Effect of curing regime and controlled permeability formwork on early chloride penetration into fly ash concrete

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ABSTRACT

Fly ash is often used as supplementing cementitious material for marine concrete structures. In these cases, the development of a dense microstructure is typically slower than for other types, and the resistance against chloride ingress at early age is at a low level, but will develop to a high level during the first 6 to 12 months.

Early chloride ingress into concrete blocks made with a binder composition of 75% low-alkali sulphate-resistant cement (CEM I 42.5 N) and 25% fly ash were investigated. The effect of wet curing and dry curing was tested on concrete blocks cast against plywood on one side and controlled permeability formwork on the other side. The development of resistance against chloride ingress was documented by means of chloride migration coefficients measured according to NT BUILD 492 at the age of 1 month and 6 months. Furthermore, chloride profiles were measured in a laboratory experiment after immersion in a 2% chloride solution for 2 months.

The investigation demonstrated that a significantly improved resistance against chloride ingress can be achieved for concrete cast against a controlled permeability formwork liner compared to concrete cast against plywood formwork. This was found to be the case both for concrete cured under wet and dry conditions. Overall, the investigation shows that the use of a controlled permeability formwork liner represents an approach associated with a good potential for extending the service life of chloride exposed concrete structures.

Keywords: Concrete, chloride penetration, controlled permeability formwork, curing, durability.

INTRODUCTION

Concrete with binders containing fly ash is often used for infrastructure constructions where low permeability is needed to give a good resistance against aggressive environmental actions, e.g. chloride exposure. However, the use of fly ash as supplementary cementitious material in concrete has the disadvantage that the development of a dense microstructure typically is slower than for other binder types. This results in a low resistance against chloride ingress at early age, but the fly ash concrete will develop a high resistance during the first 6 to 12 months. The occurrence of an initially high permeability is particularly prominent when fly ash is combined with low-alkali sulphate-resistant cements as is customary for Danish infrastructure constructions.

It would be very attractive for building owners and contractors if the initial permeability of fly ash concrete could be sufficiently reduced to prevent a large early ingress of chloride. If this could be achieved, it would prolong the service life, which is of interest for building owners, and it would facilitate earlier exposure to chlorides, which is of interest for contractors to shorten the duration of the building phase.

This paper presents the results from an investigation of early chloride ingress into blocks of fly ash concrete with an eqv. w/c-ratio of 0.40. The main goal of the investigation was to determine and evaluate the effect of using a wet versus a dry curing regime for concrete blocks cast against plywood on one side and a Controlled Permeability Formwork (CPF) liner on the other side. The positive effect of CPF liner has been reported in several cases for concrete types with w/c-ratios of 0.45 or higher, e.g. Basheer et al. (2008).

DESIGN AND PRODUCTION OF CONCRETE BLOCKS

Two concrete blocks (0.2 x 0.5 x 1.0 m) were cast for the investigation of the effect of CPF liner and different curing regimes on early chloride ingress in concrete. Identical concrete was used for the casting of the two blocks.

Concrete mix design
The concrete mix design for the two blocks is based on a binder composition with 75% low-alkali sulphate-resistant Portland cement and 25% pulverized fly ash and an eqv. w/c-ratio of 0.40, i.e. a concrete composition which could be used for Danish infrastructure constructions. Details of the concrete mix design are given in Table 1.

Mixing and casting
The concrete was mixed in a 250 liter industrial counter-current mixer and poured into a mould with plywood on one side and CPF liner on the other side. The mould was separated in the middle with a vertical plywood plate in order to cast two concrete blocks with identical dimensions and composition. A copper/constantan thermocouple was inserted to monitor the temperature and the mould was covered with thick plastic. Fresh concrete properties in terms of slump, density and air content were determined according to DS/EN 12350-2 (2009), DS/EN 12350-6 (2012), and DS/EN 12350-7 (2012), respectively. The obtained values are shown in Table 1. Supplementary Ø100 x 200 mm concrete cylinders were cast for compressive strength tests.

