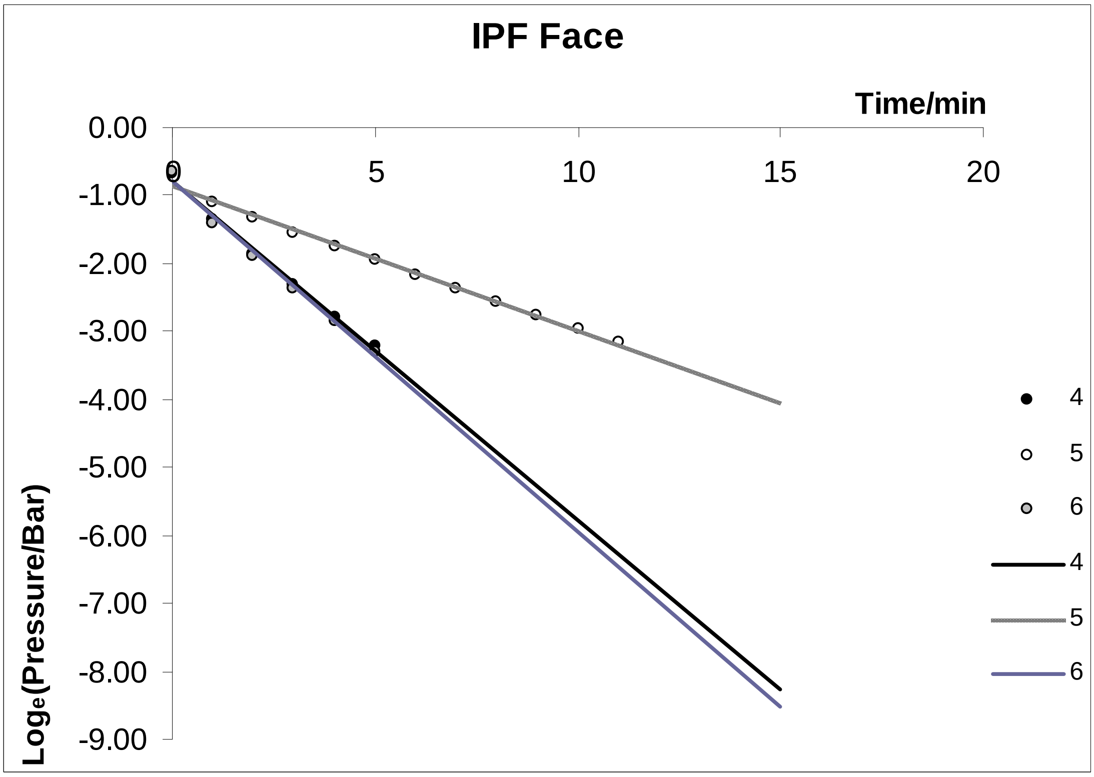




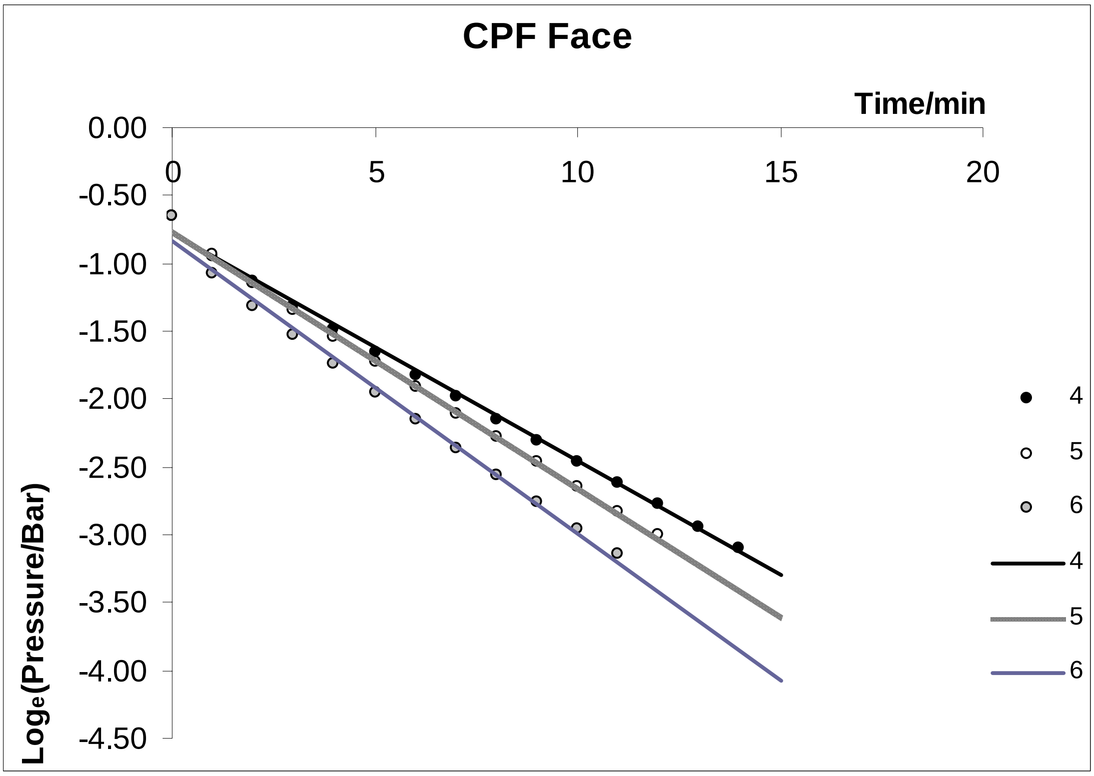
C2. 0.5 water cement ratio

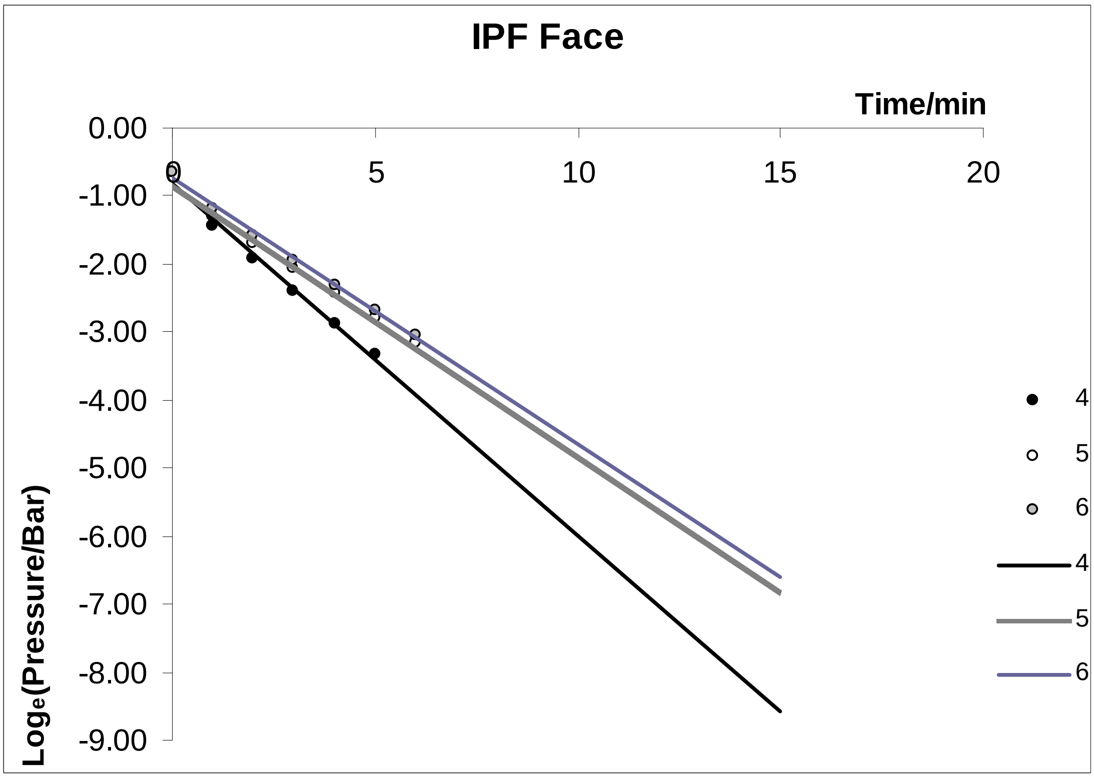
1st use of Formtex CPF liner





2nd use of Formtex CPF liner

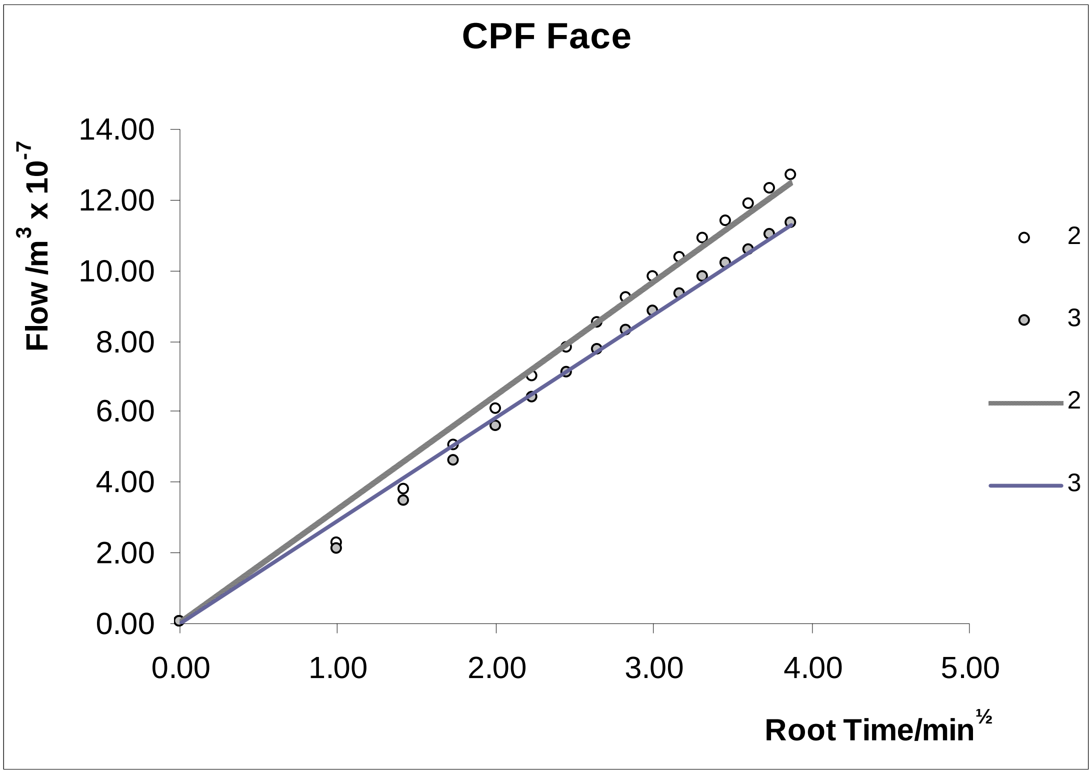


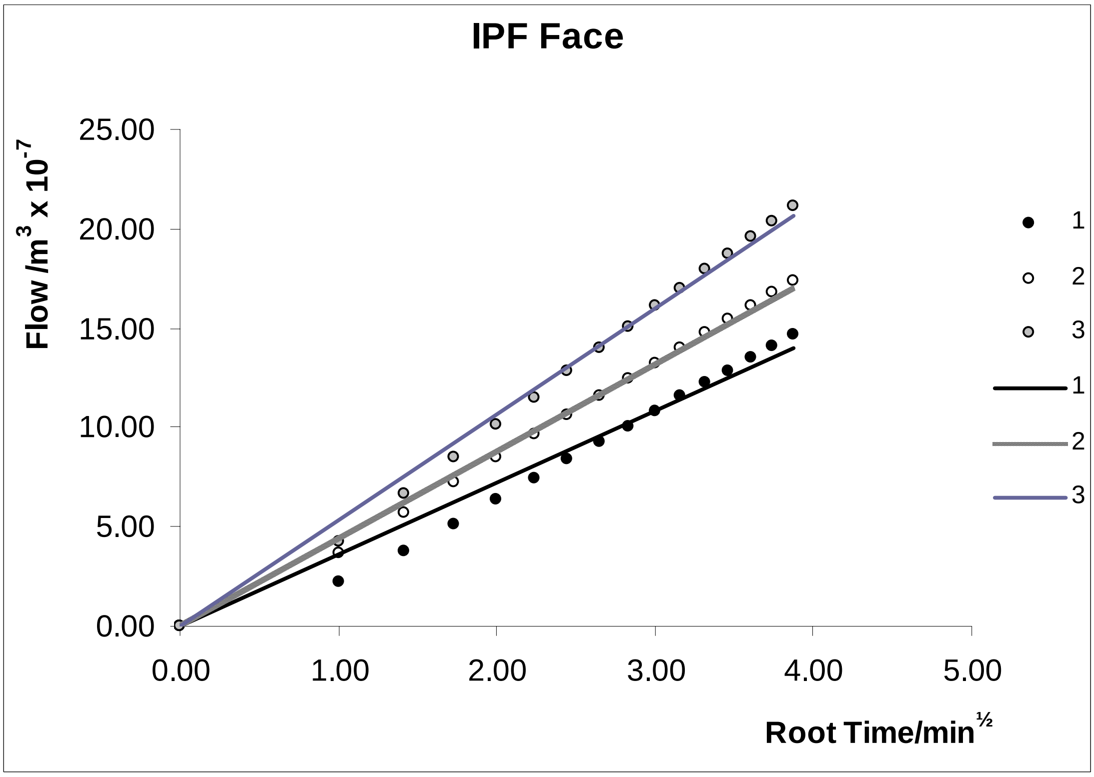


D. Water Absorption Results

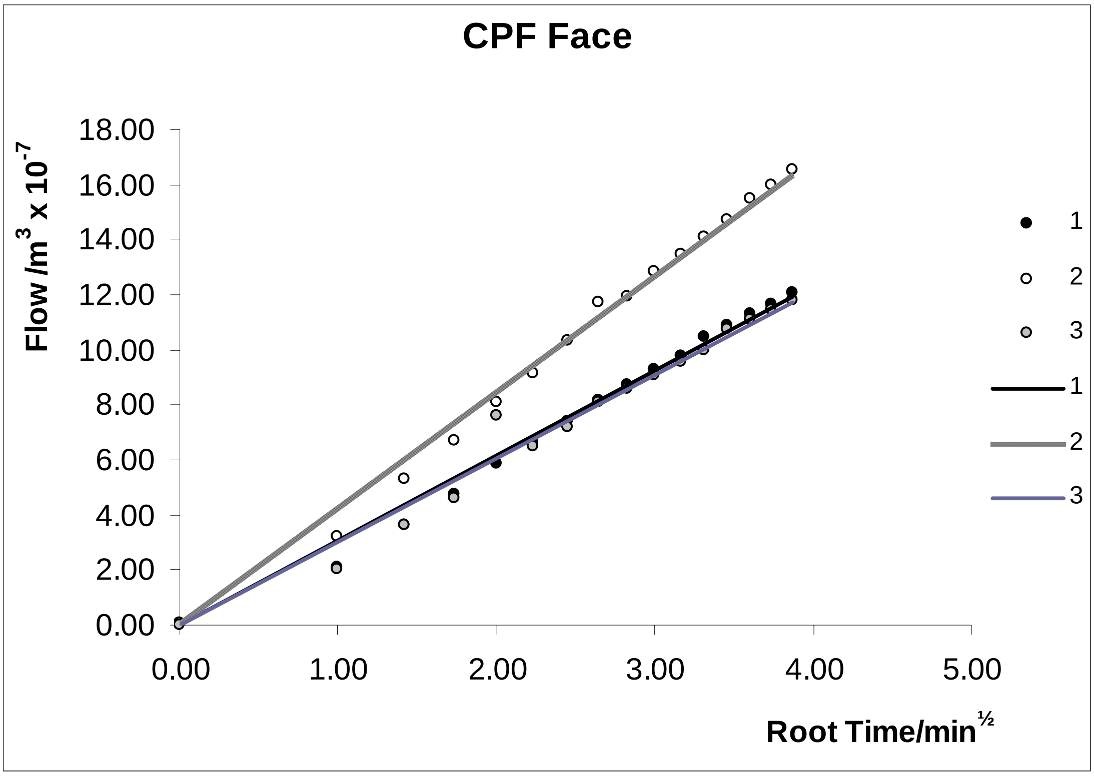
D1. 0.45 water-cement ratio

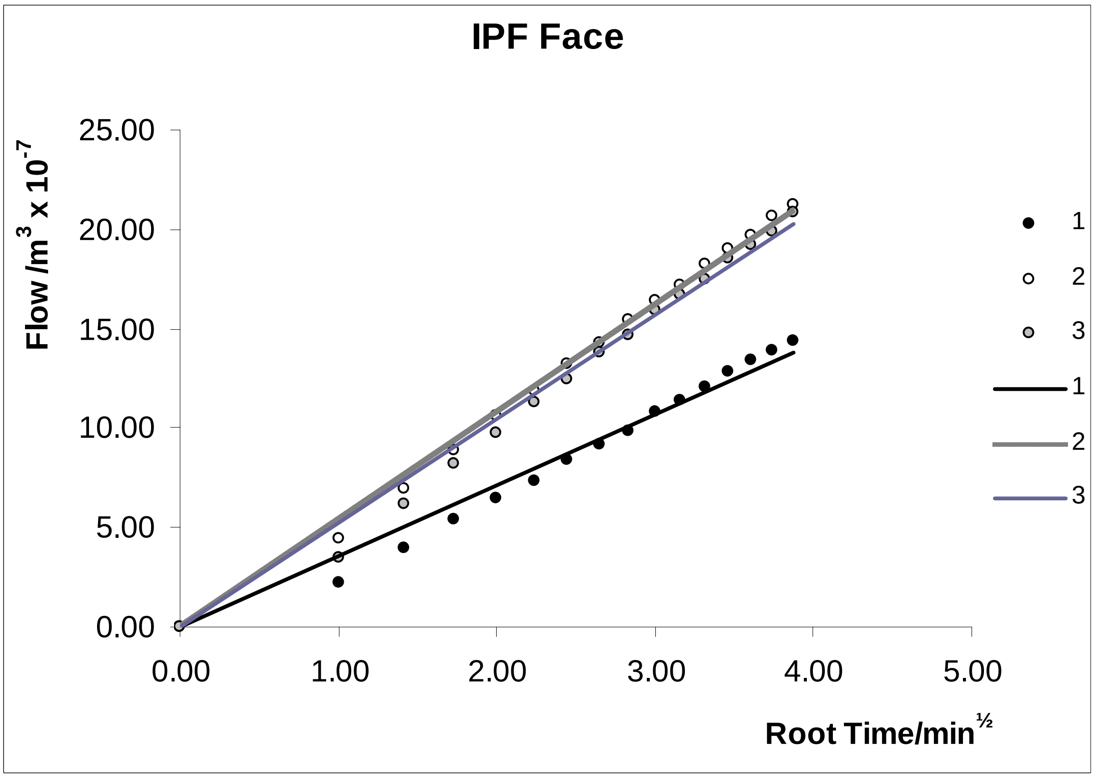
1st use of Formtex CPF liner





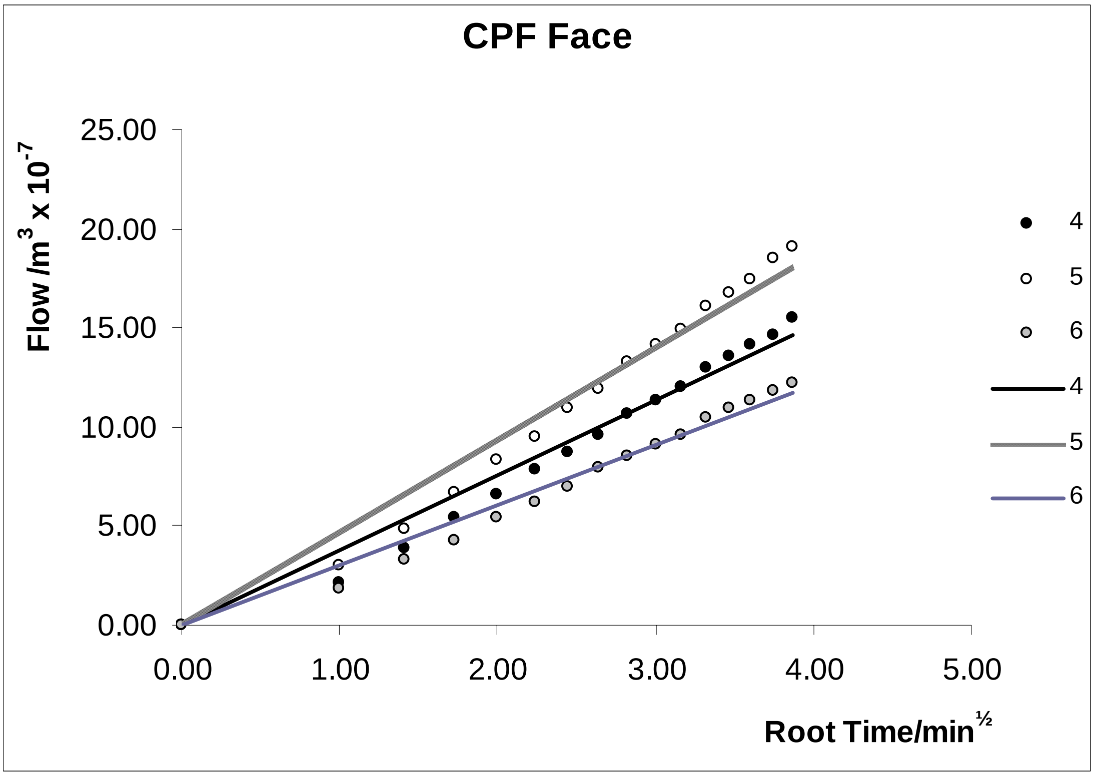
2nd use of Formtex CPF liner

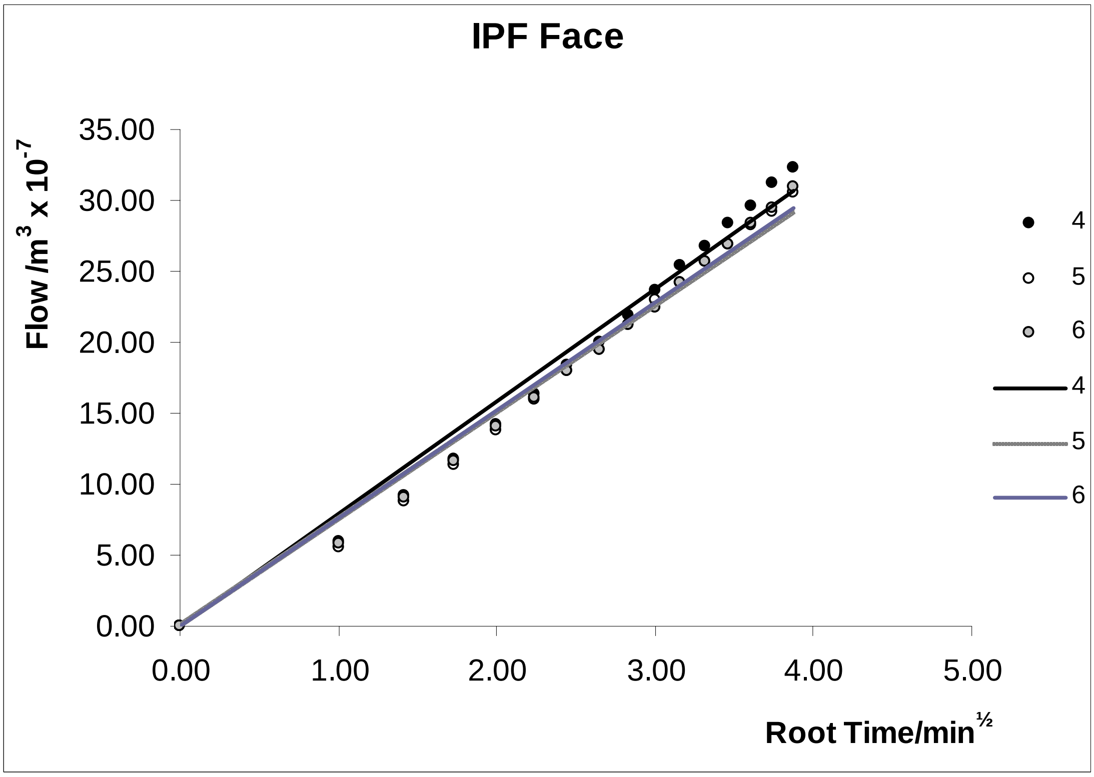




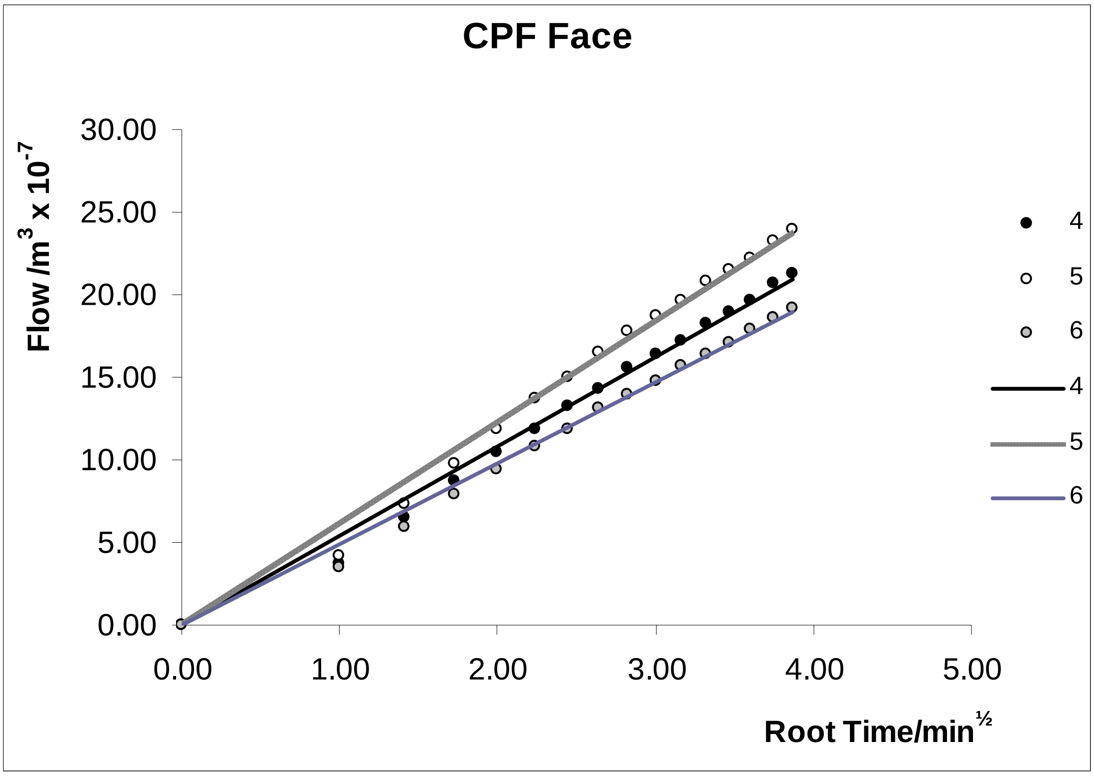
D2. 0.5 water-cement ratio

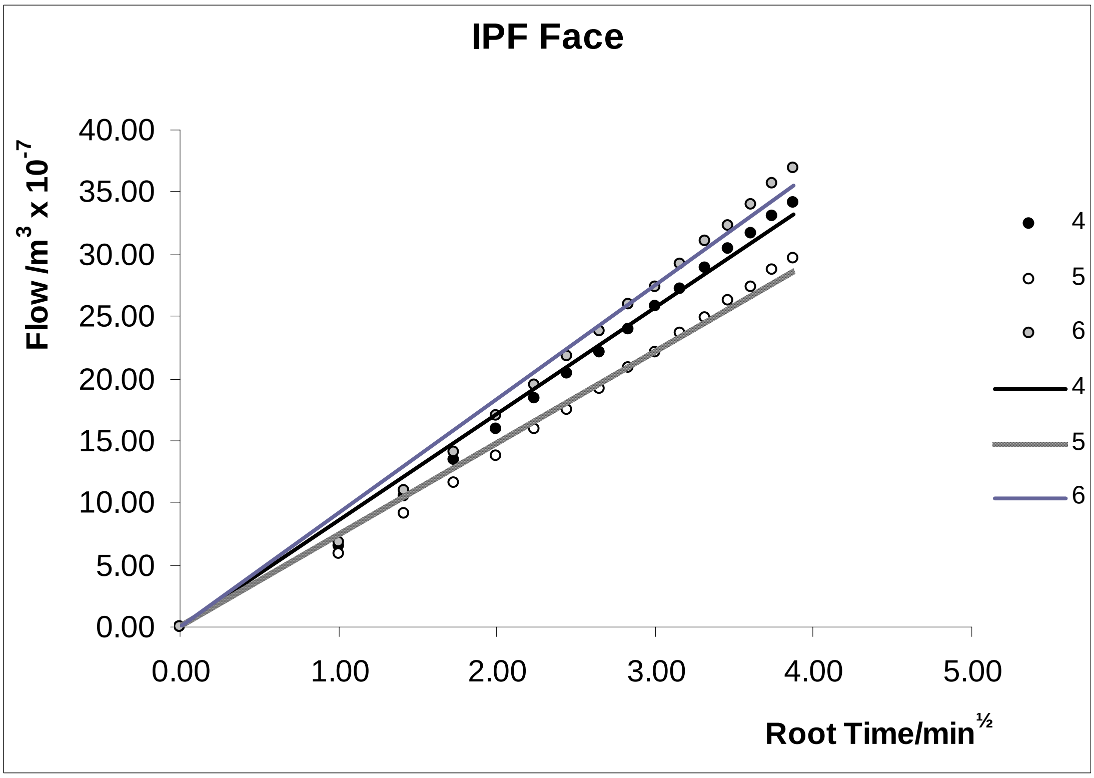
1st use of Formtex CPF liner





2nd use of Formtex CPF liner





E. Depth of Carbonation

All values are depths in millimetres. When each core was split the halves were labelled a and b. There were three cores for each concrete mix, hence three sets of results for each use of Formtex CPF.

0.45 w/c Ratio	CPF face		IF face	
	a	b	a	b
1st use of CPF	0.7	0.9	10.3	10.7
	0.3	0.1	9.1	8.4
	0.1	0.0	9.0	10.1
2nd use of CPF	0.1	0.9	10.6	10.0
	0.1	0.0	12.7	10.1
	0.3	0.0	8.9	9.3

0.5 w/c Ratio	CPF face		IF face	
	a	b	a	b
1st use of CPF	0.3	0.4	17.7	16.7
	0.1	0.1	13.1	11.3
	0.9	1.1	10.0	9.1
