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In-situ performance of CPF concrete in a coastal environment

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Abstract

The paper describes the work of an investigation carried out to evaluate the performance of controlled permeability formwork (CPF) in a seawall. Tests were carried out in the splash (SP) and inter-tidal (I/T) regions of the seawall at two locations (built in two phases, approximately 1 year apart), which used CPF, and on a groyne where the system was not used (reference (Ref) concrete). The tests were made both in-situ and on cores removed from the walls, in the laboratory. Properties measured included, core strength, surface hardness, capillary porosity, absorption, carbonation, chloride profiles, half-cell potentials and concrete resistivity. The results indicate that CPF gave improved performance compared to the Ref concrete for almost all properties. Comparisons with other laboratory and early site-based data indicate that the benefits observed in these for CPF concrete were obtained in the test concretes of the study. In addition, there appeared to be no depletion in CPF concrete performance due to the aggressive conditions.

Keywords: Durability; Chloride; Concrete; Controlled permeability formwork (CPF)

1. Introduction

Controlled permeability formwork (CPF) has been in use in modern concrete construction for about 10 years. The system, which comprises a filter fabric and drain elements, is attached to formwork and, under the actions of concrete pressure and compaction, allows drainage of excess water and expulsion of air from concrete at the form face and migration of fines to the outer surface, giving a dense, consistent finish, free of imperfections.

Data obtained from short-term laboratory tests, over a number of years [1–4] have shown that CPF gives enhanced concrete surface properties and improved resistance to almost all forms of concrete deterioration. However, given its relatively short period of availability, little longer-term data exists on CPF concrete performance under real exposure conditions, in particular, where there is a high level of aggression.

This paper describes the work of an experimental programme carried out in mid 1999, at a seawall on the South Coast of England, to examine CPF concrete under coastal exposure conditions, after several years service. A range of tests were carried out in-situ, to evaluate concrete surface properties and durability performance and, cores were taken to carry out further tests in the laboratory. Comparisons were made with (i) similar reference (Ref) concrete in an adjacent groyne (mass concrete-containing no reinforcement), where CPF was not used and (ii) data obtained for CPF in a related study [5], considering laboratory and in-situ produced concrete.

2. Details of concrete specification and construction

The seawall, approximately 3.0 km long, is located on the South Coast of England (exposed to the English Channel), and was constructed to replace part of the existing wall (built in the 1930s), in two phases. The first phase (Phase I) was built between mid-1993 and late 1994 and the second (Phase II) between mid-1995 and late 1996. During Phase II, several mass concrete groynes were also constructed. CPF liner was used during both construction phases on the seawall faces in direct contact with seawater, but was not on the groynes.

The same concrete specification was used in both construction phases of the seawall and for the groynes. The concrete was a mix of max w/c ratio 0.45, min cement content 370 kg/m^3 (max cement content 400 kg/m^3),

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containing GGBS at a level of 30% (used to control heat), with flint aggregate of up to 40 mm maximum size and polypropylene fibres included at 900 g/m^3. The concrete cover to reinforcement used in the seawalls was 125 mm. The reinforcement was of various bar sizes up to 25 mm diameter. Typical cube strengths for the wall during construction were in excess of 50 N/mm^2 [6].

The seawall was cast in panels of up to 6.0 $\times$ 6.0 m and had a curve return, to allow for wave action, and a parapet at the top. The groynes were cast in similar panel sizes (but no return). Concreting was carried out by pump, except at low levels of the groyne, where it was directly discharged. Compaction was carried out by internal vibrating pokers.

Steel formwork was used and for the main seawall, a Type II CPF liner [7] (thermally bonded, non woven polypropylene fabric of 30 μm aperture size; Zemdrain, Classic) was tensioned on the formwork between hinged stretchers on the vertical sides and a timber batten and steel spreader bar on the top and bottom. For the curve return, steel shoes on a bar and the concrete pressure itself were used to hold the CPF in place [3,6]. The liner was used twice and cleaned between uses by high water pressure jet, which gave a consistent surface finish. The formwork was left in place for 36 hours after concreting, prior to striking and exposure [3]. Expansion joints, including water stops and filler material were used between wall sections.

