QUALITY OF REINFORCED CONCRETE IN THE COVER ZONE OF DIAPHRAGM WALLS

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ABSTRACT

The cover thickness of the reinforcements in concrete casted against the soil is defined both to ensure safe transmission of bond forces and durability with respect to the corrosion of the reinforcements in the environmental conditions according to the Eurocode 2, but also because of constraints of execution for tremie concrete, where a cover is required when concrete is cast directly against the ground, according to execution standards EN 1538 and EN 1536. This article is focused on the comparison of durability and quality characteristics of reinforced concrete in the hardened state between concrete in the cover zone of a diaphragm wall panel and closed to reinforcement and the concrete nearer to the core of a panel within the reinforcement cage. Two cases are investigated: Le Port du Havre, a quay extension in marine environment at Le Havre Harbor in Normandy, and the Grand Paris in the suburb of Paris, in France. The comparison between the cover zone and the core of the structure is based on the main durability and transfer properties involved in the evaluation of the performances in environment with a risk of corrosion: chloride migration coefficient, porosity, carbonation.

Keywords: Diaphragm wall, reinforced concrete, durability, cover, transfer properties

INTRODUCTION

In France the rules for the minimum and nominal covers on sites are given in NF EN 1992-1-1 for structural and durability purpose, and NF EN 1538 for the execution of diaphragm walls.

The rules of best practice for diaphragm walls followed NF EN 1538.

Diaphragm wall is a reinforced concrete wall that is cast in sections or panels excavated in the ground (Fig.1). The trench is held open during excavation, and installation of reinforcement and during casting by the use of a supporting slurry. The slurry forms an impervious deposit (cake) on the walls of the trench, isolating the hydraulic pressure of the slurry from the surrounding soil and ground water, such that this pressure exerts sufficient outward force to keep the trench open. The slurry mix can be based on the use of bentonite, or polymers or a mixture of the two.

Temporary guide walls are constructed in advance and consist of two reinforced-concrete sections each about 30cm thick and 1m deep. The guide-walls have several functions:

- to provide physical confirmation of the location of the wall,
- to guide the excavation tool,
- to provide a reservoir and buffer for drilling mud,
- to provide a fixed support for suspension of the reinforcement cages.

Individual panel lengths are determined by several factors including trench stability and the sensitivity of the surroundings to movement. Typically, they do not exceed 7m. The wall can be constructed very close to existing structures though a minimum clearance is required for the thickness of the guide wall. When excavation of a panel is complete the slurry is treated to reduce the specific weight of the slurry and the quantity of sand in suspension to predetermined acceptable levels. Thereafter, the reinforcement cage is installed, and concrete poured using a tremie pipe. The joint between adjacent panels can be achieved in one of two ways:

- by use of a temporary steel stop end allowing the placement of a waterstop across the joint and providing at the same time a guide for the excavating tool.
- by cutting back into the concrete of the previously constructed panel when excavating with a hydromill trench cutter.

The standard thicknesses of diaphragm walls varies between 0.50m and 2.00m, 1.00 m being the most common.

In addition to a good design, achieving good, uniform tremie concrete quality results require to follow best practice with respect to

- the execution
- the characteristics and control of Tremie fresh concrete
- the management of the drilling fluids

Joint EFFC DFI guides are available for best practice in tremie concrete.

