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The combined benefits of CPF and RHA in improving the durability of concrete structures

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Abstract

The work presented is a laboratory study of controlled permeability formwork (CPF) applied to concrete where cement was partially replaced (10%, 15% and 20%) with Portuguese rice husk ash (RHA). Portuguese rice husk is a by-product which may be incinerated industrially. Various tests were carried out to evaluate the durability of concrete made with RHA at 10%, 15% and 20% replacement of cement by weight and cast with both the usual formwork and CPF. Tests carried out so far, reported in this paper, concern strength, absorption by capillarity and chloride ion penetration. Results lead to the conclusion that CPF enhances concrete performance even further when using partial cement replacement by RHA.

Keywords: Controlled permeability formwork (CPF); Rice husk ash (RHA); Partial cement replacement; Concrete durability; Testing

1. Introduction

The majority of concrete deterioration cases are connected to corrosion of reinforcement due to carbonation or chloride induced depassivation of steel bars. On the other hand it has been well established that sustainable development of the cement and concrete industries can be achieved by the complete utilization of cementitious and pozzolanic by-products [1].

During the 20th century there has been an increase in the consumption of mineral admixtures by the cement and concrete industries. This rate is expected to increase. The increasing demand for cement and concrete is met by partial cement replacement. Substantial energy and cost savings can result when industrial by-products are used as a partial replacement for the energy-intensive Portland cement. The presence of mineral admixtures in concrete is known to impart significant improvements in workability and durability. The use of by-products is an environmental-friendly method of disposal of large quantities of materials that would otherwise pollute land, water and air. The current cement production rate of the world, which is approximately 1.2 billion tons/year, is expected to grow exponentially to about 3.5 billion tons/year by 2015. Most of the increase in cement demand will be met by the use of supplementary cementing materials, as each ton of Portland cement clinker production is associated with a similar amount of CO_2 emission [2].

Rice husks, an agricultural waste, constitute about one-fifth of 300 million tons of rice produced annually in the world [3]. By burning the rice husks under a controlled temperature and atmosphere, a highly reactive rice ash is obtained [3,4].

In fact the ash consists of non-crystalline silica and produces similar effects in concrete as silica fume. However, unlike silica fume, the particles of rice husk ash (RHA) possess a cellular structure – Fig. 1, which is responsible for the high surface area of the material even when the particles are not very small in size [3].

Changes to the bulk composition of concrete can be used to improve durability but as the concrete surface itself is the first line of resistance to penetration of chlorides and carbonation, modification to the surface zone itself may be more effective [5].

Controlled permeability formwork (or CPF) is one of the few techniques developed recently for directly improving the concrete surface zone. This technique

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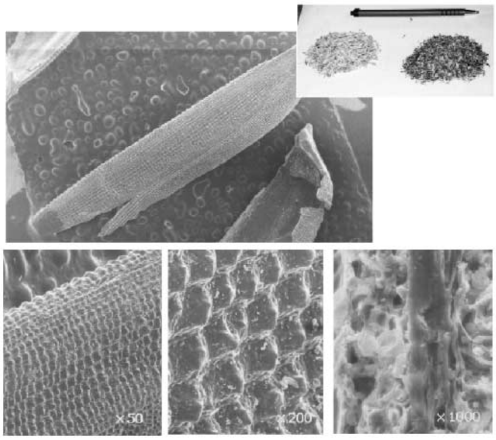

Fig. 1. Portuguese rice husks – cellular structure responsible for the high surface area.

reduces the near-surface water/binder ratio and reduces the sensitivity of concrete to poor site curing. Recent developments in CPF manufacturing intended to simplify the practical use of the technology and the role of CPF as part of a multibarrier strategy. This, along with other measures such as coatings and penetrants, can improve the durability of concrete structures [5].

CPF is also a solution to obtain a good protective outer layer of the concrete. CPF consists of using a textile liner on the usual formwork, allowing air bubbles and surplus water to drain out but retaining the cement particles and so enabling the water–cement ratio of the outer layer to become very low and the concrete to hydrate to a very dense surface skin as the filter makes enough water available at the right time to activate optimum hydration – Fig. 2. So CPF enhances durability by providing an outer concrete layer which is richer in cement particles, with a lower water/binder ratio, less porous and so much less permeable than when ordinary formwork is used.