3. Exposure conditions and test locations

The seawall and groynes are subject to cyclic wetting and drying conditions. The exposure is very harsh due to wave action, which is exacerbated by shingle on the beach. This aggression meant that, in design, cover loss was anticipated during service. This had occurred at some locations, particularly inter-tidal (I/T) regions, where an exposed aggregate appearance was noted, and some patch repairs had been carried out. However, the condition of the wall, assessed during routine in-service inspections, was considered to be better than expected for concrete against ordinary formwork [3].

The test areas for evaluation of CPF were selected, based on (i) access for testing, given the tidal water variations and (ii) availability of Ref concrete, required to allow comparisons in performance to be made. Three test locations of similar exposure conditions, covering Phases I, II and Ref concrete were selected, see Fig. 1. These were east facing (reflecting the Ref groyne direction) and were divided into splash (SP) and I/T regions, identified from water level observations, tidal charts and markings on the walls. Areas around wall joints (including ends of pours) were avoided, when carrying out testing. Test faces could be considered to be subject to seawater and limited wear from wave action/shingle on the concrete surface.

4. Site/laboratory test programme

The test programme was concerned with the strength and surface properties of the concrete and the resistance to reinforcement corrosion from chloride ingress. A range of tests, the details of which are summarized in Table 1, was therefore carried out both in-situ and on cores removed from

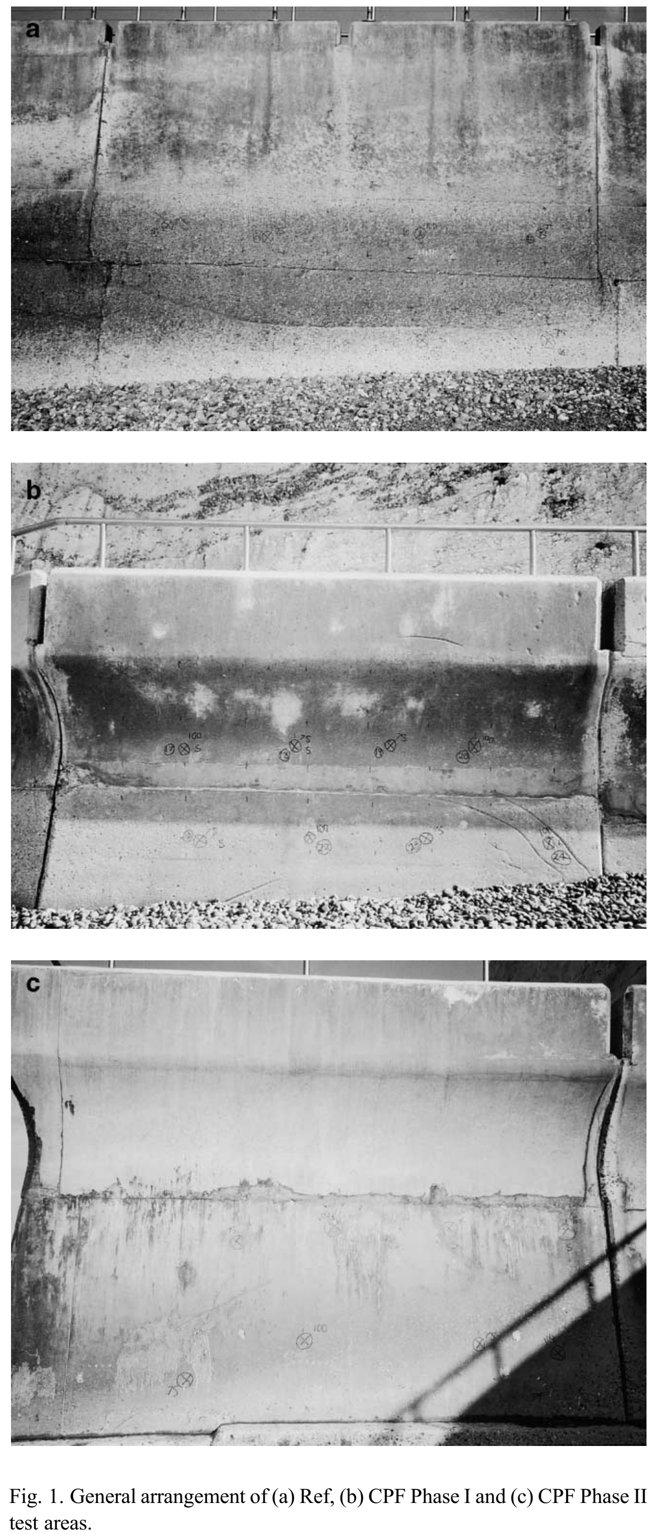

Fig. 1. General arrangement of (a) Ref, (b) CPF Phase I and (c) CPF Phase II test areas.