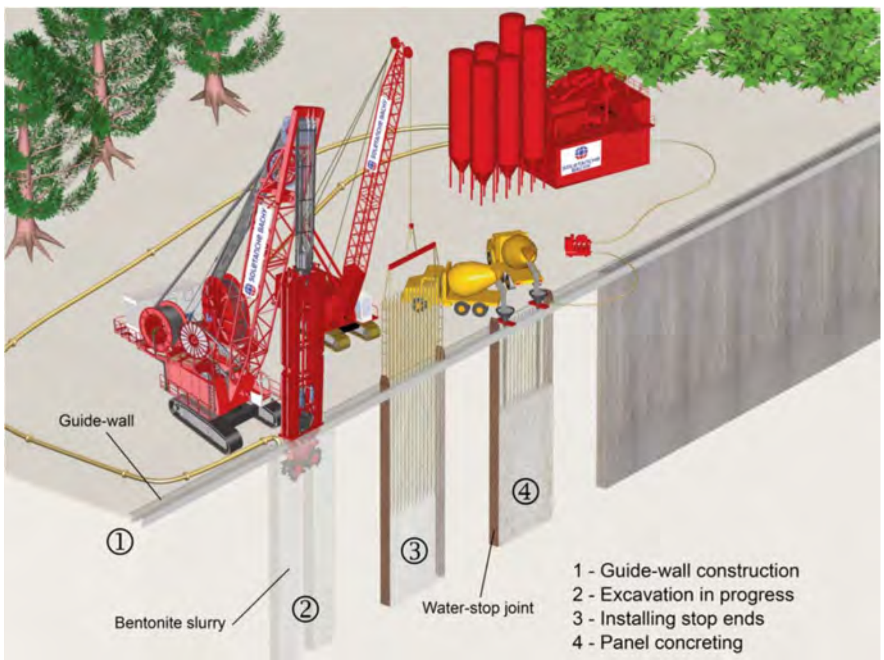

Fig. 1. Diaphragm wall method

The goal of this study is to verify if the conditions of casting have an influence on the performance of the cover zone near to the reinforcement (cover zone A in Fig.2) towards the risk of corrosion development by comparison of the main durability and transfer properties involved in the evaluation of the performances in environment with a risk of corrosion between this zone and the core of the concrete. This study is based on samples taken from two projects in France: Le Havre Port 2000 phase 3 (project in marine environment) and, Le Grand Paris Express Ligne 15 project in urban environment.

CASE STUDIES AND MATERIALS

The stabilizing fluid used is a bentonite slurry for the two case studies.

Port 2000 phase 3

Port 2000 phase 3 consists of 2 wharfs of 350 linear meters each. The diaphragm walls are 1.5m and 1.0m thick, 40m deep. The concrete mix design is in table 1. The concrete contains 400kg/m^3 of slag cement CEM III/B with 72% of Ground Granulated Blast Furnace Slag (Table 1.). The prescriptive concrete mix design approach meets the regulatory requirement in France for a 100-year service life concrete structure subjected to several environmental actions including chloride from sea water, and carbonation.

Table 1 – Concrete mix design O.D, Port 2000

Type	Constituent	Quantity Kg/ m3
Sand 1	0/4 SCL Rec	840
Gravel 1	4/12,5 SCL	330
Gravel 2	10/20 SCL	530
Cement	CEM III/B 42,5 N LH/SR CE PM NF	400
Limestone Filler	Betocarb - EC	40
Plasticizer	MasterPolyheed 787	0.95 %C
Retardarder	MasterSet R250	0.35 %C
Water		180

Twelve samples were cored in the panels P21, P23 and P25 at Por 2000.Panel P21, P23 and P25 were cast respectively on October 15th, October 30th, and September 30th, 2020.
The samples were cored horizontally on concrete between 7.7 m and 8.6 below the platform in February 2021.

Grand Paris Express Ligne 15 Sud T3A Issy station

Grand Paris express ligne 15, lot T3A Issy is a station part of the metro line 15 contract. The concrete mix design is in table 2. The concrete contains 385 kg/m^3 of slag cement CEM III/A with 62% of Ground Granulated Blast Furnace Slag (Table 2.)
The prescriptive concrete mix design approach meets the regulatory requirement in France for a 100-year service life concrete structure subjected to carbonation.

Table 2 – Concrete mix design O.D, Ligne 15 T3A Issy

Type	Constituent	Quantity Kg/ m3
Sand	0/ 4 mixed SCL	861
Gravel	4/ 20 mixed SCL	885
Cement	CEM III/A 52,5 L LH CE PM ES CP1 NF	385
Plasticizer	Omega 144	1.00 %C
Water		185

Nine samples were cored in panel P33, which was casted on December 12th, 2018.