2nd use of CPF	0.1	0.4	9.9	12.1
	0.3	0.1	10.7	11.1
	0.3	0.3	10.3	10.9

F. Depth of Penetration of Chloride Ions

All values are depths in millimetres. When each core was split the halves were labelled a and b.

0.45 w/c Ratio	CPF face		IF face	
	a	b	a	b
1st use of CPF	14.4	15.4	20.1	21.1
2nd use of CPF	13.9	14.7	20.3	20.3

0.5 w/c Ratio	CPF face		IF face	
	a	b	a	b
1st use of CPF	13.7	15.3	25.1	24.7
2nd use of CPF	12.4	14.9	23.3	24.9

G. Chloride Content at Different Depths

G1. 100 days exposure to chlorides

G1.1. 0.45 water-cement ratio

1st use of Formtex CPF liner

CPF face		
Depth of layer (mm)	Average Depth (mm)	% Chloride Content
1 - 3	2	0.35
3 - 5	4	0.12
5 - 7	6	0.02
7 - 9	8	0.00
9 - 11	10	0.00
11 - 13	12	0.00
13 - 15	14	0.00
15 - 17	16	0.00

IF face		
Depth of layer (mm)	Average Depth (mm)	% Chloride Content
1 - 3	2	0.21
3 - 5	4	0.16
5 - 7	6	0.12
7 - 10	8.5	0.06
10 - 13	11.5	0.00
13 - 16	14.5	0.00
16 - 19	17.5	0.00
19 - 22	20.5	0.00
22 - 25	23.5	0.00

2nd use of Formtex CPF liner

CPF face		
Depth of layer (mm)	Average Depth (mm)	% Chloride Content
1 - 3	2	0.47
3 - 5	4	0.26
5 - 7	6	0.19
7 - 9	8	0.10
9 - 11	10	0.05
11 - 13	12	0.00
13 - 15	14	0.00
15 - 17	16	0.00

IF face		
Depth of layer (mm)	Average Depth (mm)	% Chloride Content
1 - 3	2	0.40
3 - 5	4	0.26
5 - 7	6	0.23
7 - 10	8.5	0.16