Table 1
Summary of experimental programme details

	Property	Test method	Test specimen/ arrangement	Number of tests on each wall[a]
Strength and surface properties	Compressive strength[b]	BS 1881: Part 120: 1983	100 mm ø core	2
	Surface hardness[c]	BS 1881: Part 202: 1986	13 point grid, 300 × 300 mm	8
	Capillary porosity[b]	BS 1881: Part 124: 1988	75 mm ø core	2
	ISA[b]	BS 1881: Part 208: 1996	100 mm ø core	2
Durability	Carbonation[b]	Phenolphthalein solution	75 mm ø core	2
	Chloride content[b]	X-ray diffraction spectrometry	75 mm ø core	2
	Half-cell potential[c]	ASTM C876 (Ag/AgCl)	500 × 500 mm grid over whole wall	2 sets
	Resistivity[c]	Wenner 4 Probe	4 points, 50 mm apart	4

All tests were carried out on both CPF walls and the reference mass (unreinforced) concrete groyne, except for half-cell.
[a] Includes both SP and I/T test regions.
[b] Tests carried out in the laboratory.
[c] Tests carried out in-situ.

each of the 6 test areas (three test locations, with two exposure regions (SP and I/T)). Given their destructive nature and damage to the seawall, tests made on core specimens involved single measurements (i.e. one SP and one I/T for each wall). At least two repeat tests or test sets were made for the in-situ tests. The corresponding results are, therefore, based on single measurements or means of duplicate tests (see Table 1).

To assess strength and surface hardness, compressive strength was measured on concrete cores (free of reinforcement) and rebound hammer tests made in-situ, following the methods described in BS 1881, Parts 120 and 202 [8,9]. Capillary porosity and initial surface absorption (ISA) of concrete were tested on oven dried cores, using the BS 1881, Part 124 and 208 methods [10,11]. Tests on core samples were also made for carbonation depth using phenolphthalein indicator solution on split surfaces and total chloride contents on powder samples, at incremental depths, using XRFS [12]. Tests for half-cell potential were made in-situ with an Ag/AgCl reference electrode in the (reinforced) CPF sections only (Ref groyne concrete contained no reinforcement), following the ASTM C876 (connection to steel) method [13]. Resistivity tests were carried out in-situ using the Wenner 4 probe test method [14], with 50 mm probe spacing, 5.0 mm holes drilled into the concrete surface and filled with cement paste to aid the probe/surface contact.

5. Visual condition of concrete

A visual assessment indicated that wear (exposure of aggregates) and marine growth were present in the Ref concrete I/T location, near the base of the wall, which reduced with height into the SP region. This reflected the greater exposure of these sections of the wall to abrasive action. In the case of CPF concretes, slight surface wear was noted near the base of the walls, with very minor aggregate exposure.

The visual observations were confirmed by colourmeter tests, which revealed that, for all test walls, the concrete colour was lightest in the I/T region, reflecting exposure of lighter coloured aggregate due to wear. The darker colour noted for the groyne in the SP region, seemed likely to reflect marine growth, which was not observed in the CPF areas tested. The darker CPF concrete found in the I/T region, was consistent with the colour differences in concrete found between normal and CP formwork in new construction [5] and reflects excess mix water drainage and increased cement content in the latter due to the action of the liner.

6. Concrete strength and surface properties

6.1. Core strength and surface hardness

The results obtained from the concrete density and core strength measurements for the three test walls and different exposure regions of each are given in Fig. 2. The results were, in the main, very similar between each of the test walls and exposure regions, with densities ranging from 2350 to 2400 kg/m^3 and core strengths 31–35 N/mm^2. The exception to this was the concrete in the SP region of the Ref wall, where both relatively low density and compressive strength were obtained. This suggests that this core was taken from an area of poor compaction, although this was not apparent from the visual condition of the concrete.