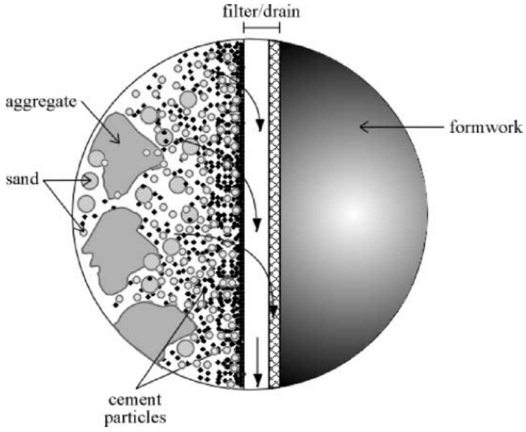

Fig. 2. Schematic functioning of CPF.

2. Research programme

The aim of the research programme is to ascertain the multiple improvement in the performance of concrete with partial cement replacement by Portuguese RHA in different percentages (10%, 15% and 20%) and when using CPF.

Results presented in this paper refer to a first phase where, besides strength at 80 days, other aspects concerning durability were studied such as absorption by capillarity and resistance to chloride ion penetration. The second phase, including mainly resistance to carbonation, permeability measured through water penetration under pressure and sulphate resistance, will be published in a next paper as results are not yet available.

3. Materials and testing

3.1. Rice husk ash

A thermal analysis (TG-DTA) was initially undertaken on a sample of rice husk and the graph in Fig. 3 was obtained.

Rice husk was incinerated in an oven at a heating rate of 10 °C per minute up to 650 °C, maintained at this temperature for 8 h, and then allowed to cool down to room temperature. The ash was then ground. Fig. 4 shows its particle size distribution.

Electron scanning microscopy (SEM-EDX) testing was undertaken on samples of RHA with a JEOL JSM 35C microscope system NORAN, Voyager and semi-quantitative standardless analysis was carried out – Fig. 5.

The specific gravity of the ash was also evaluated and a value of 2.15 g/cm^3 was obtained.

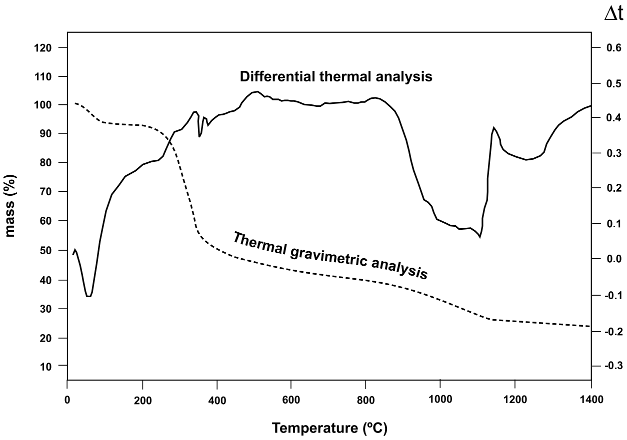

Fig. 3. Thermal analysis curves for rice husk.

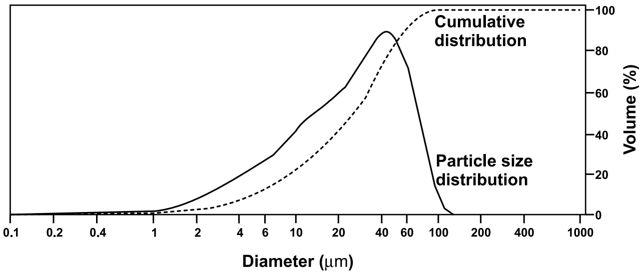

Fig. 4. Particle size distribution of the RHA.

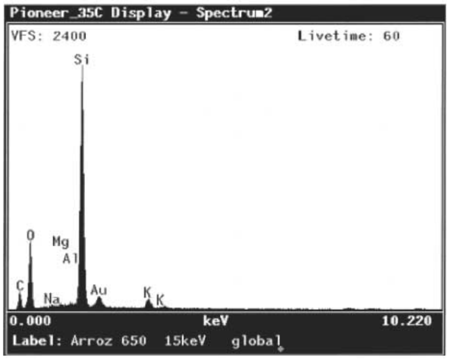

Fig. 5. Semi-quantitative standardless analysis of rice husk.

The BET surface area was 22.36 m^2/g and the XR diffraction pattern confirmed that RHA is mainly amorphous silica – Fig. 6.

3.2. Formwork

Each mould used was of impermeable plywood formwork (PERI) but one of the broader faces (30×80 cm^2 (see Section 3.3)) was covered with a filter/drain (Zemdrain MD1) used for CPF, prior to casting.

3.3. Concrete specimens

Five test specimens of $30 \times 20 \times 80$ cm^3 were produced, one corresponding to a control concrete (CTL), a second (SF) with 10% cement replacement with silica fume (commercially available) and three others with 10% (10% RHA or 1A), 15% (15% RHA or 1A5) and 20% (20% RHA or 2A) cement replacement with RHA obtained in the laboratory, as described before. Mixture proportions of the different mixes are shown in Table 1.

