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Technical-economical consequences of the use of controlled permeable formwork

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ABSTRACT: A series of tests, applied on a 16-year old panel with one face de-watered by the use of "Zemdrain" CPF, showed an improvement in hardness and a reduction in the "penetrability" of the treated surface, compared to that in direct contact with the formwork. The series included NDT (Rebound and Air-Permeability) and tests on drilled cores: Chloride Migration, Water sorptivity and microscopy observation (both last conducted at different depths). The application of the CPF resulted in an improvement of all the properties tested and can be associated to a w/c reduction from 0.55 to about 0.40. The tests conducted at different depths showed that the CPF's effect of reducing the w/c ratio extends to a depth of 10–30 mm. The cost-efficiency of the use of CPF depends on the local conditions and the surface/volume ratio of the element; for Switzerland, the treatment may become convenient only for relatively thick walls. However, the spread of the use of CPF goes hand-in-hand with the adoption of performance-based specifications, particularly those specifying and controlling the "penetrability" of the concrete on site (end product).

1 INTRODUCTION

It is widely accepted that the surface layers of a concrete structure (the "covercrete"), responsible to resist the penetration of aggressive substances, are of poorer quality [Torrent et al. (2007)] than the core and than the cast specimens used for quality control.

In order to revert that situation, i.e. achieve a lower "penetrability" of the surface layers, some techniques have been developed (e.g. impregnation/sealing of the surface, de-watering through vacuum treatment of horizontal surfaces or through the use of Controlled Permeable Formwork liners on vertical/inclined surfaces, etc.).

Controlled Permeable Formwork (CPF) liners are sheets of synthetic fibers fabric, capable of retaining cement-sized and larger particles, but of allowing water and air to flow through under hydrostatic pressure, intensified during vibration. Thus, the surface strata lose water and air and is enriched by cement dragged from the inner layers [Leow (2004)], with a reduction of the water/cement ratio.

The efficiency of CPF to reduce the "penetrability" of the treated surface has been proved by several investigations [Cullen (1998), Malone (1999), COWI-Almoayed Gulf WLL (2002), Leow (2004), Basheer et al (2005)], typically conducted on elements cast under vibration and tested at relatively young ages (about 1 month).

Some medium-term tests (ND and on cores), conducted on existing structures at 6 months and 3 years of age confirm the positive effect of CPF found on laboratory specimens [Malone (1999)].

Regarding the depth of concrete affected by the use of CPF, there is contradictory information: [COWI-Almoayed Gulf WLL (2002)] state that it reaches just 5 mm, whilst [Malone (1999)] talks of a 25–50 mm range.

Despite their technical advantages, the application of CPF has been hindered by some questions raised by potential users:

a. Is the effect permanent or decays with age?
b. What is the depth of the treatment?
c. Is it really cost-effective?

The investigation here reported aims at providing answers to these questions.

2 EXPERIMENTAL LAYOUT

2.1 *Test panel*

A panel measuring W = 600 mm, H = 500 mm and D = 200 mm was cast on 16 October 1995 with a concrete having the following composition (kg/m³): CEM I 52.5N (OPC) = 385, 0–3 mm Natural Sand = 957, 4–16 mm Natural Gravel = 815 and Water = 213 (w/c = 0.55). The mix had a Flow (EN 12350-5) = 520 mm (equivalent roughly to 120–150 mm slump), 0.7% air and fresh density = 2370 kg/m³; the aspect was "sandy". The 28-day cube compressive strength was 42.0 MPa.

The concrete was poured inside a wooden formwork, one of its faces covered with a CPF Liner: Zemdrain Classic and carefully compacted with internal poke vibration. During and immediately after casting, it was possible to observe water being drained to the floor through the CPF.

The panel was demoulded at 24 hours and stored permanently in a dry room (20°C, 50% RH), till the age of test (16 years).