Given the concrete specification (minimum cement content 370 kg/m^3 and maximum w/c ratio 0.45) and the concrete test cube strengths during construction, the in-situ (core) strengths are what may have been expected [15]. Clearly, any changes to the concrete surface properties, through the use of CPF, hydration reactions and mineral formation during seawater exposure leading to densification (aragonite was detected, using XRD techniques, at the surface of some of the CPF concretes), or wear of the concrete surface due to exposure, were not apparent from the results. The similarity of the results indicates that the comparison of properties between the test surfaces of the different walls was approximately at equivalent strength.

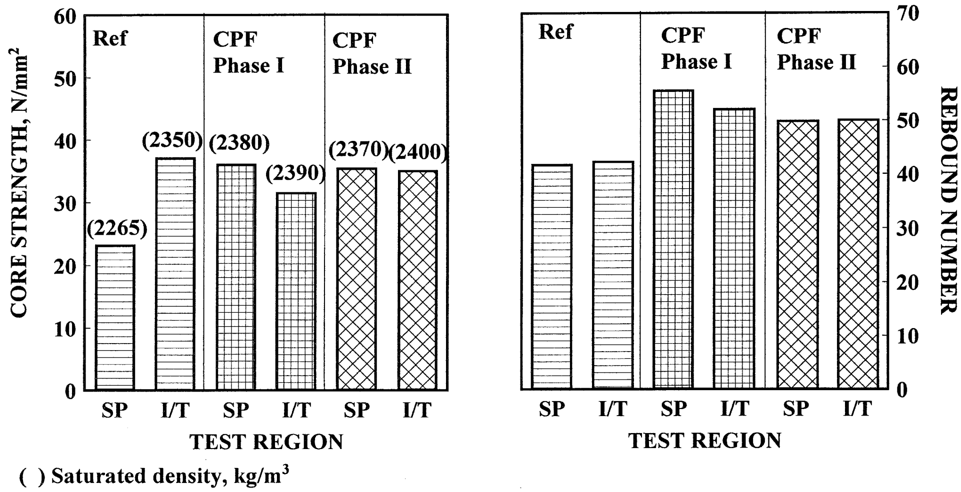

Fig. 2. Core strength and surface hardness of test concretes.

Surface hardness results are also given in Fig. 2. These indicate similar surface hardness for the two test regions of a given wall. Between test walls, CPF concrete was typically 8 to 14 units higher than the Ref concrete, with Phase I CPF concrete exhibiting highest surface hardness. These results compare well with the differences of 25 to 30% in surface hardness (using rebound hammer) noted for the concretes when tested 4 days after construction [3]. The differences in surface hardness between CPF walls, given the similarity in core strengths, suggests that for Phase I concrete, the liner was new when used, while for Phase II, other data suggests that this concrete may have been produced following a second or re-use of the liner [16].

6.2. Capillary porosity and ISA

Capillary porosity, measured in the outer 20 mm of the wall test surfaces and the results from ISA tests, both carried out in the laboratory, are given in Fig. 3. As indicated, the near-surface porosity was highest for the Ref concrete (with the SP region higher than the I/T by approximately 1.0% units) compared to those of CPF concrete, by between 1.0% and 3.0% units. In agreement with the surface hardness tests, the Phase I construction exhibited the lowest porosity values between CPF concretes, by approximately 0.7% units. For these concretes, there was little or no difference in porosity between SP and I/T regions.

ISA values, Fig. 3, were broadly in line with the porosity results and followed generally expected behavior in terms of ISA reduction with test duration up to 60 minutes. The Ref concretes exhibited the highest values, with the I/T concrete the greater of these. For the remaining concretes, the ranking was Phase II CPF-SP, Phase II CPF-I/T, Phase I CPF-I/T and Phase I CPF-SP. Flatter lines, ie less reduction in ISA with time, are indicative of less variability in concrete quality with depth and were more apparent in the CPF concretes.

The results from these surface property tests indicate general agreement in ranking of concretes between the various test walls and suggestion of liner re-use in Phase II concrete.