10 - 13	11.5	0.09
13 - 16	14.5	0.00
16 - 19	17.5	0.00
19 - 22	20.5	0.00
22 - 25	23.5	0.00

G.1.2 0.5 water-cement ratio

1st use of Formtex CPF liner

CPF face		
Depth of layer (mm)	Average Depth (mm)	% Chloride Content
1 - 3	2	0.38
3 - 5	4	0.23
5 - 7	6	0.19
7 - 9	8	0.11
9 - 11	10	0.05
11 - 13	12	0.00
13 - 15	14	0.00
15 - 17	16	0.00

IF face		
Depth of layer (mm)	Average Depth (mm)	% Chloride Content
1 - 3	2	0.14
3 - 5	4	0.16
5 - 7	6	0.17
7 - 10	8.5	0.18
10 - 13	11.5	0.14
13 - 16	14.5	0.09
16 - 19	17.5	0.05
19 - 22	20.5	0.00
22 - 25	23.5	0.00

2nd use of Formtex CPF liner

CPF face		
Depth of layer (mm)	Average Depth (mm)	% Chloride Content
1 - 3	2	0.50
3 - 5	4	0.21
5 - 7	6	0.11
7 - 9	8	0.09
9 - 11	10	0.05
11 - 13	12	0.02
13 - 15	14	0.00
15 - 17	16	0.00

IF face		
Depth of layer (mm)	Average Depth (mm)	% Chloride Content
1 - 3	2	0.38
3 - 5	4	0.29
5 - 7	6	0.28
7 - 10	8.5	0.20
10 - 13	11.5	0.15
13 - 16	14.5	0.09
16 - 19	17.5	0.04
19 - 22	20.5	0.01
22 - 25	23.5	0.00

G.2. 178 days exposure to chlorides

G.2.1. 0.45 water-cement ratio

1st use of Formtex CPF liner

CPF face		
Depth of layer (mm)	Average Depth (mm)	% Chloride Content
1 - 3	2	0.41
3 - 5	4	0.29
5 - 7	6	0.17
7 - 10	8.5	0.12
10 - 13	11.5	0.05
13 - 16	14.5	0.00

IF face		
Depth of layer (mm)	Average Depth (mm)	% Chloride Content