2.2 *Non-Destructive (ND) surface tests applied*

In order to compare the performance of the face of the panel in contact with the CPF liner (identified as "Z") with that in direct contact with the formwork (identified as "F") two ND tests were applied directly on the surfaces:

- Schmidt Hammer Rebound **R** [EN 12504-2 (2001)] using the [*DigiSchmidt2*]
- Coefficient of Air-Permeability **kT** according to [SIA 262/1-E (2003)], using the [*PermeaTORR*]

The purpose of these tests was to provide an answer to question a).

On each surface, 16 measurements of kT and 20 measurements of R were conducted.

Figures 1 and 2 show the panel under Rebound and Air-permeability testing, respectively.

2.3 *Drilling of cores and tests applied*

After finishing the ND tests, 15 cores (Ø50 mm) were drilled through the whole depth on different locations of the panel.

On each of two cores, the 16-year carbonation depth was measured on ten different points along the circular surface after spraying the fresh cut surfaces with phenolphthalein solution [RILEM (1988)]. Another core was used for optical microscopy analysis (Section 2.4).

From the remaining 12 cores, the following specimens, 50 mm long, were saw cut (figures indicate distance in mm of the specimens faces from "Z" surface, with £ symbol indicating the face under test):

- Four samples (200$^{£}$–150) and four samples (0$^{£}$–50), for Chloride Migration Test [SIA 262/1-B (2003)], based on NT Build 492, (Fig. 3).
- Four samples each (0$^{£}$–50, 25$^{£}$–75, 55$^{£}$–105, 125$^{£}$–175, 200$^{£}$–150) for Water Sorptivity test [SIA 262/1-A (2003)]. Only results of water suction after 24 h are reported here.

The chloride solution of the Migration test was put in contact with the external surfaces of the cores (original "Z" and "F" faces without removal of the skin). Similarly, for Water Sorptivity specimens 0-50 and 200-150, the external surfaces of the cores were put in contact with 3 mm of water.

The purpose of these tests was to provide further information regarding questions a) and also to b).

Figure 1. Application of Rebound Hammer on "Z" surface of the panel.

Figure 2. Application of site air-permeability test on "F" surface of the panel.

Figure 3. Chloride migration test on Ø50 × 50 mm core.

2.4 *Microscopy observation*

One Ø50 × 200 mm core was used for microscopy investigation. It was cut into two halves (100 mm long) which were subsequently impregnated with fluorescent epoxy resin. Then, a thin slice about 10 mm thick was cut from the centre of the cores.

The analysis was performed with a microscopy under reflected UV light on the cut core.

The fewer the pores filled with the epoxy resin, the less UV light is reflected from the surface, the intensity of the yellow colour thus giving a relative indication about the porosity of the sample.

3 TEST RESULTS

3.1 *ND tests*

The results of the ND tests conducted on both faces of the panel are summarized in Table 1.

The air-permeability value of "F" Face is in good agreement with previous values obtained for old concretes of similar composition [Jacobs (2006)].

Using the *DigiSchmidt2* default calibration curves, the estimated cube compressive strength for "F" and "Z" faces is 50 and 67 MPa, respectively, which is consistent with the measured value at 28 days (42.0 MPa) and the effect of carbonation and age.

The results indicate that, after 16 years of conservation in a dry room, the performance of the Zemdrain face is significantly superior to that of the Formwork face, both in terms of Hardness and Air-permeability.

An analysis of the differences in R and kT values measured on both faces, based on established relations between kT [CEB-FIP (1990)] as well as R (through estimated compressive strength) [*DigiSchmidt2* and Neville (1995)] with w/c ratio, indicate that the CPF has reduced the w/c ratio of the "Z" surface by around 0.15.

3.2 *Carbonation test*

Figure 4 shows a picture of both Ø50 mm × 200 mm cores, immediately after spraying them with phenolphthalein. The results of 16-year natural carbonation, (twenty readings per surface in total) are presented in Table 2.

The results indicate that, after 16 years of conservation in a dry room, the carbonation at the Zemdrain face is about 2/3 that of the Formwork face.