The samples were cored horizontally in 2021 on concrete over 90 day old, at depth between 13 m and 15m below ground level.

METHODS

The comparison between the cover zone A (concrete near to the reinforcement) and the core of the structure (Fig.2) is based on the microstructure of the concrete and on the study of the microstructure and the main durability and transfer properties involved in the evaluation of the performances in environment with a risk of corrosion: chloride migration coefficient, porosity, carbonation rate (Table 3).

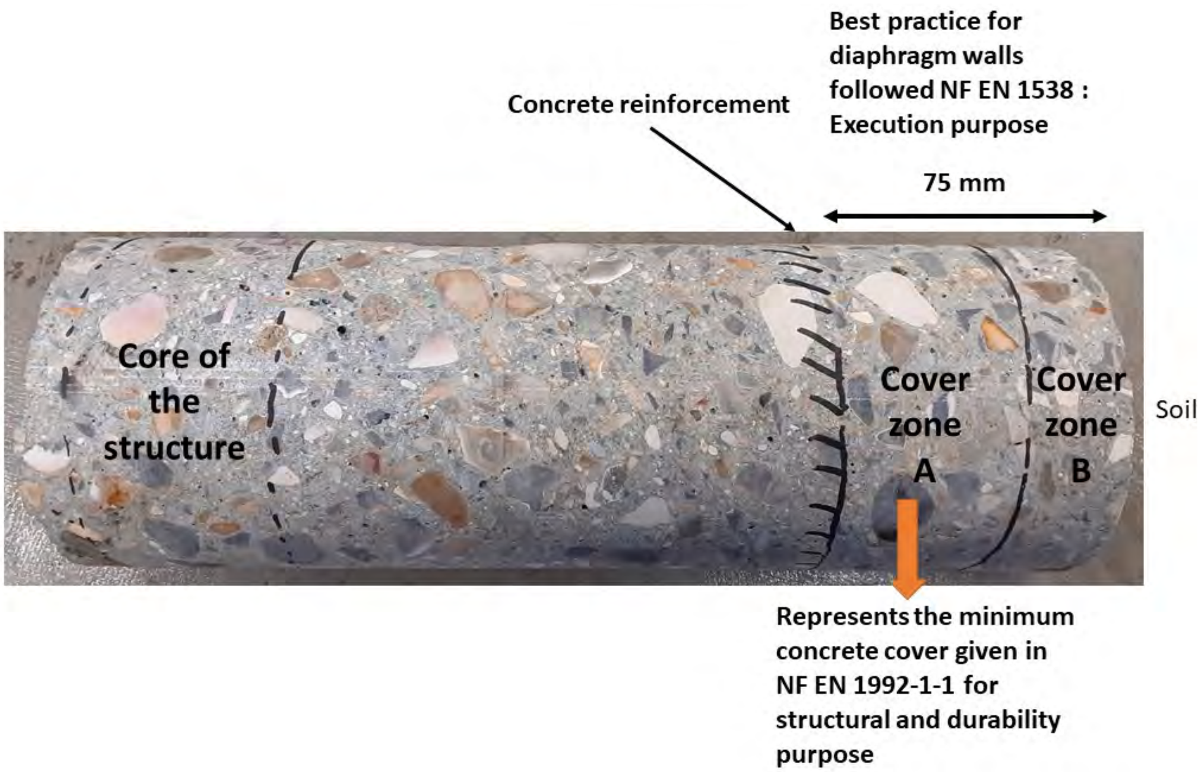

Fig. 2. Sampling of the test specimen in the so-called "cover zone A" and in the "core of the concrete"

Table 3 - Tests carried out on the two zones and two construction sites (cover zone A and core of the structure)

Carbonatation rate
Porosity
Chloride migration coefficient
Scanning electron microscope (SEM)
UV observations

Microstructure Analysis

The compactness of the concrete can be evaluated by studying the concrete microstructure. Samples for SEM analysis were taken from the concrete cover zone A and from the core per structure (Fig.2). They were coated and then polished before being plated. The size of the samples was approximately 20 mm diameter and 10 mm height.