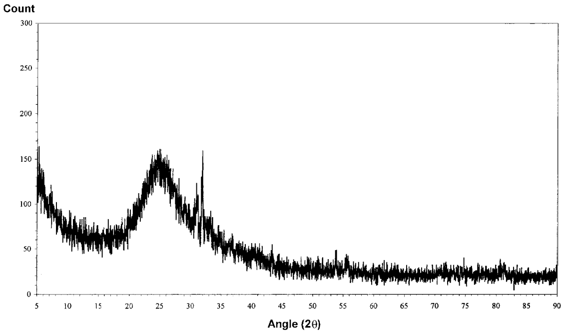

Fig. 6. XR diffraction of RHA.

Cement used was CEM Type II 32.5 in accordance with European Standards, fine and coarse sand are of natural origin and both types of coarse aggregate, of granitic origin. Particle size distributions are shown in Fig. 7.

Concrete was produced for each mix, the slump was measured (Table 1) and each mould was filled with successive layers and vibrated with a suitable poker.

The top face was then covered with plastic and the formwork was stripped off 30 h later and wet-cured for a further 5 days at room temperature (20 °C). Later and after analysing the concrete surface finish, cores from each test specimen were drilled out according to the location shown in Fig. 8.

Test cores used for absorption by capillarity were sawn in half, one half corresponding to the usual formwork face and the other corresponding to the CPF face.

Test cores used for chloride resistance and strength, located as shown in Fig. 8, were sawn in three parts, the two top 50 mm discs corresponding to the usual

Table 1
Concrete mixture proportions

Mixture proportions	Control	Partial cement replacement of			
	CTL	10% RHA	15% RHA	20% RHA	10% SF
Cement (kg/m^3)	354	321	303	283	320
Silica fume (kg/m^3)	–	–	–	–	35
Rice husk ash (kg/m^3)	–	35	53	72	–
Fine sand (kg/m^3)	151	152	152	153	152
Coarse sand (kg/m^3)	739	743	745	746	742
Coarse agg., 5/15 (kg/m^3)	436	438	439	440	438
Coarse agg., 15/25 (kg/m^3)	568	571	572	574	571
Superplasticizer (%/B)	1.2%	1.2%	1.2%	1.2%	1.2%
Water (w) (l/m^3)	151	152	152	153	152
Water/binder (w/B)	0.43	0.43	0.43	0.43	0.43
Slump (mm)	145	15	20	20	35

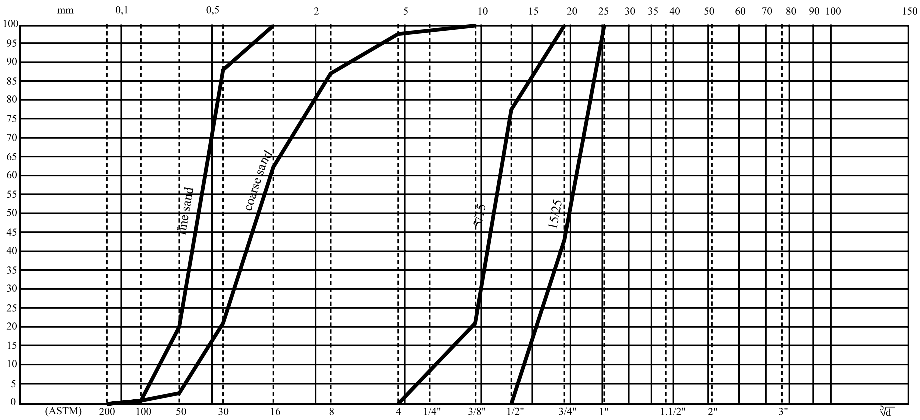

Fig. 7. Particle size distribution of aggregates used.

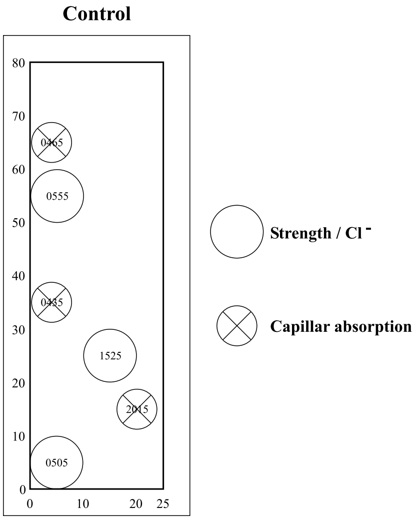

Fig. 8. Location of test cores in each test specimen. (The axes x and y were marked on each of the five 30×80 cm^2 faces at 5 cm distance from each bottom left corner of the front face.) Front face: usual formwork. Back face: CPF.

formwork face and the CPF face, both for chloride resistance testing and the middle 100 mm part for strength testing.