1 - 4	2.5	0.36
4 - 7	5.5	0.40
7 - 10	8.5	0.25
10 - 13	11.5	0.17
13 - 16	14.5	0.08
16 - 19	17.5	0.06
19 - 22	20.5	0.02
22 - 25	23.5	0.02

2nd use of Formtex CPF liner

CPF face		
Depth of layer (mm)	Average Depth (mm)	% Chloride Content
1 - 4	2.5	0.42
4 - 5	4.5	0.29
5 - 7	6	0.25
7 - 10	8.5	0.16
10 - 13	11.5	0.13
13 - 16	14.5	0.06
16 - 19	17.5	0.04

IF face		
Depth of layer (mm)	Average Depth (mm)	% Chloride Content
1 - 4	2.5	0.45
4 - 7	5.5	0.33
7 - 10	8.5	0.28
10 - 13	11.5	0.23
13 - 16	14.5	0.16
16 - 19	17.5	0.14
19 - 22	20.5	0.11
22 - 25	23.5	0.03

G.2.2 0.5 water-cement ratio

1st use of Formtex CPF liner

CPF face		
Depth of layer (mm)	Average Depth (mm)	% Chloride Content
1 - 4	2.5	0.40
4 - 7	5.5	0.21
7 - 10	8.5	0.16
10 - 13	11.5	0.09
13 - 16	14.5	0.06
16 - 19	17.5	0.03
19 - 22	20.5	0.01
22 - 25	23.5	0.00

IF face		
Depth of layer (mm)	Average Depth (mm)	% Chloride Content
1 - 4	2.5	0.40
4 - 7	5.5	0.35
7 - 10	8.5	0.30
10 - 13	11.5	0.25
13 - 16	14.5	0.23
16 - 19	17.5	0.19
19 - 22	20.5	0.14
22 - 25	23.5	0.10
25 - 28	26.5	0.05
28 - 32	30	0.00

2nd use of Formtex CPF liner

CPF face		
Depth of layer (mm)	Average Depth (mm)	% Chloride Content
1 - 4	2.5	0.45
4 - 7	5.5	0.25
7 - 10	8.5	0.21
10 - 13	11.5	0.14
13 - 16	14.5	0.09
16 - 19	17.5	0.06
19 - 22	20.5	0.04
22 - 25	23.5	0.00