3.3 *Chloride migration test*

Table 3 summarizes the results of Chloride Migration tests conducted on Ø50 mm × 50 mm specimens. The reported values are the Coefficient of Chloride Migration D_{Cl} and the penetration depth of the chlorides X_d.

The D_{Cl} and kT values of Tables 1 and 3 fit well to a previous relationship between these properties, established by [Jacobs (2006)].

The application of the CPF liner has reduced the Coefficient of Chloride Migration by 40% compared to the "F" face.

3.4 *Water sorptivity tests*

Table 4 summarizes the results of water sorptivity tests conducted on Ø50 mm × 50 mm specimens.

Table 1. Results of ND measurements on test panel.

Test	Rebound [–]		kT (10^{-16} m²)*	
Face	Median	St. dev.	GeoMean	sLOG
Formwork face	46	4.8	6.6	0.16
Zemdrain face	54	2.1	0.79	0.14

*Since the kT values are log-normally distributed, the geometric mean of the values and the standard deviation of the LOG10 of the values are reported [Jacobs et al (2009)].

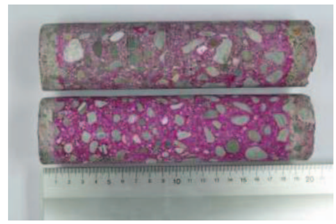

Figure 4. Carbonation of "Z" (left) and "F" (right) faces.

Table 2. Results of carbonation test on cored samples.

Test	Carbonation depth (mm)	
Face	Mean	Maximum
Formwork face	23	27
Zemdrain face	15	18

Table 3. Results of chloride migration test on cored samples.

	D_{Cl} (10^{-12} m²/s)		X_d (mm)	
Face	Mean	St. Dev.	Mean	St. Dev.
Formwork face	29	3.3	43	4.4
Zemdrain face	18	1.5	26	2.2

Table 4. Results of water sorptivity @ 24 h on cored samples.

	Water uptake (kg/m²) at depth from "Z"				
Core	0–50	25–75	55–105	125–175	200–150
1	3.10		3.16		2.68
2		3.01		3.69	
3		3.15		4.01	
5		3.33		3.81	
6	1.21		2.89		2.90
8		4.01		3.83	
11	3.50		5.81		5.39
12	4.06		5.09		5.81
Mean	2.97	3.38	4.24	3.83	4.19

The ranges indicated in the 2nd row of the Table are the distances from the faces of the specimens from the "Z" face, with the first value corresponding to that in contact with water.

The Water Sorptivity and kT values of Tables 1 and 4 fit reasonably well to a previous relationship between these properties, presented by [Denarié et al (2011)].

The application of the CPF liner has reduced the Water sorptivity @ 24 h by 30% compared to the "F" face.

Table 4 shows a significant scatter between the water sorptivity of some cores (1 and 6 lower than 11 and 12). As the trend repeats itself at the three depths, it can be attributed to heterogeneity within the panel's concrete quality.

Figure 5 presents the results of Table 4 in graphical form, including the individual cores as well as the average of four samples for each depth.

Figure 5 indicates that the effect of the CPF liner in reducing water sorptivity is still noticeable at a depth of 25 mm from the external surface. For layers beyond 50 mm, the sorptivity does not differ significantly from that of the "F" surface. These results are in agreement with the range (20–50 mm) indicated by [Malone (1999)].

3.5 *Microscopy observation*

Figure 6 presents photographs of the samples, taken from the microscope, corresponding to the "F" (left) and "Z" (right) faces.

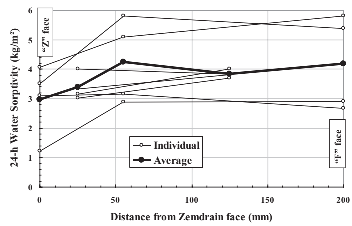

Figure 5. Water sorptivity variation with distance from "Z" face.