4. Testing

Test results reported in this paper concern strength at 80 days, absorption by capillarity and chloride resistance.

4.1. Strength

Strength testing was undertaken at 80 days, on cores of 94 mm diameter and approximately 100 mm long obtained, as described above. Results are shown in Table 2 and Fig. 9.

4.2. Surface finish

Observing the test specimens, one for each mix (CTL, SF, 10% RHA, 15% RHA and 20% RHA), all the surfaces cast with CPF were slightly textured and had no blowholes – Fig. 10. The corresponding surfaces cast with usual formwork were lighter in colour, dustier and had many imperfections and blowholes.

4.3. Absorption by capillarity

These tests were undertaken on cores 105 days old, approximately 74 mm diameter by 100 mm length obtained, as described above, from cores drilled as located in Fig. 8. Test cores corresponding to the usual formwork are designated simply according to the corresponding mix: This is: control – CTL, 10% silica fume – SF, 10% RHA – 1A or 10% RHA, 15% RHA – 1A5 or 15% RHA and 20% RHA – 2A or 20% RHA. Test cores corresponding to CPF are designated according to the corresponding mix plus the symbols "CPF" (i.e. CTL–CPF stands for control mix concrete cast with CPF).

Test cores were previously prepared with a 10 mm wide ring of epoxy resin applied to the round surface next to the formwork face so that water would only be absorbed through this face. Then they were put to dry in a ventilated heater at 40 °C until the difference between two consecutive weights was less than 0.5% of the original weight. For the test itself, cores were placed

Table 2
Strength at 80 days (MPa)

Location		0505	1525	055	Average
Control	CTL	36.2	35.4	33.7	35.1
Silica fume	SF	39.4	38.6	38.1	38.7
10% RHA	1A	41.0	42.3	41.2	41.5
15% RHA	1A5	40.7	44.3	40.1	41.7
20% RHA	2A	42.6	42.7	43.7	43.0

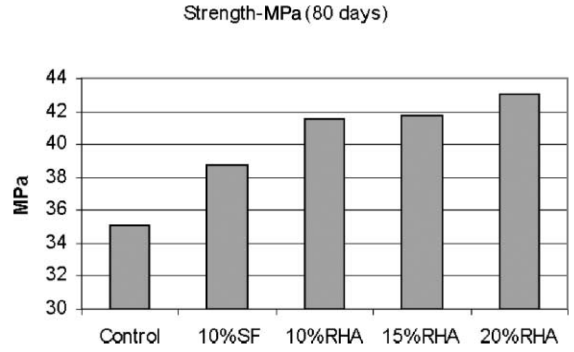

Fig. 9. Average strength.

Fig. 10. Surface finish of the CPF faces of two of the test specimens (20% RHA and 15% RHA).

formwork face downwards in a shallow water bath and supported on rods. Water level was adjusted so that the formwork face was dipped to a depth of approximately 3 mm. During the test, water was drawn into the core, only through the formwork face, by capillary forces and weighed at time intervals up to 4 h from the start of the test.

The absorption of water into concrete under capillary action is dependent on the square-root of time [6] and may be modelled by the following equation:

$$A = a_0 + St^{0.5}, \tag{1}$$

where A (mg/mm^2) is the water absorption by unit area of concrete surface since the moment the core is dipped in water, S is the sorptivity of the material, t is the elapsed time and a_0 (mg/mm^2) is the water absorbed initially by pores in contact with water. The above equation was found to provide a very good fit to the data with coefficients of correlation over 0.994, as can be seen in Fig. 11 and Table 3. Table 3 and Fig. 12 present the average sorptivity values for each mix and formwork type.

4.4. Resistance to chloride penetration – AASHTO test

Resistance to chloride penetration may be assessed with the AASHTO T277-83 test method, "rapid determination of chloride permeability of concrete". Briefly, the above method consists of monitoring the amount of electrical current which passed through an approximately 100 mm diameter by 50 mm thick concrete specimen, when a potential difference of 60 V is maintained across the specimen for a period of 6 h. Chloride ions are forced to migrate out of a NaCl solution subjected to a negative charge through the concrete into a NaOH solution maintained at a positive potential – Fig. 13.