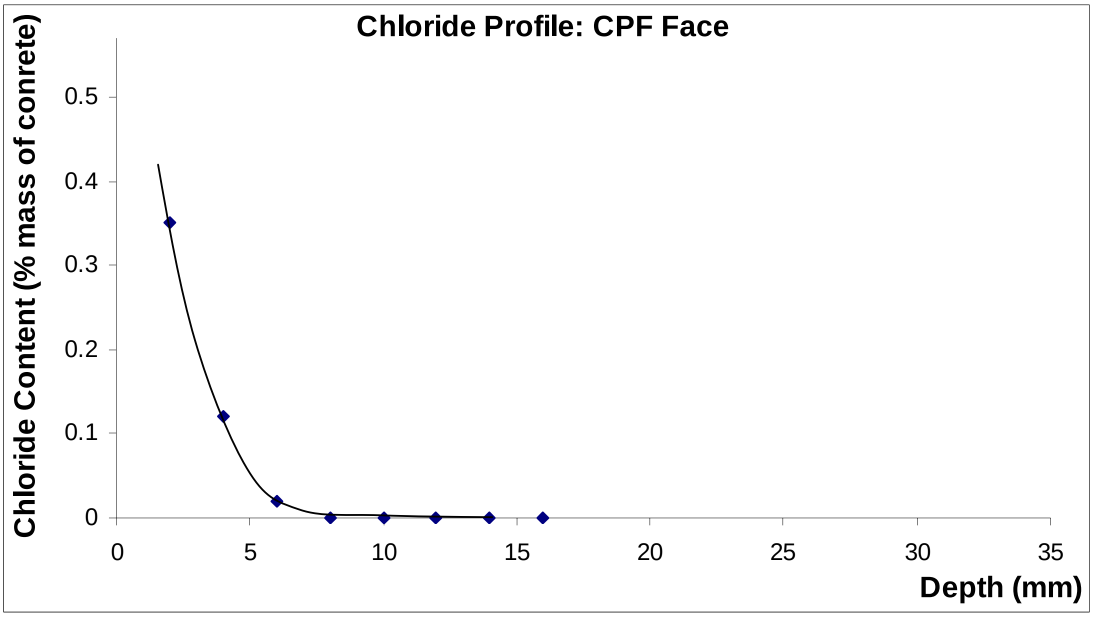
IF face		
Depth of layer (mm)	Average Depth (mm)	% Chloride Content
1 - 4	2.5	0.56
4 - 7	5.5	0.45
7 - 10	8.5	0.39
10 - 13	11.5	0.33
13 - 16	14.5	0.27
16 - 19	17.5	0.22
19 - 22	20.5	0.15
22 - 25	23.5	0.11