The two concrete blocks were demoulded after 6 days, which in this case is equal to an age of 8 maturity-days (Figure 1). The bottom part of each block measuring approx. 0.2 x 0.2 x 0.5 m was cut off and sealed in plastic at 20°C to be used later for chloride migrations tests. One block was cured immersed in water and the other block was cured in dry laboratory climate at an average temperature of 22.9°C and a relative humidity varying between approx. 45% and 78% (average: 60.3%). Both blocks were cured until an age of 27 days (= 31 maturity-days).

Table 1. Concrete mix design (target and achieved values) and measured fresh concrete properties. The cement was delivered by Aalborg Portland.

Constituent	Unit	Target	Achieved
Low alkali SR Portland cement (CEM I 42,5 N)	kg/m^3	300	298
Pulverized Fly Ash (Danish product)	kg/m^3	100	99
Aggregate 0/4 mm (quartz sand)	kg/m^3	632	630
Aggregate 4/8 mm (granite)	kg/m^3	367	364
Aggregate 8/16 mm (granite)	kg/m^3	271	271
Aggregate 16/22 mm (granite)	kg/m^3	540	539
Air entraining agent (Amex SB 22)	kg/m^3	2.00	1.99
Superplasticizer (Glenium SKY 631)	kg/m^3	2.25	3.24
Added water	l/m^3	135.6	135.0
Air	%	5.0	5.2
Effective water	l/m^3	140	139.4
Equivalent w/c-ratio (FA activity factor: 0.5)	-	0.400	0.401
Fresh concrete property	**Unit**	**Measured value**	
Slump	mm	140	
Air content	%	5.2	
Density	kg/m^3	2365	

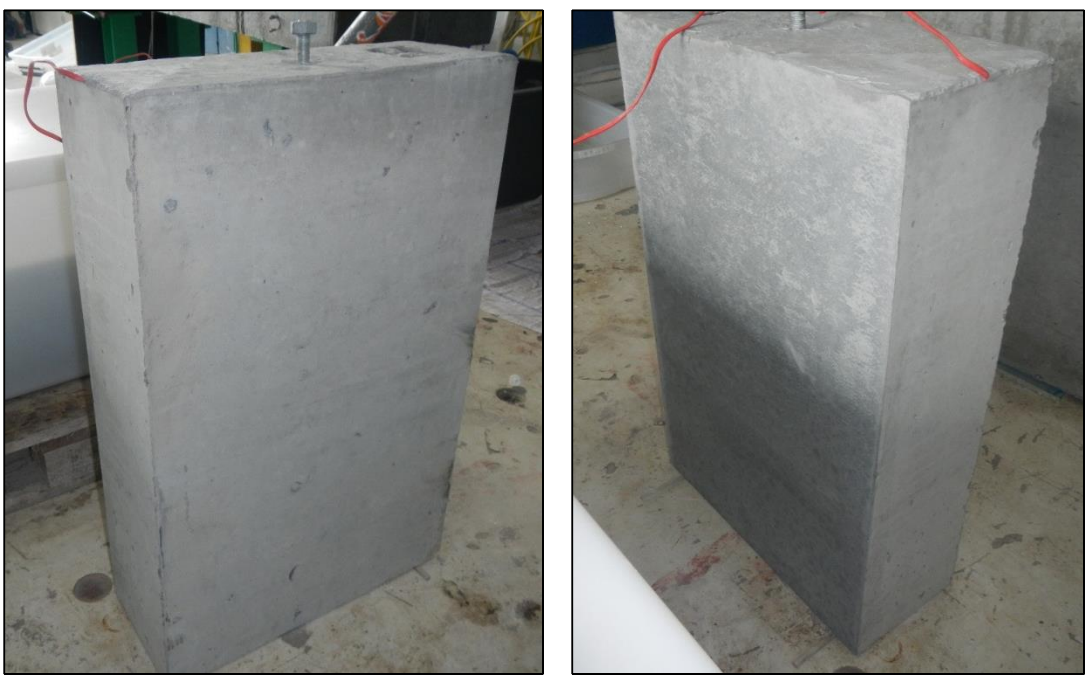

Figure 1. Left: One of the two concrete blocks after demoulding with visible side cast against plywood. Right: Same concrete block with visible side cast against CPF liner.