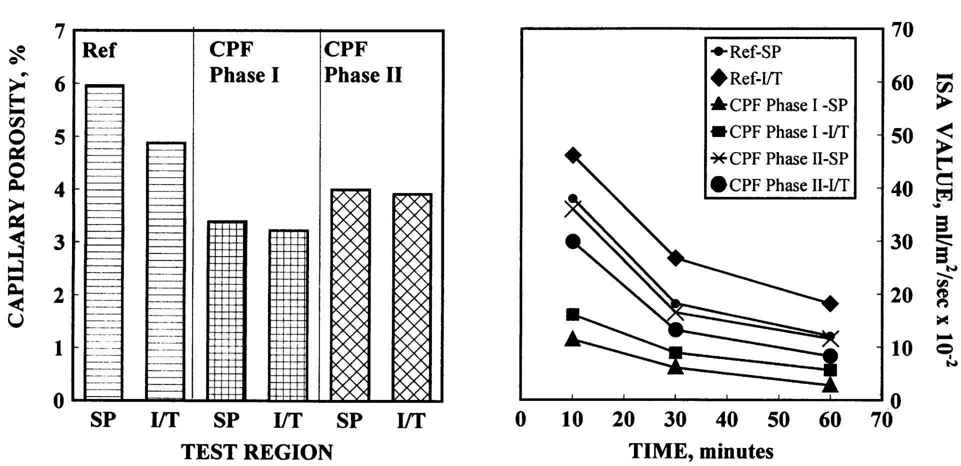

Fig. 3. Capillary porosity and ISA values for test concretes.

7. Concrete durability

7.1. Carbonation

No carbonation was detected in any of the test walls. This is reasonable for concrete in an almost continuously wet environment, where there are relatively short periods of drying.

7.2. Chloride profiles

The total chloride content profiles at incremental depths up to approximately 50 mm for the three test walls are given in Fig. 4. The results followed the generally expected behavior in terms of reducing contents with depth. The chloride content was highest in the SP region in all cases, while the ranking for both SP and I/T regions with improving chloride resistance was Ref, Phase II and Phase I CPF concretes. As with the other test results, the CPF concrete of longest exposure (Phase I) exhibited best overall chloride resistance.

The chloride profile shapes suggest that there was a more rapid reduction in chloride content from the surface in CPF concrete, as noted previously [17]. Therefore, chloride may have a tendency to collect in this denser region of CPF concrete and pass more slowly into the interior, thereafter. This effect with CPF is clearly of benefit, given the typical covers to reinforcement that are used for chloride containing environments.

7.3. Half-cell electrode potentials and concrete resistivity

The potentials recorded for Phase I CPF concrete ranged from 0 to − 250 mV, with the majority of results lying in the − 170 to − 180 mV range. The potentials suggest that no corrosion was occurring in the SP region [12], but results indicative of possible corrosion were found in the I/T region. Similar type of data was obtained for Phase II concretes, with potentials ranging from − 150 to − 300 mV, and majority between − 200 and − 210 mV. Again, more negative potentials were obtained in the I/T than SP regions. No measurements were made on the Ref plain (unreinforced) groyne concrete.

The results from Wenner 4-probe concrete resistivity tests, also carried out in-situ in the different test walls, indicated that this property was higher in the SP region and in CPF concretes for most measurements, (the latter for which it was almost always > 20,000 Ω.cm) appearing to reflect reduced moisture content and denseness of concrete microstructure. Considering these data, the half-cell potential and chloride content results and a visual examination of recovered steel from both Phase I and II CPF faces, no corrosion seemed to be occurring.

8. Comparison with laboratory and other CPF field data

In addition to examining the performance between CPF and Ref concretes, a comparison of the data obtained (average between the two CPF test locations) in the coastal exposure was made, with that obtained from short-term tests in a related study [5] for CPF concretes prepared in the laboratory and under in-situ conditions, and covering a range of properties and concrete types (tests made on 28-day air or site-cured concrete). This allowed an evaluation to be made of relative performance between normal and CPF concretes over short and longer exposure period and to establish if the influences of CPF were affected by aggressive exposure conditions.