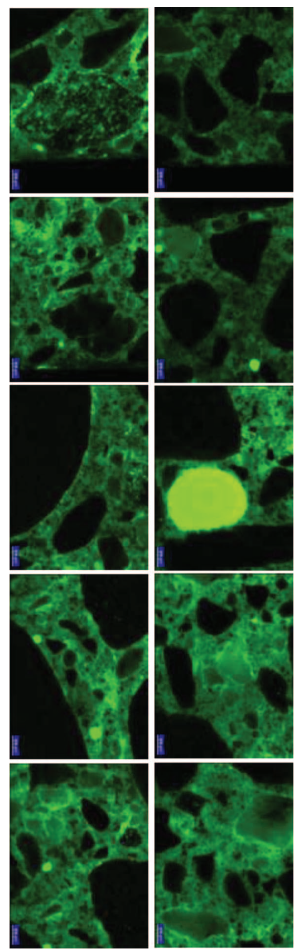

Figure 6. Microstructure of "F" (l.) and "Z" (r.) faces with depth from top to bottom. Each frame covers ≈ 5 mm depth.

The first two frames corresponding to the "Z" face are distinctively darker than those corresponding to the "F" face, indicating a reduced porosity. For deeper frames, there is not a clear difference in darkness between both faces.

Therefore, the effect of "Zemdrain" on the porosity of the concrete, qualitatively observed through the microscope, seems to reach a depth of 10 mm.

The mean carbonation depths identified under the microscope reach 22 mm for the "F" face and 12 mm for the "Z" face, which are somewhat smaller than those reported in Table 2 for the phenolphtalein test.

4 CPF AS ALTERNATIVE SOLUTION FOR DURABLE STRUCTURES

The performance of the "Z" face of the panel, compared to that of the "F" face, in terms of Hardness, Air-Permeability, Carbonation, Chloride Migration and Water Sorptivity, shows clearly the beneficial effect of the CPF.

One can then expect a significant potential for an increased service life for the treated surface, compared to the untreated face. In the case of Chlorides diffusion, applying 2nd Fick's law for equal surface chloride concentration, the service life results inversely proportional to the coefficient of chloride diffusion. Assuming a linear relationship between that coefficient and the Chloride Migration, measured on both surfaces of the panel, we can estimate that the potential service life associated with the "Z" face could be around 60% longer than for the "F" face.

On the other hand, the absolute values of the transport properties of the "Z" face are not as good as could be expected for a concrete of w/c = 0.40. This can be attributed to the permanent long lasting dry storage conditions of the panel.

The results confirm that using CPF in conjunction with a concrete of higher w/c ratio than the one specified is a valid alternative for durable construction.

5 COST-EFFECTIVENESS OF CPF

The cost-effectiveness of the CPF liner solution will depend on a number of factors, especially on its capability to reduce w/c ratio, specified strength, cost of installed CPF, price of concrete as function of w/c ratio and surface/volume ratio of the structure.

Let us analyze the situation for a wall element of volume V = H*W*D (m^3) that has a surface area S = H*W (m^2) exposed to an aggressive environment XD3. The maximum w/c ratio specified for that exposure class is 0.45 and the required strength class is C30/37 [SN EN 206-1 (2000?)].[1]

Based on the results of the experiment here reported for the investigated type of concrete we can assume that, to achieve a w/c = 0.45 at the exposed surface, we can cast a concrete with w/c = 0.60 and apply a CPF covering the whole exposed surface area S.