Testing of hardened concrete properties
The measured hardened concrete properties were compressive strength of cast cylinders according to DS/EN 12390-3 (2012) at 7 and 28 days after water curing at 20°C and chloride migration coefficient according to NT BUILD 492 (1999), i.e. Rapid Chloride Migration (RCM) test, at 35 and 180 days (= 37 and 182 maturity-days, respectively) after sealed curing in plastic. As prescribed by NT BUILD 492 specimens were subjected to vacuum treatment in a saturated $Ca(OH)_2$ solution prior to testing. The chloride migration coefficient was measured on samples from three different situations: a) surface cast against plywood formwork, b) bulk concrete from internal position, and c) surface cast against CPF liner.

CHLORIDE EXPOSURE AND TESTING OF CHLORIDE INGRESS

After 27 days (= 31 maturity-days) both blocks were submerged in 2% chloride solution prepared by dissolving NaCl in demineralized water. Concrete cores were drilled after chloride exposure in the laboratory for 71 days (= 76 maturity-days) and the chloride ingress was measured by determination of chloride profiles according to the procedures for profile grinding and chloride analysis described in NT BUILD 443 (1995).

TEST RESULTS

Hardened concrete properties
At 7 days and 28 days, compressive strengths of 33 MPa and 57 MPa were measured, respectively, for the fly ash concrete. The measured chloride migration coefficient values (Table 2) show that the average D_{RCM}-value for samples cast against the CPF liner is 23% lower than for the samples cast against plywood formwork after 35 days and it is 32% lower after 180 days. After 180 days the D_{RCM}-values for the samples cast against CPF liner are approx. 1/3 of the D_{RCM}-values for the bulk concrete. The corresponding D_{RCM}-values for samples cast against plywood formwork are approx. 1/2 of the D_{RCM}-values for bulk concrete.

Chloride ingress
The measured chloride profiles after submersion in 2% chloride solution for 71 days (Figure 2 and Figure 3) show that the chloride ingress is less in samples cast against CPF liner compared to the sample cast against plywood formwork. This is true both for wet cured and dry cured samples. The dry cured sample cast against plywood formwork has a very low chloride content in the outmost layer and also rather low chloride contents in the following layers compared to the wet cured sample cast against plywood formwork. The dry cured samples cast against CPF liner do not show the same effect, although the chloride contents are generally somewhat lower than for wet cured samples cast against CPF liner.

Chloride ingress depths
The penetration depths of 0.05% chloride by concrete mass (Table 3) have been estimated by linear interpolation on the measured chloride profiles. These values show

that the penetration depths are higher in the wet cured samples than in the corresponding dry cured samples. The effect of the CPF liner is an average reduction of penetration depth of 0.05 % Cl from 12.7 mm to 8.7 mm (31% reduction) for wet cured samples and from 11.2 mm to 7.8 mm (30% reduction) for dry cured samples.

Table 2. Chloride migration coefficients (D_{RCM}) measured according to NT BUILD 492 (1999) at 35 and 180 days (= 37 and 182 maturity-days). The D_{RCM} value was measured on samples from three different situations: a) surface cast against plywood formwork, b) bulk concrete from internal position, and c) surface cast against CPF liner.

Sample	**Chloride migration coefficient** D_{RCM} [x10^{-12} m^2/s] at 35 days		
	Plywood	Bulk	CPF liner
Core 1	8.7	8.4	7.5
Core 2	9.5	9.2	7.3
Core 3	9.3	10.2	6.4
Average	9.2	9.3	7.1
Sample	**Chloride migration coefficient** D_{RCM} [x10^{-12} m^2/s] at 180 days		
	Plywood	Bulk	CPF liner
Core 1	0.89	1.7	0.55
Core 2	0.72	1.3	0.49
Core 3	0.77	1.5	0.58
Average	0.79	1.5	0.54