The results of this comparison are given in Table 2. As indicated, in the majority of cases, the coastal results lay within the range of improvements found in the various laboratory and site reference and CPF concretes. In the case of surface hardness, capillary porosity and ISA (10 minute)

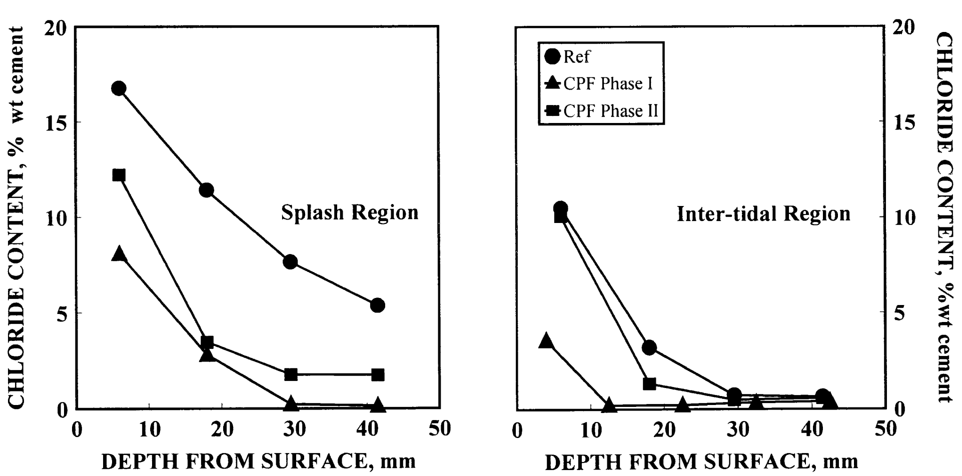

Fig. 4. Chloride variation with depth for test concretes.

Table 2
Comparison of CPF and Ref performance for laboratory/site and coastal site concrete

Property	Laboratory and site data [5]			Coastal site data	
	Number of data pairs	Relative performance (CPF/Ref)		Relative performance (CPF/Ref) average	
		Mean	Range	SP	I/T
Surface hardness	36	1.29	1.09 – 1.62	1.26	1.19
ISA test	36	0.26	0.00 – 0.67	0.61	0.49
Capillary porosity	33	0.68	0.40 – 0.95	0.61	0.73
Chloride diffusion	24	0.18	0.02 – 0.53	0.19	0.66

tests, the results lay around the mean for capillary porosity and slightly below for surface hardness and above for ISA tests. These results and those of the early rebound tests at 4 days [4] suggest that the typical differences in properties obtained through the use of CPF compared to Ref concrete were maintained during service. Therefore, the effects occurring at the concrete surface in a coastal exposure noted earlier (wear, mineral formation, etc., see Section 6.1) have either had limited effect on the test concretes, or influenced them to a similar degree. In addition the concrete maturity on exposure to the environment did not appear to have any significant effect on relative performance.

The results for the chloride diffusion tests, lie within the range for concrete in the SP region, but slightly out with in the I/T concrete. The significance of this is unclear. However, it should be noted that the tests used to establish these were different, with laboratory/site data [5] determined using a two compartment cell, compared to a graphical procedure on the chloride profiles (Fig. 4) for the coastal data. In addition, the differences in concrete maturity on exposure to chloride and the variable moisture levels between tests could have an influence. Overall, the reductions in chloride ingress for CPF concrete from laboratory data appear to be achieved for the coastal concrete in service.

9. Conclusions

The greatest signs of visual damage through wear and exposure of aggregates were noted in the Ref concretes in the I/T region. Only minor effects were found in the CPF test concretes.

The compressive strength of the cores was broadly similar between test walls. CPF concretes exhibited increases in surface hardness compared to the Ref concretes by between 20% and 25%. The capillary porosity of the CPF concretes was between 1.0% and 3.0% units lower than the Ref, while corresponding reductions for ISA (10 min) values were on average between 40% and 50%.

No carbonation was found in any of the test concretes. The chloride contents were highest in the SP region of all test walls. For comparable exposures, the chloride content at a given depth was lower in the CPF concretes. There was a suggestion of a more rapid decrease in chloride content from the outer surface of CPF walls compared to that of the reference concrete. Corrosion tests (half-cell electrode potential, concrete resistivity and visual observations) indicated that reinforcement corrosion was not occurring in CPF concrete.

Differences in the performance of CPF concretes over the range of properties tested may relate to re-use of the system and slight loss in efficiency, due to 'clogging' of pores. This appears to confirm that Type II CPF liners should be used once for optimum performance [3] (cf. the newer Type III liners maintain performance at two uses). Comparisons with related laboratory and site produced concrete (but not exposed to aggressive conditions) suggest that the benefits of CPF are maintained under aggressive exposure conditions. In addition, differences in chloride resistance between CPF and reference concretes in the coastal exposure is broadly what would be expected based on laboratory chloride diffusion tests on similar concretes.

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