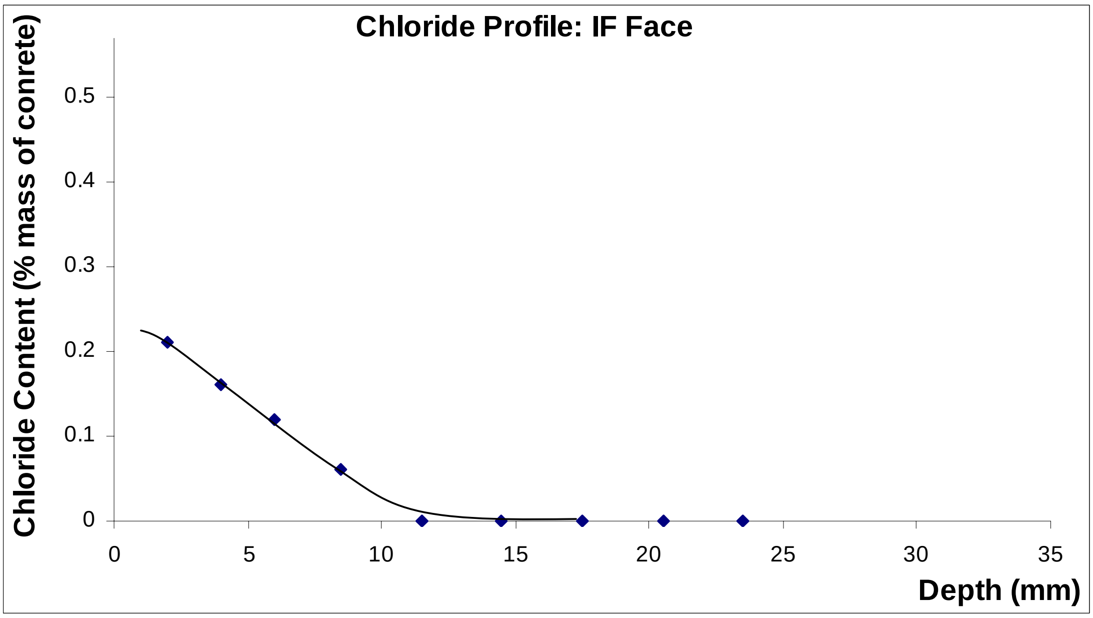
H. Chloride Profiles

H.1. 100 days exposure to chlorides

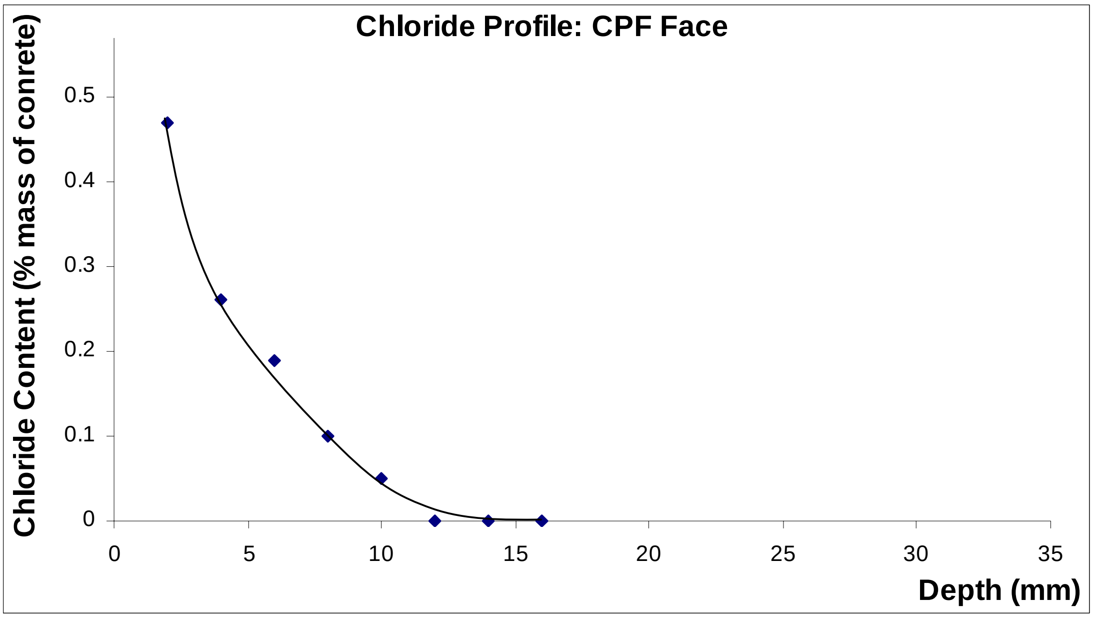
H1.1. 0.45 water-cement ratio

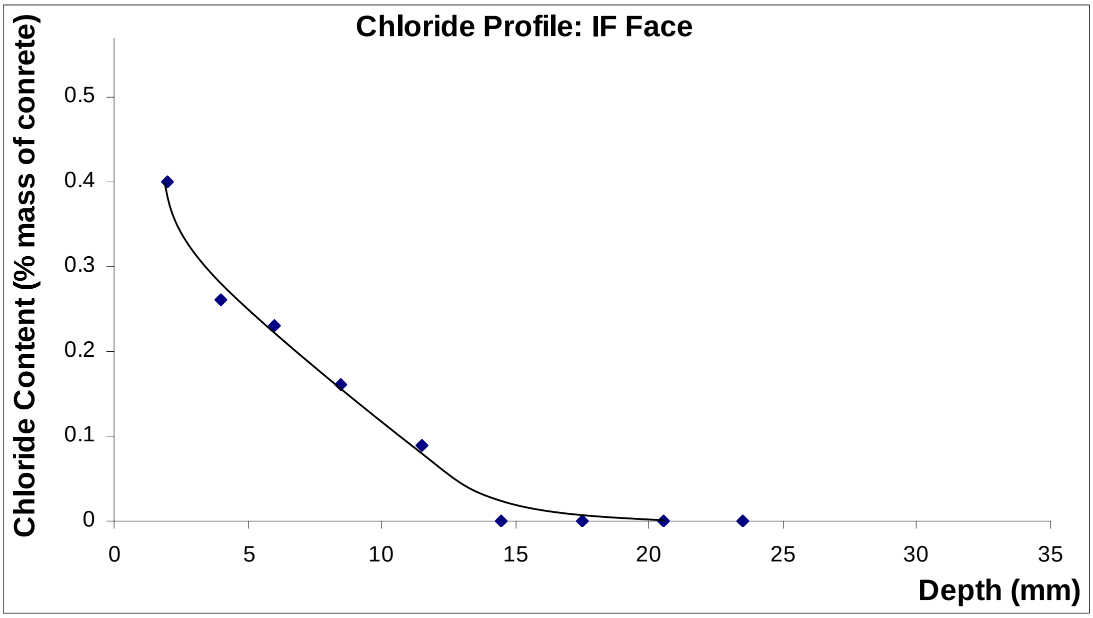
1st use of Formtex CPF liner





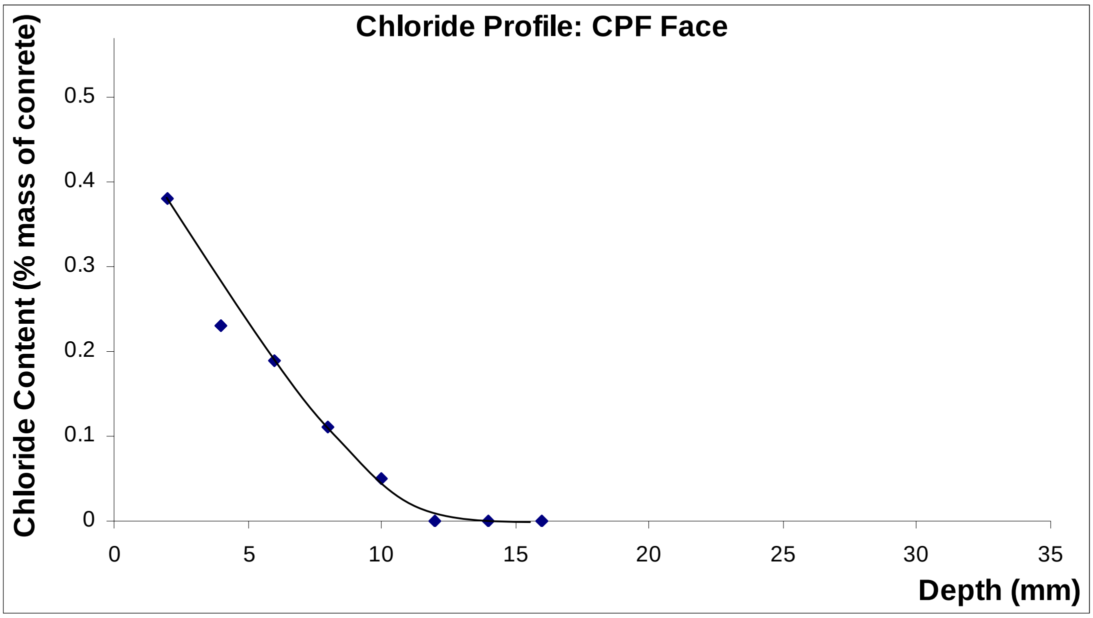
2nd use of Formtex CPF liner

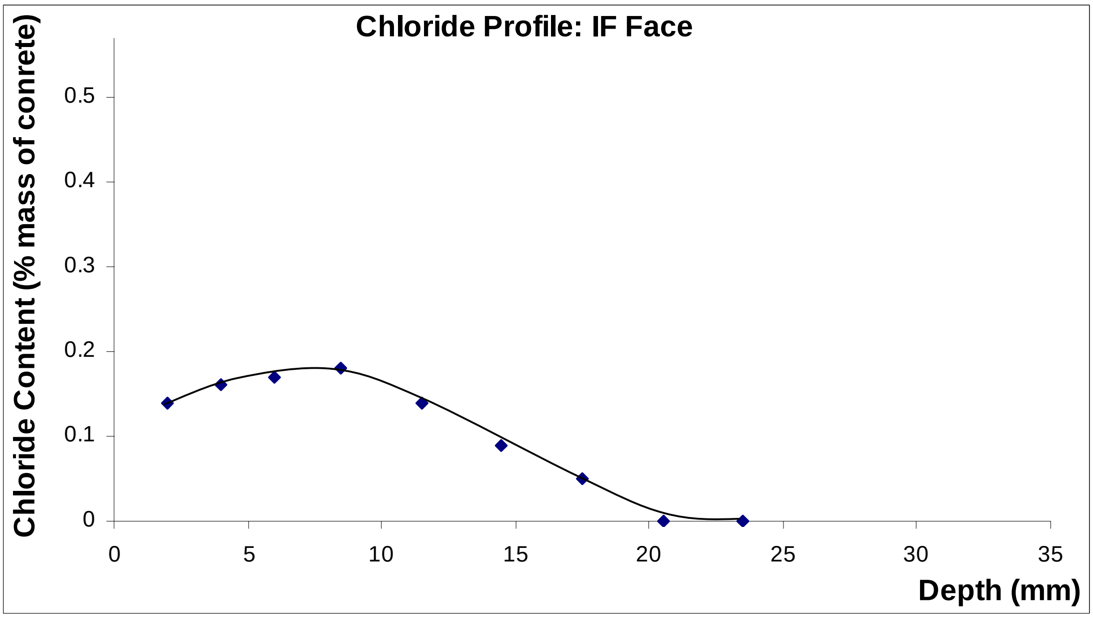




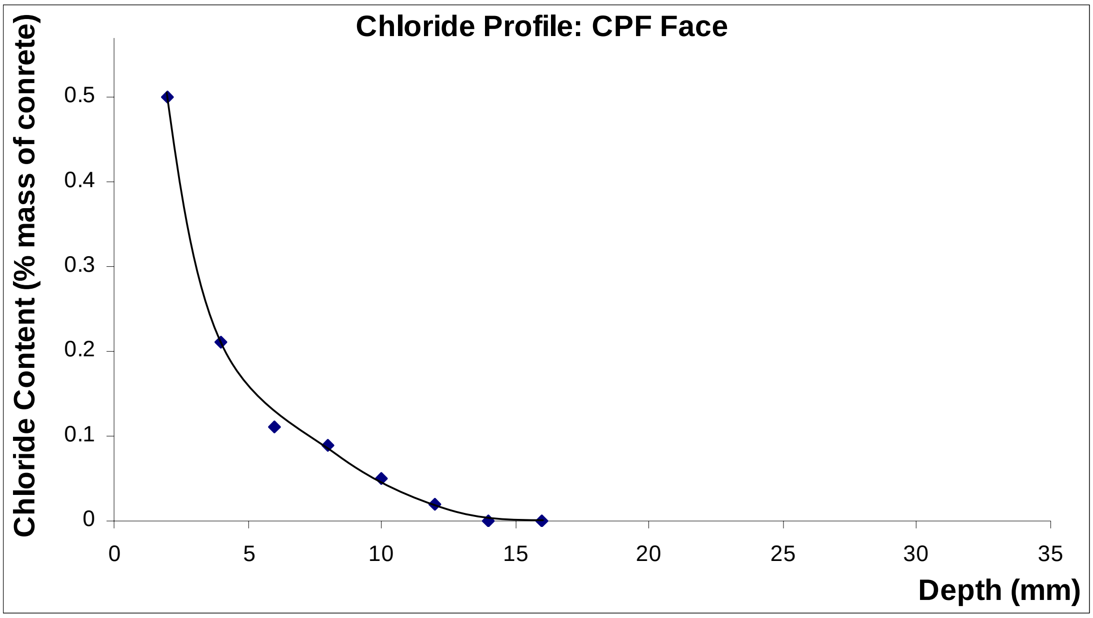
H.1.2 0.5 water-cement ratio

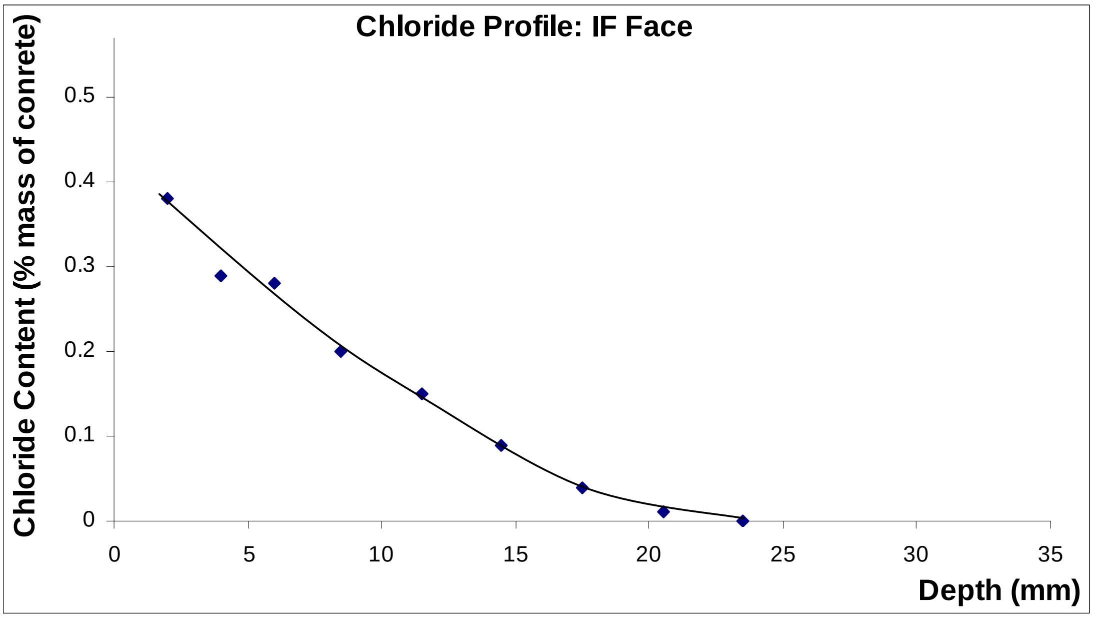
1st use of Formtex CPF liner





2nd use of Formtex CPF liner

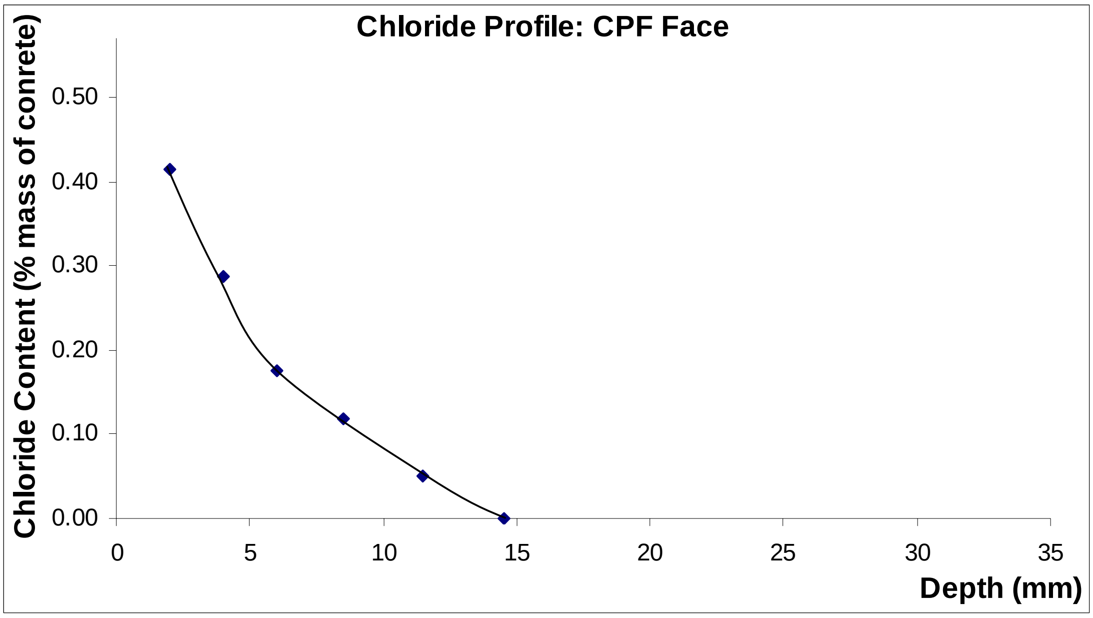


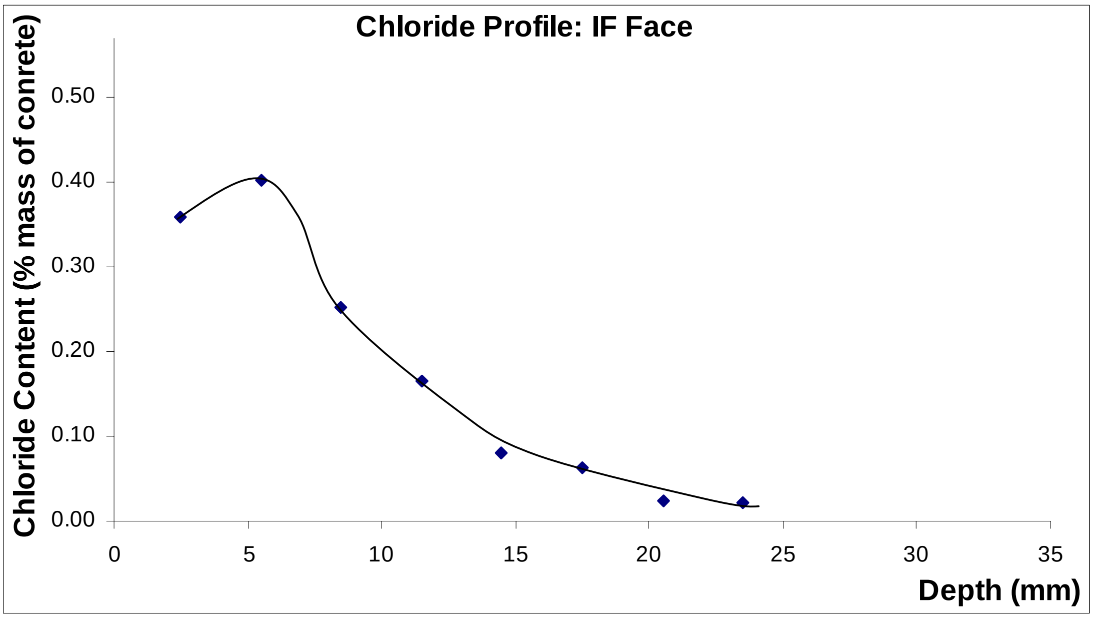


H.2 178 days exposure to chlorides

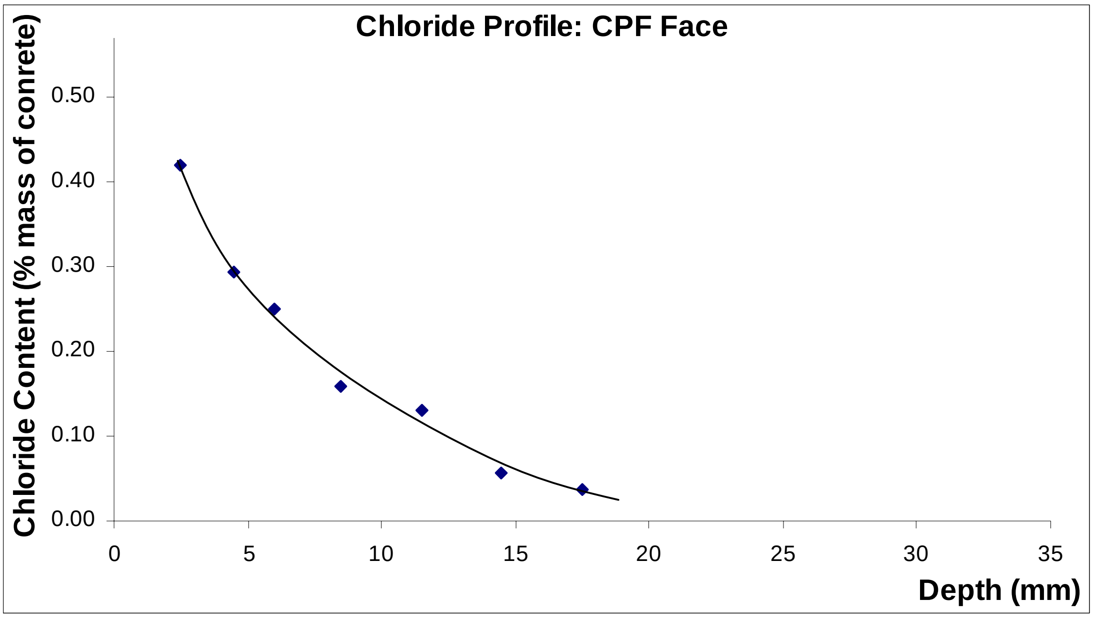
H.2.1 0.45 water-cement ratio

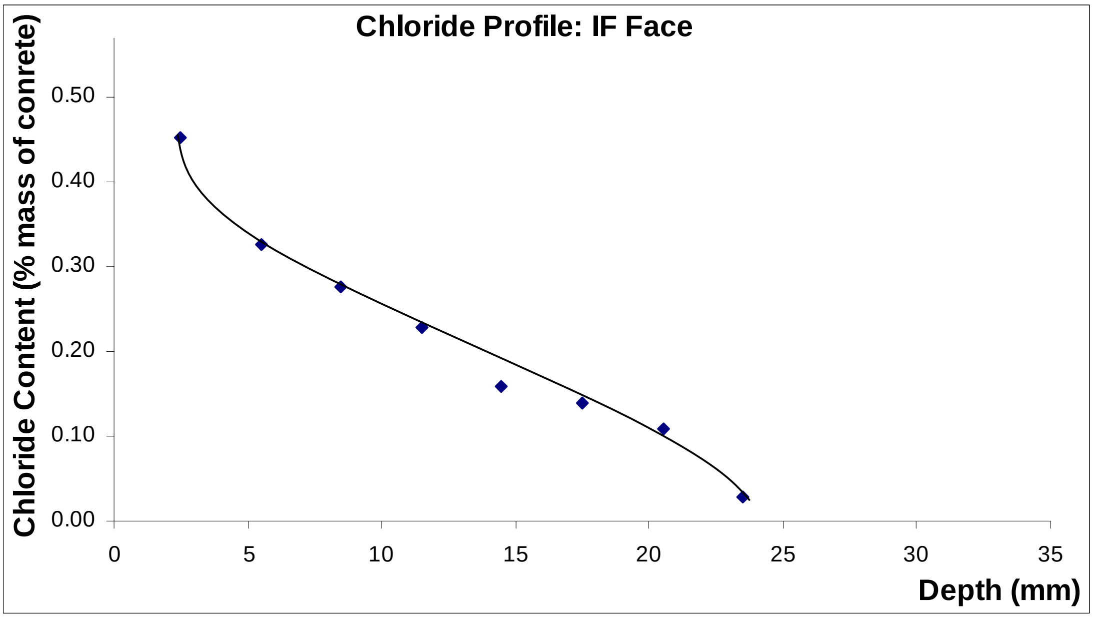
1st use of Formtex CPF liner





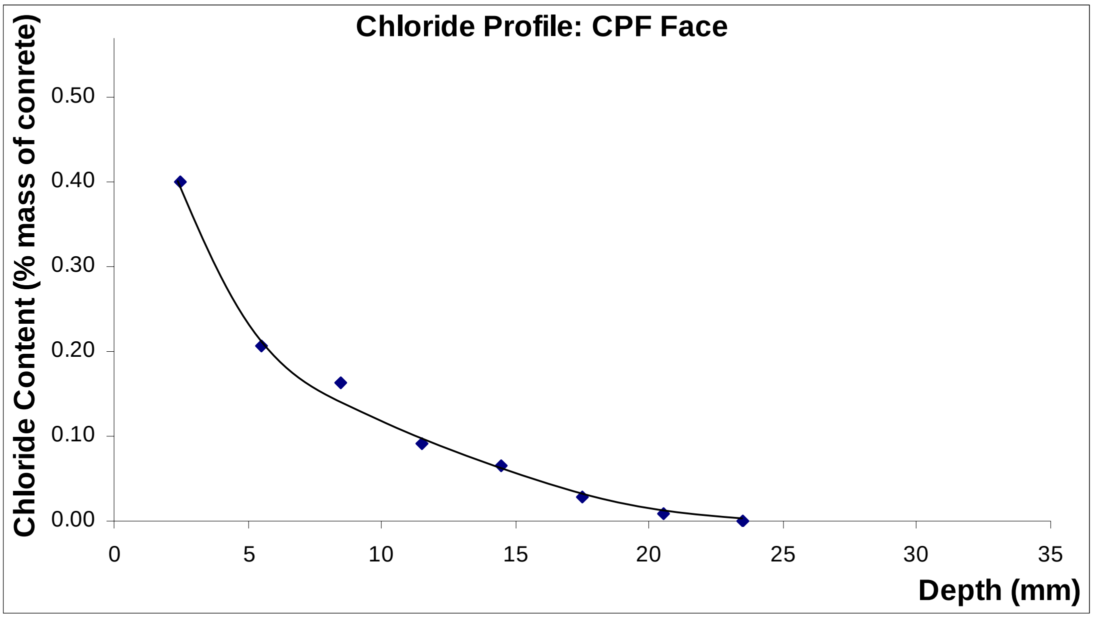
2nd use of Formtex CPF liner