The conditioning of the concrete disc specimens for the test procedure consists of 1 h of air drying, 3 h of vacuum (pressure <600 mm Hg), 1 h of additional vacuum with specimens under deaerated water, followed by 18 h of soaking in water. The total charge passed, in Coulombs, is used as an indicator of the resistance of the concrete to the passage of chloride ions [7].

Results of this test carried out between 90 and 100 days are shown in Table 4 and Fig. 14.

4.5. Resistance to chloride penetration – CTH rapid method

The AASTHO test method, although an important contribution as a simple and quick method, has been subject to some criticism [8,9] and other tests have been idealized, including the CTH rapid method.

The CTH rapid method is a non-steady-state migration method based on a theoretical relationship between diffusion and migration which enables the calculation of the chloride diffusion coefficient from an accelerated test [10].

It is based on measuring the depth of colour change of a silver nitrate solution sprayed on specimens previously submitted to a migration test and application of the following equations [10,11].

$$D_{\mathrm{ns}} = \frac{\mathrm{RTL}}{\mathrm{ZFU}} \frac{x_{\mathrm{d}} - \alpha\sqrt{x_{\mathrm{d}}}}{t}, \tag{2}$$

$$\alpha = 2\sqrt{\frac{\mathrm{RTL}}{\mathrm{ZFU}}}\varepsilon, \quad \varepsilon = \mathrm{erf}^{-1}\left(1 - \frac{2C_{\mathrm{d}}}{C_0}\right), \tag{3}$$

where D_{ns} is the apparent diffusion coefficient obtained in a non-steady-state migration test (cm^2/s); R the gas constant $R = 8.314$ J/(mol K); T the absolute temperature (K); L the thickness of specimen (cm); Z the ion valence; F is Faraday constant, $F = 9.648 \times 10^4$ J (V mol); U the effective voltage applied (V); x_{d} the depth

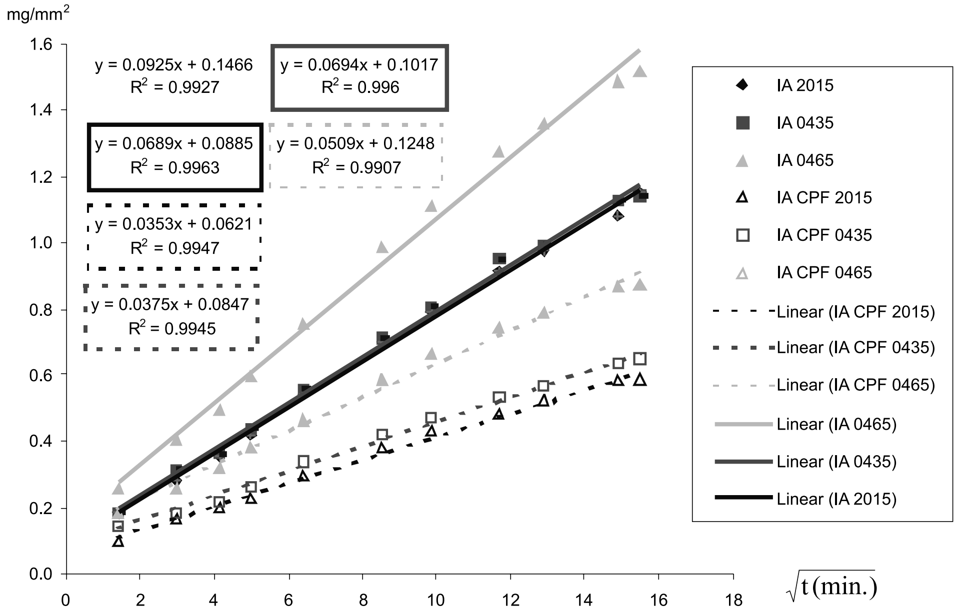

Fig. 11. Linear regression for absorption by capillarity during 4 h on test cores corresponding to 10% RHA concrete cast with usual formwork (1A) and CPF formwork (1A–CPF).

Table 3
Sorptivity (S), a_0 and R^2 values at 105 days – S (mg/(mm^2 × min$^{1/2}$))