UV plates were also made to observe the porosity distribution of the cover concrete from a more global view. The size of the plates observed was 90 mm large and 90 mm length.

The mercury porosimetry test is used to determine the pore size distribution of porous solids. Mercury is used as a non-wetting intrusion fluid. The sample, approximately $1 cm^3$ in volume, is placed in a penetrometer. The assembly is placed in the porosimeter and the intrusion pressure is increased incrementally in two phases: a low pressure phase corresponding to the high porosity of the sample and a high pressure phase corresponding to the low porosity of the sample. pressure phase corresponding to the larger porosity and a high-pressure phase corresponding to the finer porosity. the finest porosity. The pores are assumed to be cylindrical in shape and using the (Washburn E. W, 1921) equation (equation 1), pore sizes and pore volume distribution by pore size are calculated. The liquid enters a pore of radius r_p under the effect of a pressure P equation 1.

$$P = \frac{-2\,\gamma\,\cos\theta}{r_p} \qquad \text{equation 1}$$

With ɣ : surface tension at the liquid-gas interface

θ : wetting angle of the liquid with the material

Water porosity

The porosity accessible to water is a general indicator of the quality of the material. The method corresponds to the French experimental standard XP P 18-459. Three test specimens were tested in the concrete cover zone A and in the core of the concrete concrete (Fig.2).

Chloride migration coefficient

The diffusion of chloride ions into concretes is one of the main phenomena responsible for the corrosion of reinforcements and the degradation of reinforced concrete structures. The accelerated test makes it possible to assess the durability of concrete intended to be exposed to chlorides, and therefore to the phenomenon of corrosion of reinforcements. The method for determining the chloride migration coefficient is in accordance with standard NF EN 12390-18 “Essais pour béton durci — Partie 18 : Détermination du coefficient de migration des chlorures”. Three test specimens were tested in the concrete cover zone A and in the core of the concrete (Fig.2).

Carbonatation test

Carbonation is one of the main phenomena responsible for the corrosion of reinforcements and the degradation of reinforced concrete structures. The accelerated test makes it possible to assess the durability of concrete intended to be exposed to ambient air, and therefore to the phenomenon of carbonation. The carbonation test was carried out in accordance with NF EN 12390-12.

RESULTS AND DISCUSSION

Analysis of microstructure properties

The microstructure of the concrete samples was observed by scanning electron microscopy on polished surfaces (Fig.3). These observations show a homogeneous distribution of the porosity, the quality of the binder-aggregate interface and the microstructure of the slag-based binder.