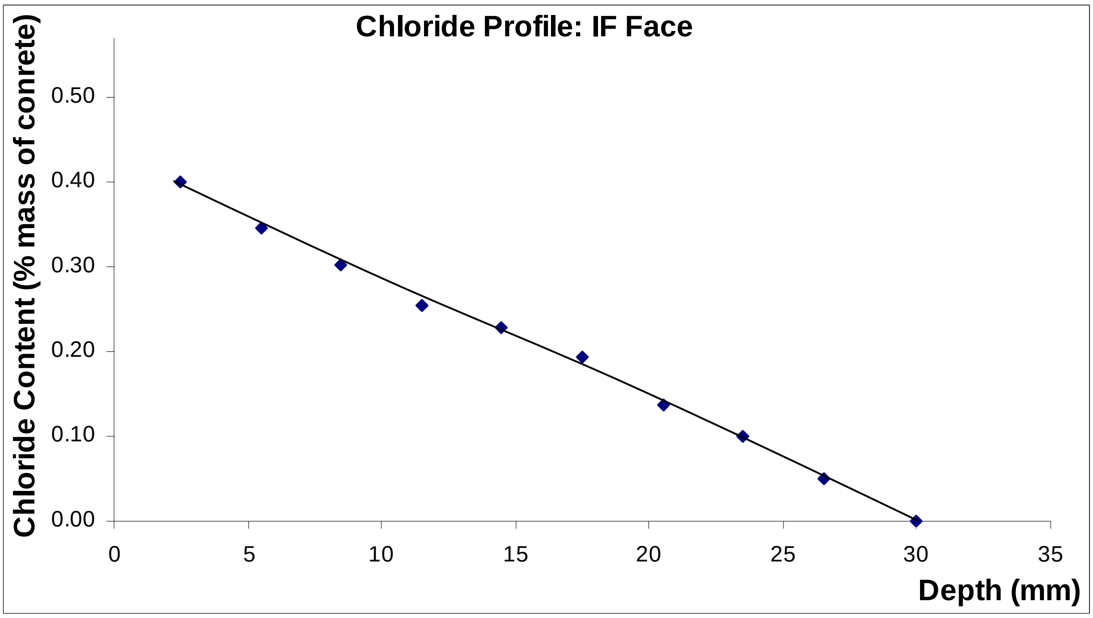




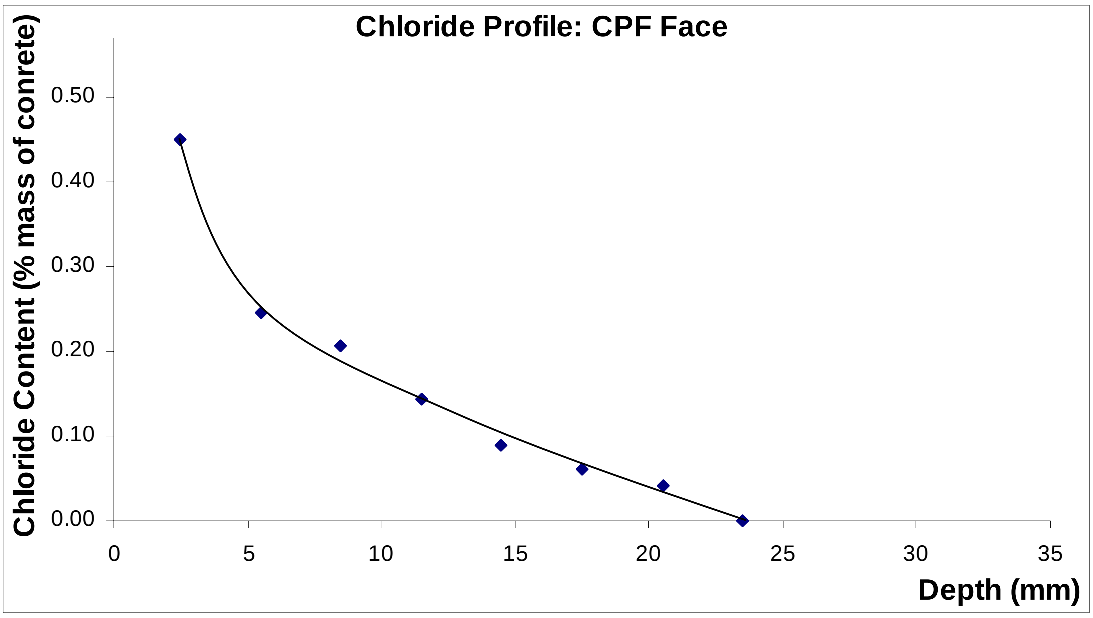
H.2.2. 0.5 water-cement ratio

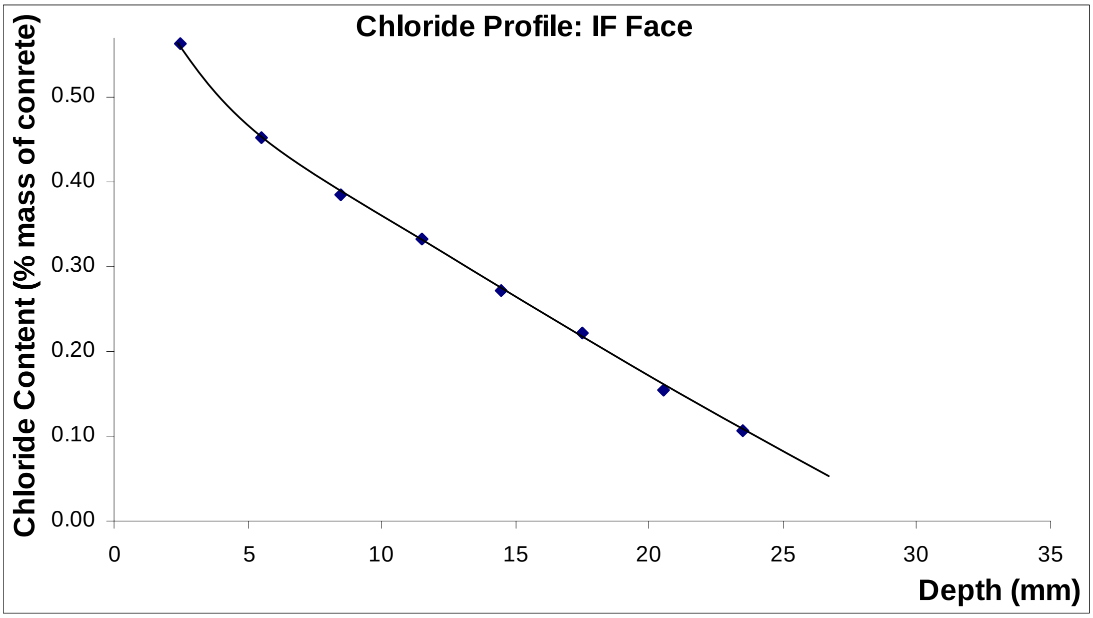
1st use of Formtex CPF liner





2nd use of Formtex CPF liner





I. Summary of Results

Pull-Off Tests

W/C Ratio	No. of use of CPF	Force (kN)		% improvement	Average improvement per w/c ratio
		CPF face	IF face		
0.45	1	8.68	6.36	27	25
	2	8.45	6.59	22	
0.5	1	7.71	3.92	49	31
	2	5.98	5.20	13	
		Overall average improvement		28	

Air Permeability Tests

W/C Ratio	No. of use of CPF	K_a		% improvement	Average improvement per w/c ratio
		CPF face	IF face		
0.45	1	0.127	0.359	65	52
	2	0.106	0.171	38	
0.5	1	0.094	0.410	77	67
	2	0.192	0.436	56	
		Overall average improvement		60	

Water Absorption Tests

W/C Ratio	No. of use of CPF	Sorptivity		% improvement	Average improvement per w/c ratio
		CPF face	IF face		