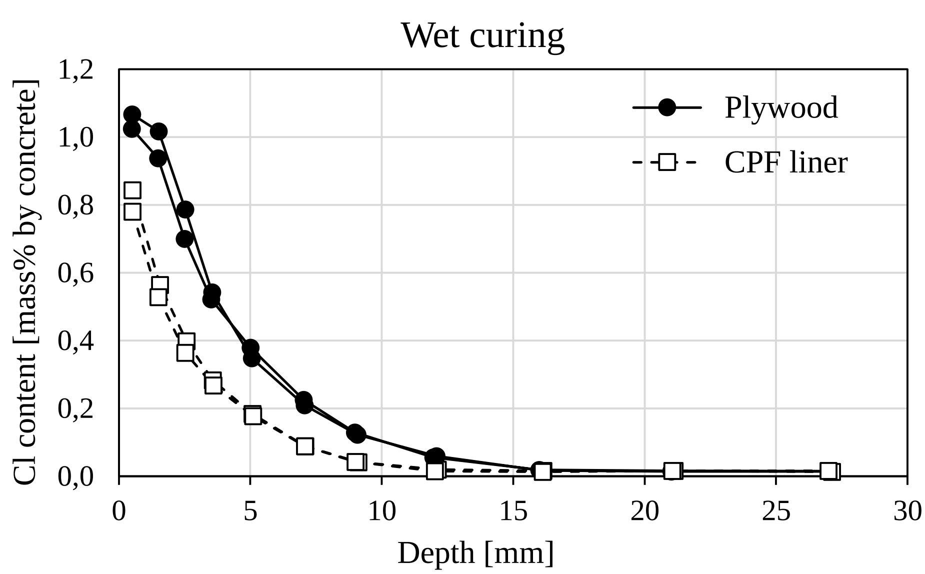

Figure 2. Chloride ingress into wet cured samples after submersion in 2% chloride solution for 71 days.

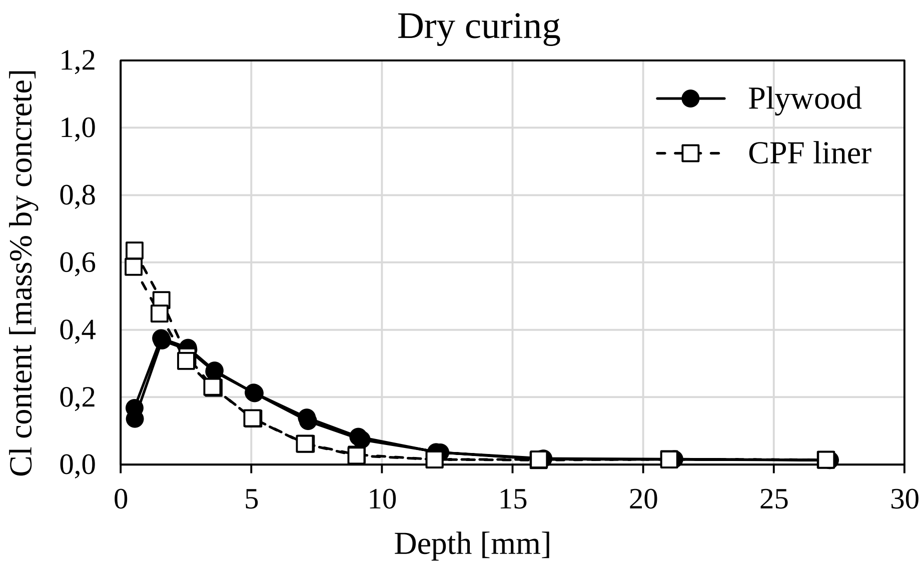

Figure 3. Chloride ingress into dry cured samples after submersion in 2% chloride solution for 71 days.

Table 3. Chloride penetration depth of 0.05 %Cl by mass of concrete ($x_{0.05}$) estimated by linear interpolation on chloride profiles. Estimations were performed on two profiles (a and b) for all combinations of curing condition (wet or dry) and formwork material (plywood or CPF liner).

Curing condition	**Penetration depth of 0.05% Cl by mass of concrete** $x_{0.05}$ [mm] after 71 days exposure	
	Plywood	CPF liner
Wet curing (chloride profiles a)	12.9	8.7
Wet curing (chloride profiles b)	12.5	8.7
Dry curing (chloride profiles a)	11.1	7.8
Dry curing (chloride profiles b)	11.2	7.7

DISCUSSION

Fresh and hardened concrete properties

The measured fresh concrete properties are corresponding to results from earlier test with the same mix design reported on the Concrete Expert Centre website (www.concreteexpertcentre.dk). The measured compressive strength of 33 MPa at 7 days and 57 MPa at 28 days are higher than earlier data from the Concrete Expert Centre website (30 MPa and 44 MPa, respectively). A possible explanation is that the source of pulverized fly ash was changed.