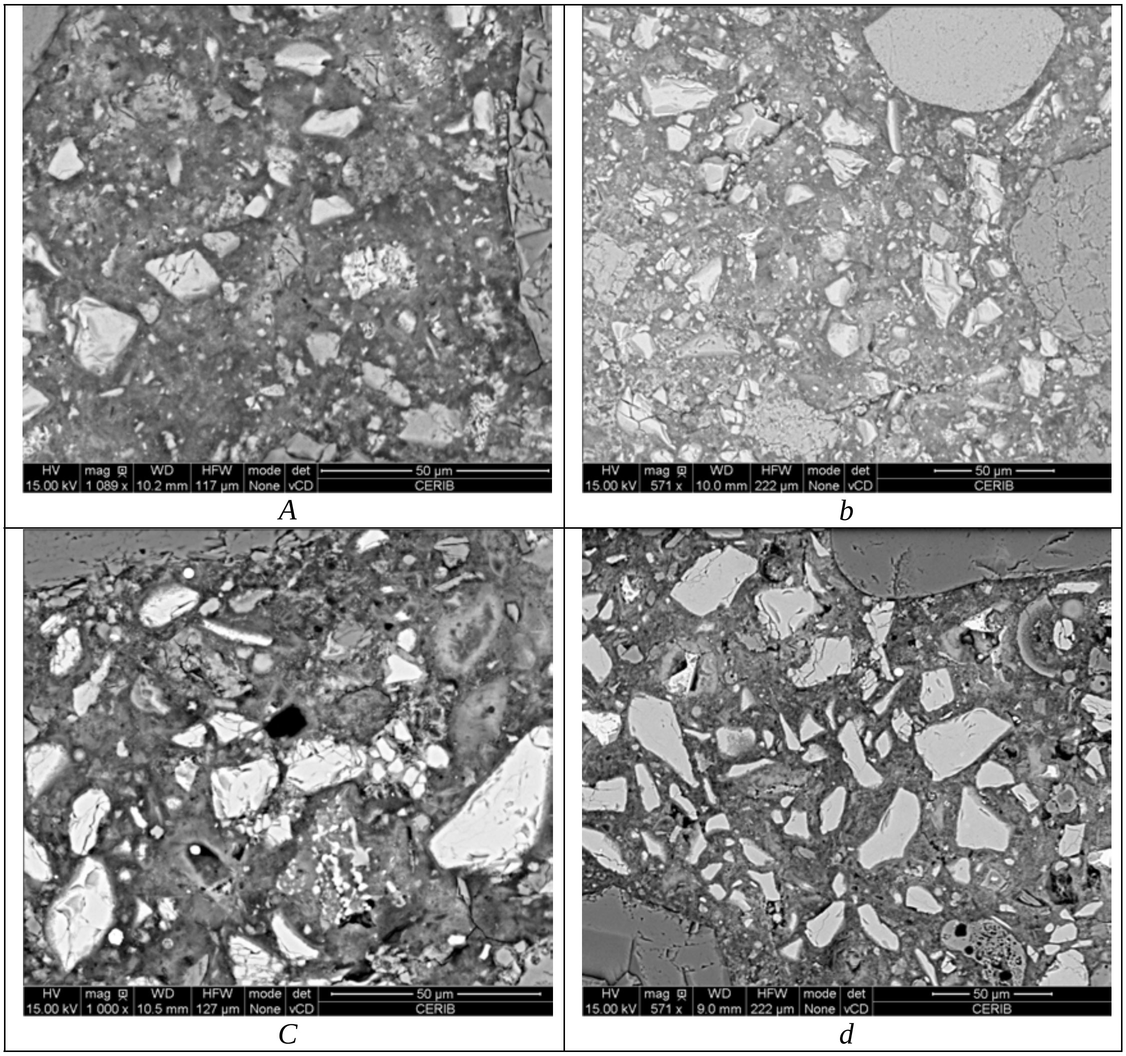

Fig. 3. a, b, c, d SEM observations of microstructure, on the top are samples « Le Havre » at the bottom are samples “Grand Paris” site. Figures at left are cover zone A and on the right is core of the structure.

The figures 3 a, b, c, d show a dense Calcium Silicate Hydrate C-S-H binder. The white grains correspond to slag, while the grayer forms correspond to siliceous aggregates.
These observations on the two samples do not show any significant difference between the cover zone A and the core of the structure for both the projects.

Pore size distribution

The distribution of the sizes of the concrete pores is similar between the cover zone A and the core of the concrete (near 0,01µm) (Fig.4). These are small capillaries pore (Mindless,2002) or mesopore, which is generally observed for slag concretes with a low free Water to Cement ratio W/C.