0.45	1	3.276	4.777	31	30
	2	3.643	5.090	28	
0.5	1	4.320	8.432	49	43
	2	5.828	9.039	36	
		Overall average improvement		36	

Carbonation Depth

W/C Ratio	No. of use of CPF	Depth (mm)		% improvement	Average improvement per w/c ratio
		CPF face	IF face		
0.45	1	0.4	9.6	96	95
	2	0.2	10.3	98	
0.5	1	0.5	13.0	96	97
	2	0.3	10.8	98	
		Overall average improvement		96	

Chloride Penetration

W/C Ratio	No. of use of CPF	Depth (mm)		% improvement	Average improvement per w/c ratio
		CPF face	IF face		
0.45	1	14.9	20.6	28	29
	2	14.3	20.3	30	
0.5	1	14.5	24.9	42	43
	2	13.6	24.1	43	
		Overall average improvement		36	

Chloride Diffusion Coefficient

W/C Ratio	No. of use of CPF	Apparent Chloride Diffusion ($D_{a)}$)		% improvement	Average improvement per w/c ratio
		CPF face	IF face		
0.45	1	0.39	2.18	82	67
	2	2.01	4.08	51	
0.5	1	2.34	6.58	64	67
	2	2.16	7.15	70	
		Overall average improvement		67	