Chloride migration coefficients

The measured chloride migration coefficients (Table 2) demonstrate that a better resistance against chloride ingress is obtained for the concrete cast against CPF liner (D_{RCM} = 7.1x10^{-12} and 0.54x10^{-12} m^2/s at 35 and 180 days, respectively) compared to the concrete cast against plywood formwork (D_{RCM} = 9.2x10^{-12} and 0.79x10^{-12} m^2/s at 35 and 180 days, respectively). D_{RCM}-values for the same concrete mix design at 28 maturity-days are reported on the Concrete Expert Centre website (www.concreteexpertcentre.dk) to be more than 27x10^{-12} m^2/s. This rather large difference between old data measured after 28 maturity-days and new data measured after 35 days (= 37 maturity-days) could be partly due to the age difference and partly due to the change of pulverized fly ash source. It is also observed that the D_{RCM}-values for the bulk concrete and concrete cast against plywood are almost identical at 35 days (9.3x 10^{-12} and 9.2x10^{-12} m^2/s), but at 180 days the D_{RCM}-value for the bulk concrete (1.5x10^{-12} m^2/s) is significantly higher than the corresponding value for concrete cast against plywood (0.79x10^{-12} m^2/s). This observation has not been further investigated here, but it might be related to the fact that the concentration of cement paste generally increases somewhat when going from the bulk towards the surface.

Generally, the observation that the resistance against chloride ingress is improved by the use of CPF liner is in agreement with the findings in previous studies by e.g. Basheer et al. (2008) and Coutinho (1999 and 2001).

Chloride ingress

It is seen in Figure 3 that the dry cured samples cast against plywood formwork have a very low chloride content in the outmost layer and also rather low chloride contents in the following layers compared to the wet cured samples cast against plywood formwork (Figure 2). This phenomenon is most likely caused by carbonation of the outmost concrete during the dry curing period. The chloride binding capacity is drastically reduced when concrete carbonates. The dry cured samples cast against CPF liner do not show the same effect, although the chloride content are generally somewhat lower than for wet cured samples cast against CPF liner. The explanation for this is most likely the development of a more dense concrete in the outer layer as an effect of the CPF liner. This dense concrete is less prone to carbonation and drying out during the dry curing period.

The results reported in Table 3 show that the penetration depths of 0.05% chloride by concrete mass are higher in the wet cured samples than in the corresponding dry cured samples. At this time, we have no explanation for that as one might expect the opposite due to an additional contribution from capillary suction in the dry cured blocks when they are submerged in the chloride solution. Further investigations by e.g. petrographic analysis could possibly clarify this.

Future investigation of field exposed concrete

Similar to the concrete blocks reported in the present paper two large concrete blocks (0.2 x 1.0 x 2.0 m) has been cast in formwork with plywood on one side and CPF liner on the other side and then cured in wet and dry conditions. Subsequently, these two large concrete blocks was exposed to sea water in 2016 in a Danish field exposure site situated in Rødbyhavn. In a future paper chloride profiles on drilled cores from exposure in submerged and splash zones will be reported for varying exposure times.

CONCLUSIONS

The effect of Controlled Permeability Formwork (CPF) liner on early chloride penetration (up to 0.5 years) into concrete with 25% fly ash content has been investigated by a comparative study with plywood formwork as reference. The main conclusion is that use of formwork with CPF liner will significantly reduce the early chloride ingress into fly ash concrete compared to formwork of plywood, thereby giving a good potential for extending the service life of chloride exposed concrete structures.

The measured chloride migration coefficient (D_{RCM}) values show that the average D_{RCM} value for samples cast against the CPF liner is 23% lower than for the samples cast against plywood formwork after 35 days and it is 32% lower after 180 days.

After submersion of concrete samples with an age of 27 days in 2 % chloride solution for 71 days the penetration depth of 0.05% chloride by concrete mass was reduced approx. 30% for both wet cured and dry cured samples as a consequence of using CPF liner instead for traditional plywood as formwork material. The average penetration was reduced from 12.7 mm to 8.7 mm in wet cured samples and from 11.2 mm to 7.8 mm in dry cured samples.

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