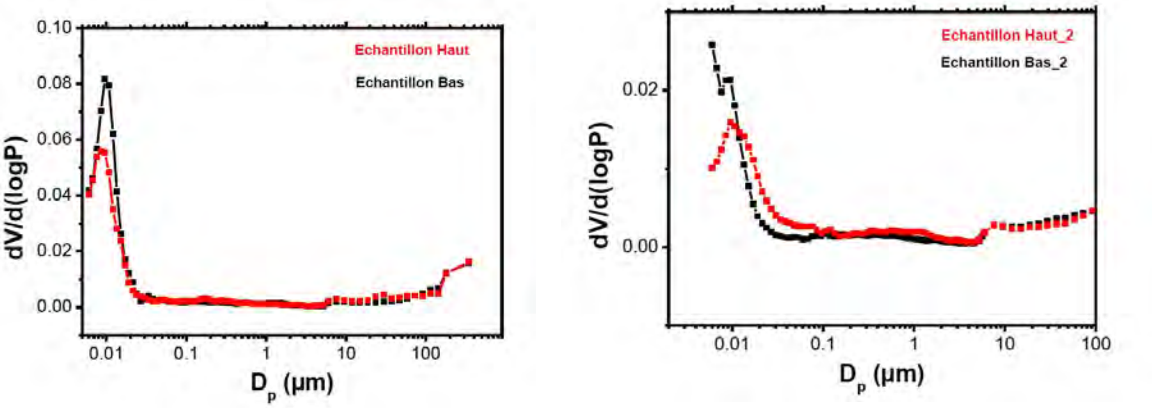

Fig. 4. Pore size distribution with mercury porosimetry test of sample "Le Havre" (left side) and "Grand Paris" (right side), red curve is cover zone A and black curve is core of the structure.

The photographs taken under UV light make it possible to study the air bubbles trapped in the matrix (Fig.5 a, b, c, d).

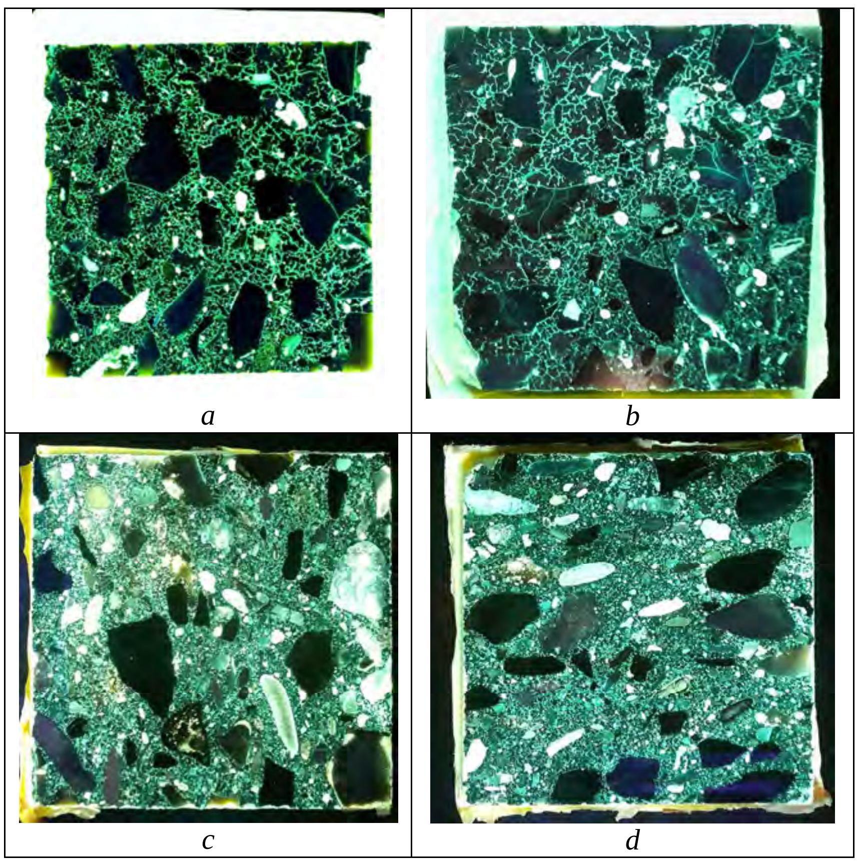

Fig. 5.a, b, c, d UV photography, on the top is sample « Le Havre » at the bottom is sample "Grand Paris". Photographs at left are cover zone A and on the right is core of the structure.

The pores present in the sample correspond to the round elements of yellow / green color. Siliceous aggregates appear black, while more porous aggregates also appear yellow / green.

The samples taken from the cover zone A and from the core of structure do not show any bubbles, or large vacuoles. The distribution of the porosity seems to be similar between the cover zone A and the core of the concrete.