Location		2015			0435			0465			Average
		S	a_0	R^2	S	a_0	R^2	S	a_0	R^2	S
Control	CTL	0.0936	0.0196	0.9986	0.0927	0.0360	0.9953	0.0951	−0.0179	0.9985	0.0938
+CPF	CTL–CPF	0.0501	0.0240	0.9985	0.0536	0.0447	0.9957	0.0675	−0.0459	0.9982	0.0571
Silica fume	SF	0.0608	0.0572	0.9987	0.0686	0.1387	0.9966	0.0596	0.1015	0.9945	0.0630
+CPF	SF–CPF	0.0503	0.0497	0.9990	0.0424	0.0399	0.9988	0.0492	0.0562	0.9982	0.0473
10% RHA	1A	0.0689	0.0885	0.9963	0.0694	0.1017	0.9960	0.0925	0.1466	0.9927	0.0769
+CPF	1A–CPF	0.0353	0.0621	0.9947	0.0375	0.0847	0.9945	0.0509	0.1248	0.9907	0.0412
15% RHA	1A5	0.0666	0.2102	0.9892	0.0567	0.1939	0.9863	0.0517	0.2157	0.9851	0.0583
+CPF	1A5–CPF	0.0354	0.1364	0.9989	0.0307	0.1048	0.9864	0.0427	0.1331	0.9991	0.0363
20% RHA	2A	0.0696	0.1589	0.9975	0.0592	0.1766	0.9893	0.0584	0.1296	0.9948	0.0624
+CPF	2A–CPF	0.0337	0.0882	0.9886	0.0365	0.0977	0.9940	0.0424	0.0536	0.9945	0.0375

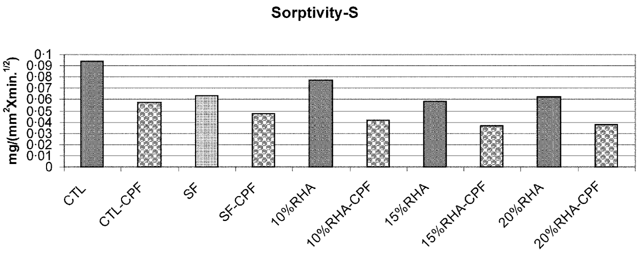

Fig. 12. Average sorptivity values S (mg/(mm^2 × min$^{1/2}$)) for each concrete mix cast with CPF and with usual formwork.

of chloride penetration measured by using a colorimetric method (cm); t the time of test duration (s); α the laboratory constant; $\varepsilon = 00.764$ if external chloride concentration of 0,5 M; C_d the concentration of free

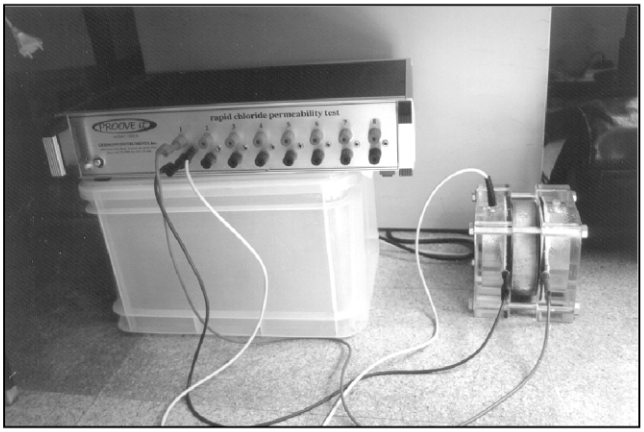

Fig. 13. Rapid determination of chloride permeability of concrete.

Table 4
AASHTO test results at 90–100 days (Coulombs)

Location		2015	0435	0465	Average
Control	CTL	2285	2565	2198	2349.3
+CPF	CTL–CPF	1923	1742	2084	1916.3
Silica fume	SF	461	439	493	464.3
+CPF	SF–CPF	400	385	382	389.0
10% RHA	1A	376	471	458	435.0
+CPF	SF–CPF	322	349	483	384.7
15% RHA	1A5	345	329	292	322.0
+CPF	1A5–CPF	234	228	273	245.0
20% RHA	2A	258	291	230	260.0
+CPF	2A–CPF	189	205	212	202.0

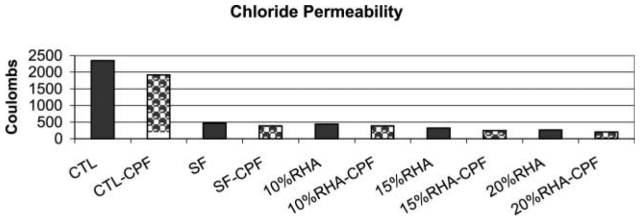

Fig. 14. Average results (Coulombs) of the AASHTO test for each mix with CPF and with usual formwork.

chloride at which the colour changes when using the colorimetric method to measure the chloride penetration depth $(\mathrm{kg_{Cl}}/\mathrm{m}^3_{\mathrm{solution}})$; and C_0 is the concentration of free chloride in the external solution.