The cost of the conventional solution (no CPF) is:

$$C_0 = P\$_{0.45} * V \tag{1}$$

where:
C_0 = cost of solution without CPF ($)
$P\$_{0.45}$ = price of concrete of w/c = 0.45 ($/$m^3$)
$ = local currency

The cost of the solution with CPF is:

$$C_Z = P\$_{0.60} * V + C\$_Z * S \tag{2}$$

where:
$P\$_{0.60}$ = price of concrete of w/c = 0.60 ($/$m^3$)
$C\$_Z$ = cost of installed Zemdrain Classic ($/$m^2$)

The savings ΔC($) by using CPF would be (deducting Eq. 2 from Eq. 1):

$$\Delta C = C_0 - C_Z = (P\$_{0.45} - P\$_{0.60}) * V - C\$_Z * S \tag{3}$$

The relative saving respect to the non CPF solution is obtained dividing (3) by (1):

$$\Delta C/C_0 = (P\$_{0.45} - P\$_{0.60})/P\$_{0.45} - C\$_Z/P\$_{0.45} * S/V \tag{4}$$

or in the case of a wall:

$$\Delta C/C_0 = (P\$_{0.45} - P\$_{0.60})/P\$_{0.45} - C\$_Z/P\$_{0.45}/D \tag{5}$$

In case of two faces exposed:

$$\Delta C/C_0 = (P\$_{0.45} - P\$_{0.60})/P\$_{0.45} - 2 * C\$_Z/P\$_{0.45}/D \tag{6}$$

Analyzing the case of Switzerland, we can assume:

$P\$_{0.60}$ = 110 CHF/m^3; $P\$_{0.45}$ = 139 CHF/m^3.[2]

$C\$_Z$ = Cost of Zemdrain Classic + 0.15 man-hour/m^2 installation = 15 CHF/m^2 + 15 CHF/m^2 = 30 CHF/m^2.

Figure 7 presents the variation of the expected savings resulting from using Classic Zemdrain as function of the thickness of the wall (for the case of one or two exposed faces), based on Swiss prices.

It can be seen that for wall thicknesses larger than 1 m (one exposed face) or 2 m (two exposed faces) the use of CPF becomes advantageous.

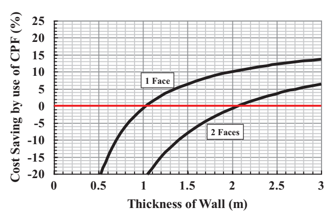

Figure 7. Savings by using CPF on walls of various thickness.

[1]A minimum cement content of 320 kg/m^3 is also specified.

[2]Both for same workability and strength class C30/37.

6 CONCLUSIONS

The results obtained in this investigation yield the following conclusions:

- As expected, the beneficial effects of the use of CPF seem to be permanent as they result from a change of structure of the pore system of the concrete rather than from a temporary sealing of pores
- Significant improvement in the following properties were measured on the "Z" face of the 16-year panel, compared to the "F" face:
  - A ten-fold reduction in the coefficient of Air-permeability kT
  - A 20% increase in surface hardness R
  - A 33–45% reduction in Carbonation depth
  - A 40% reduction in the coefficient of Chloride Migration D_{Cl}
  - A 30% reduction in water sorptivity
- That improvement allows the design of concretes, treated with CPF, of moderate strength (higher w/c ratio) and still of good durability in terms of low "penetrability" of the cover
- The use of such leaner mix leads to a more sustainable solution and, particularly for rather massive elements, to reduced cracking susceptibility
- The cost-efficiency of applying a CPF liner (to achieve the specified w/c ratio or durability performance) depends on local conditions and on the surface/volume ratio of the element. For Swiss conditions, a wall at least 1 m thick with one face exposed to an aggressive environment may benefit from the use of CPF
- The water sorptivity tests conducted at different depths and the microscopy observation of the microstructure indicate that the effect of CPF in reducing w/c ratio extends 10 to 30 mm from the treated surface.

These conclusions provide answers to questions a) to c) stated in the Introduction.

Despite the advantages of using CPF to enhance the durability of concrete structures, its use is hindered by the strict application of prescriptive specifications (maximum w/c, minimum cement content) and/or specifications based on separately cast control specimens. The application of performance specifications, such as those proposed by the Swiss Federal Highway Administration [Jacobs et al (2009)], based on measuring the coefficient of Air-permeability on site, will certainly facilitate the diffusion of this technology.

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