Durability properties

Water porosity

The results of the porosity tests show no significant difference between the core of the structure and the cover zone A and are representative of homogeneous concrete through the structure.

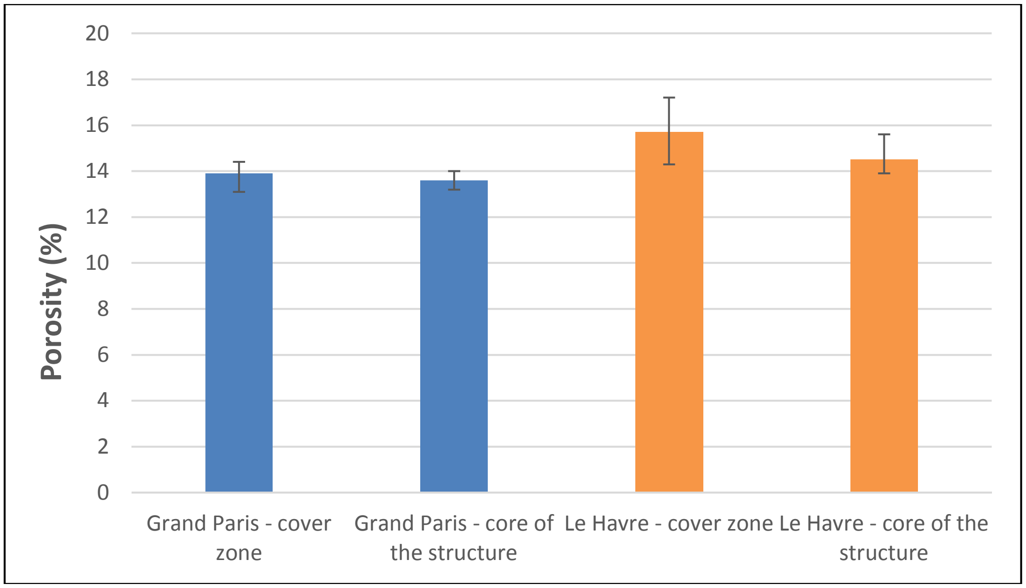

Fig. 6. Porosity results. Results are mean values based on three specimens.

Chloride migration coefficient

The evaluation of the chloride diffusion coefficient for the concretes studied in “Le Havre” and “Grand Paris” is presented in Fig.7. Even considering the strongest dispersion of the results for “Grand Paris - cover zone” concrete, the chloride ion diffusion coefficients are very low and representative of high-performance concrete in XS and XD type environments (lower than 10^{-12}m²/s).

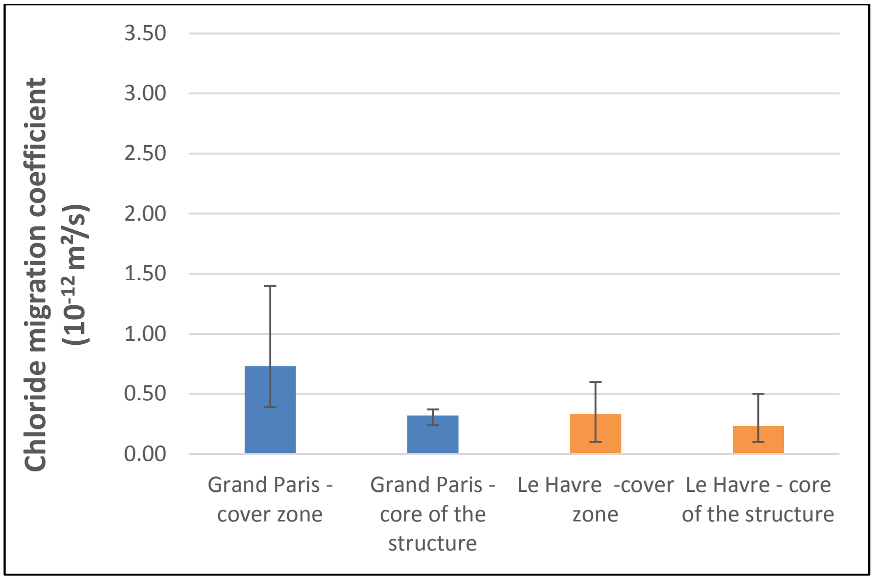

Fig. 7. Chloride migration coefficient obtained for « Grand Paris » and « Le Havre ». Results are mean values based on three specimens.