The procedure for determining the apparent diffusion coefficient (D_{ns}) consisted of: after switching off the electrical field, the specimens were split in two halves and the penetration of chlorides was measured by using the colorimetric method. This method consists of spraying silver nitrate solution over the split faces, storing them in a dark place for an hour and then exposing them under a fluorescent light for a few hours, after which the average front of the white zone in the central part of each specimen is measured with a precision of 0.5 mm [10]. Apparent diffusion coefficient D_{ns} results are shown in Table 5 and Fig. 15.

5. Discussion and conclusions

Considering results of the tests carried out in this first phase, that is, strength, surface finish, absorption by capillary and resistance to chloride penetration, the following conclusions may be drawn out:

- Using RHA as a partial cement replacement enables higher compressive strength than control concrete (0% RHA) and also higher than 10% SF concrete.
- Using CPF enables a blowhole free surface area (all cases) compared to the same concrete mix cast with the usual formwork.
- Considering absorption by capillarity tests, sorptivity values for concrete with 10%, 15% and 20% replacement by RHA are lower than for control concrete. Using CPF further reduces the sorptivity values (Table 6, Fig. 16).
- Comparing sorptivity values for concrete with 10%, 15% and 20% replacement by RHA are still lower than for silica fume concrete. Using CPF further reduces these sorptivity values (Table 7, Fig. 17).

Table 5
Values of the apparent diffusion coefficient D_{ns} (cm^2/s)

Location		2015	0435	0465	Average
Control	CTL	29.5×10^{-8}	23.7×10^{-8}	23.7×10^{-8}	25.6×10^{-8}
+CPF	CTL–CPF	23.7×10^{-8}	14.0×10^{-8}	12.1×10^{-8}	16.7×10^{-8}
Silica fume	SF	5.4×10^{-8}	4.5×10^{-8}	7.3×10^{-8}	5.7×10^{-8}
+CPF	SF–CPF	1.7×10^{-8}	2.6×10^{-8}	5.4×10^{-8}	3.2×10^{-8}
10% RHA	1A	5.4×10^{-8}	3.1×10^{-8}	3.5×10^{-8}	4.0×10^{-8}
+CPF	SF–CPF	0.8×10^{-8}	0.03×10^{-8}	2.6×10^{-8}	1.1×10^{-8}
15% RHA	1A5	3.5×10^{-8}	0.8×10^{-8}	5.4×10^{-8}	3.2×10^{-8}
+CPF	1A5–CPF	2.5×10^{-8}	0.3×10^{-8}	3.1×10^{-8}	2.0×10^{-8}
20% RHA	2A	3.1×10^{-8}	1.2×10^{-8}	1.7×10^{-8}	2.0×10^{-8}
+CPF	2A–CPF	0.03×10^{-8}	0.03×10^{-8}	0.3×10^{-8}	0.1×10^{-8}

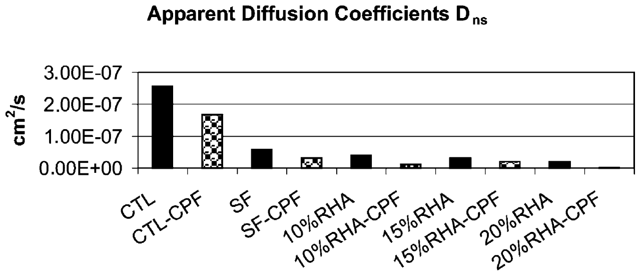

Fig. 15. Average apparent diffusion coefficients (D_{ns}).

- Results of the rapid determination of chloride permeability of concrete test (AASHTO) and of the CTH rapid method show that using RHA as a partial cement replacement drastically enhances resistance to chloride penetration compared to control concrete (on average, around seven times higher for the AASHTO test and about eight times higher for the CTH method) and even compared to 10% SF concrete. If CPF is used there is a further enhancement on the resistance to chloride penetration (Tables 6 and 7, Figs. 16 and 17).

So, analysing the results of this first phase it can generally be concluded that:

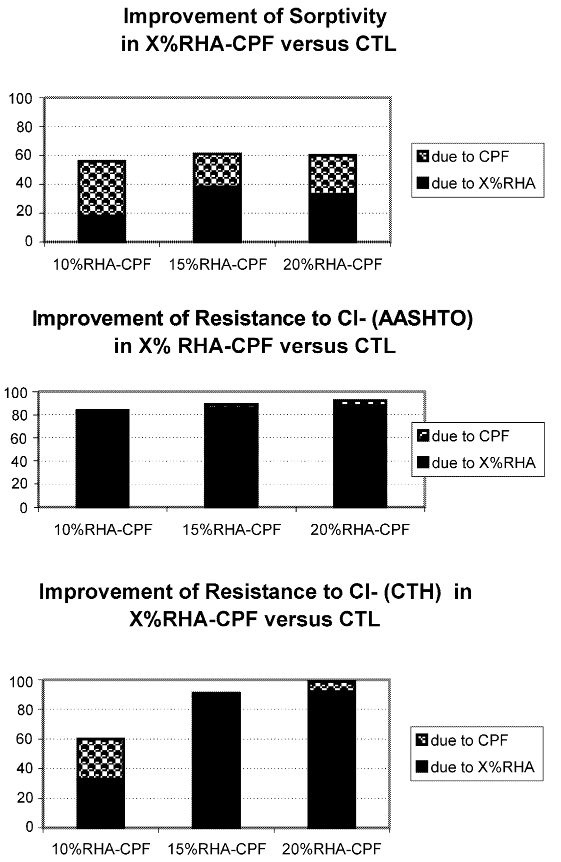

Fig. 16. Comparison of test results on specimens of RHA concrete cast with CPF versus test results on specimens of control concrete (0% RHA) cast with usual formwork.

- The effect of using 15% and 20% cement replacement by RHA enhances the concrete performance and is even further enhanced when CPF is used, compared to performance of both control concrete and silica fume concrete.
- The effect of using 10% cement replacement by RHA enhances concrete performance and is even further enhanced when CPF is used, compared to the performance of control concrete and also to silica fume concrete except for sorptivity values. In this case,

Table 6
Improvement of each concrete mix cast with CPF versus control concrete (0% RHA) cast with usual formwork (CTL)

	Sorptivity	Chloride resistance	
		AASHTO test	CTH method
Improvement of X% RHA–CPF versus CTL: (*due to X% RHA*) + (*due to CPF*)			
10% RHA–CPF	18% + 38% = 56%	82% + 2% = 84%	84% + 12% = 96%
15% RHA–CPF	38% + 23% = 61%	86% + 3% = 89%	88% + 4% = 92%
20% RHA–CPF	33% + 27% = 60%	89% + 2% = 91%	92% + 7% = 99%

Table 7
Improvement of each concrete mix cast with CPF versus silica fume concrete cast with usual formwork (SF)

	Sorptivity	Chloride resistance	
		AASHTO test	CTH method
Improvement of X% RHA–CPF versus SF: (*due to X% RHA*) + (*due to CPF*)			
10% RHA–CPF	−22% + 57% = 35%	6% + 11% = 17%	30% + 51% = 81%
15% RHA–CPF	7% + 35% = 42%	31% + 16% = 47%	44% + 21% = 65%
20% RHA–CPF	1% + 39% = 40%	44% + 12% = 56%	65% + 33% = 98%

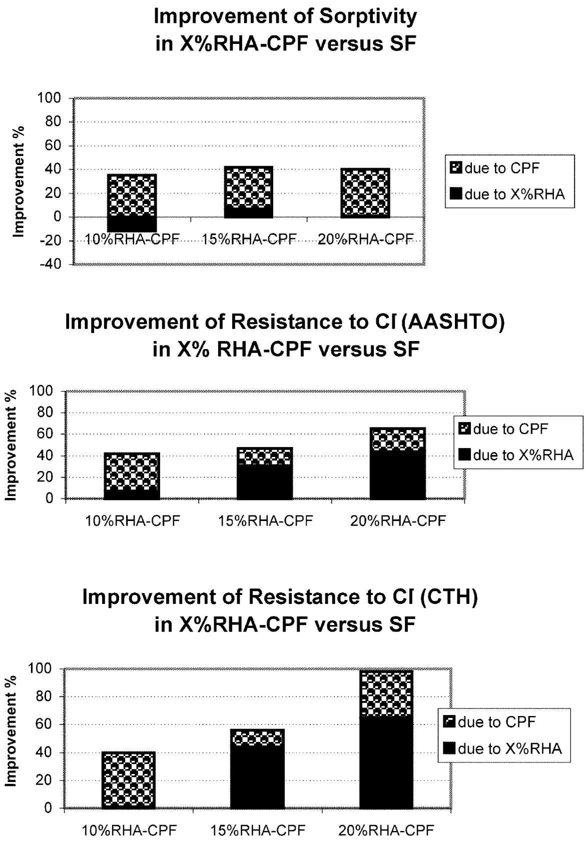

Fig. 17. Comparison of test results on specimens of RHA concrete cast with CPF versus test results on specimens of silica fume concrete cast with usual formwork.

the average sorptivity value for 10% RHA is a little higher than that for SF concrete (Table 3).

CPF and RHA enhance concrete durability and can be used as a two-level method to delay corrosion of reinforcement in concrete structures.

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