Carbonation rate

The figure 8 shows the carbonation rate for the concrete "Le Havre", around 0.75 mm/days $^{1/2}$ for the cover zone A and core of the structure. The carbonation rates should be taken with caution because the linear regression coefficient is less than 0.95 most certainly due in the absence of carbonation at 7 days. However, the comparison of carbonation rates between cover zone A and the core of the structure (Fig.2) shows very similar performances of concrete.

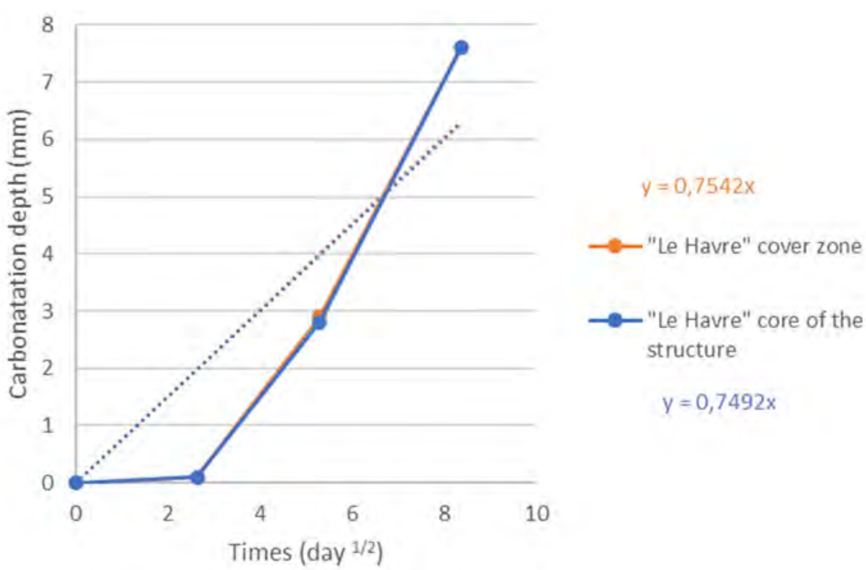

Fig. 8. Carbonatation depth for « Le Havre ». Results are mean values based on three specimens.

The concrete from "Grand Paris" project does not show any carbonation depth after 28 days of testing. At the time of writing this paper, the tests are still in progress until 70 days.

SUMMARY AND CONCLUSIONS

The diaphragm wall structures built following EN 1538 require a high cover concrete due to constraints of execution for tremie concrete where a cover is required when concrete is cast directly against the ground (75mm). This concrete cover is much higher to the minimum concrete cover $c_{min,dur}$ required by EN 1992- 1- 1 for durability purpose. The goal of this study was to verify if the quality of the cover thickness designed with EN 1992-1-1 is affected by the conditions of casting.
The comparison of transport properties, the microstructure analysis, and the pore size distribution between the cover zone near to the reinforcement (thickness of specimen between 30mm and 50mm from the reinforcement in zone A in figure 1) and the core of two diaphragm wall structures (Port 2000 phase 3 in Le Havre and Grand Paris Express Ligne 15 Sud T3A Issy station) made it possible to verify the homogeneity of the physicochemical properties of the concrete. The prescriptive concrete mix designs approach met the regulatory requirement in France for a 100-year service life concrete structure subjected corrosion prone environmental actions.
The conditions of casting directly against the ground in these two structures did not have an impact on the transfer properties in the concrete near to the reinforcement (cover zone A in Fig.2) and so on the resistance to corrosion. Further research should be carried out, focusing on zone B and the transition zone between A and B to determine the additional margin available with similar transfer properties.

ACKNOWLEDGMENTS

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