Influence of curing on the pore structure of concrete

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ABSTRACT: Most concrete structures are designed to last for at least a hundred years or more. During this lifetime the structure is exposed to several environmental influences. Whether a concrete structure can resist these environmental influences depends, among other things, on the ingress rate of liquids and gasses. The rate of ingress has a direct relation with the pore structure and its connectivity, inside the concrete. The pore structure and its connectivity are influenced by several factors during design and construction. An important factor during the construction phase is the curing of concrete. To achieve the requested durable structure the concrete has to be cured. To perform this curing several methods are applicable: liquid membrane, plastic film, fresh water etc.

To investigate the effect of each curing method experiments are performed with two types of cement (CEM I and CEM III/B). The experiments consist of water penetration and rapid chloride migration tests. In the paper the results of the experiments are presented. Based on the results can be stated that concrete made with CEM III/B is more sensitive for curing than CEM I and it seems that water curing for concrete made with CEM I is less effective than for concrete made with CEM III/B.

1 INTRODUCTION

Concrete is a material, which is already used more than hundred years in structures. Some of these structures are made in the beginning of the previous century and especially the infrastructural ones are still in function. In the Netherlands we have examples like the Hofpleinviaduct (figure 1) in Rotterdam (build in 1907) and the Noordersluis near IJmuiden (build in 1928). All those structures perform very well: only few problems occurred during the years.

On the other hand the majority of the structures in the Netherlands is made between 1960 and 1980. Some of these structures are also performing well; others are showing small or large damage. If there is any damage, it is mainly caused by the ingress of liquids and gasses, which led to the corrosion of the reinforcement.

In the last decade large investments in infrastructural structures are made (High Speed Link and Betuweroute) and new investments are foreseen. These structures are and will be designed for a lifetime of 80 or 100 years. Not only for technical reasons, but also for economical reasons. During this lifetime the structure is exposed to several environmental influences. Whether a concrete structure can resist these environmental influences depends, among other things, on the ingress rate of liquids and gasses.

Figure 1. Hofpleinviaduct Rotterdam 1907.

These two different reasons lead to an interest in the transport phenomena in concrete and especially in the parameters, which have an influence on the transport properties of concrete. In that point of view special attention has to be made to the fact that not the bulk concrete, but the concrete in the cover-zone protects the reinforcement.

Environmental conditions and curing regime will have an effect on the transport properties of the concrete, especially in the cover-zone.
2 CURING METHODS

Curing has a major impact on the formation of a sufficiently dense pore structure, as it represents the process of preventing moisture loss after concrete placement and maintaining the proper moisture conditions to promote optimum cement hydration. As the cement paste approaches complete hydration, the total volume of gel pores increases along with an increase in the volume of cement gel that may be sufficient to isolate the capillary pores. Obviously, it is very desirable to attain segmentation of the capillary pores, especially if they are located at the concrete surface zone because this results in impermeable cover concrete with improved durability (Powers).

However, proper moisture conditions are not always ensured in the concrete surface zone. As soon as the concrete is exposed to its environment, moisture exchange will take place until an equilibrium is established (Wang). As a result, in most cases it is considered necessary to apply curing techniques for keeping the water in the concrete.

Concrete curing methods can be divided in three basic techniques: ‘water-adding’, ‘water-retaining’ and ‘water-losing’ techniques (Kolyvas) (see for instance figure 2). The first provides concrete with water or moisture continuously, an example is water ponding. The second prevents water loss from concrete, for example with keeping the formwork in place. The last technique allows the loss of water, this could be without proper curing, named uncured or air-cured concrete.

3 EXPERIMENTAL PROGRAM

An extensive experimental program was carried out in order to investigate the influence of curing on the durability properties of concrete. In this experimental program the three basic curing techniques are applied to a concrete surface:

– water (W): water-adding by placing a water layer of approx. 1 cm above the concrete surface (water: W)
– sealed (S): water-retaining by sealing the concrete surface with a cover and plastic foil
– unsealed (U): water-losing by air curing, so evaporation is allowed

Two mixes (both concrete and mortar) with different type of cement (CEM I and CEM III/B) were cast and cured in the laboratory. The mix design is based on the following conditions:

– the water cement ratio is 0,50
– the particle size distribution of the aggregate complies with the so-called Fuller distribution
– the thickness of the paste layer around the aggregate particles is equal for both the concrete mix and the mortar, therefore the paste amount/the aggregate ratio is for concrete 0,68 and for mortar 0,43.

The exact compositions of the mixes used are presented in table 1. The environmental conditions in the laboratory are given in table 2.

As the scope of the research program was to study durability properties of concrete, two kinds of test methods were used that are considered capable to investigate permeation properties of cover concrete:

1. Rapid Chloride Migration (RCM), according to NT Build 492
2. water penetration test, according to EN 12390-8

The water penetration test is performed with the concrete mixes 1B and 2B, the rapid Chloride Migration test is performed with both the concrete and the mortar mixes: 1B, 1M, 2B an 2M.

All the RCM test results are the average of three tests. All the water penetration results are the average of two tests.

The tests are performed at an age of 28 days and at an age of 84 days. During the period before testing the samples were kept in their moulds and the top surface is treated with one of the mentioned curing methods.

<table>
<thead>
<tr>
<th>Table 1. Mix design (values in kg/m³).</th>
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<tbody>
<tr>
<td>Mix 1B concrete</td>
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<tr>
<td>CEM I 380</td>
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<tr>
<td>CEM III/B Water 190</td>
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<tr>
<td>Aggregate 1794</td>
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<th>Table 2. Environmental conditions laboratory.</th>
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<td>Ambient temperature</td>
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<td>Relative humidity</td>
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<td>Wind</td>
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<td>Sun</td>
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4 EVALUATION METHOD

The results of the tests are evaluated based both on their actual values and on the Curing Efficiency Factors (CEF).

The effect of the curing method on the actual results of the durability tests are evaluated at two (water penetration) or three (RCM) points:

- time
- type of cement
- in case of the RCM: concrete and mortar

The CEF is established to evaluate the improvement/declination over the sealed case of durability characteristics due to the application of various curing methods. The Curing Efficiency Factor (CEF) is given by:

\[
CEF_{(X)} = \frac{\text{test result}_{(X)}}{\text{test result}_{(S)}}
\]

Where \(CEF_{(X)}\) is the Curing Efficiency Factor of X curing method, \(\text{test result}_{(X)}\) is the result of the durability test (water penetration or RCM) of the specimen cured with X curing method and \(\text{test result}_{(S)}\) is the result of the durability test (water penetration or RCM) of the sealed specimen.

A value for CEF larger than 1 means a more permeable concrete and a value smaller than 1 a more impermeable concrete than the concrete cured in sealed conditions.

5 RAPID CHLORIDE MIGRATION

The first test method which is considered to be capable to investigate permeation properties of cover concrete is the Rapid Chloride Migration test. This test is prescribed in NT Build 492 and consists of an external electrical potential, which is applied axially across the specimen and forces the chloride ions outside to migrate into the specimen. After a certain test duration, the specimen is axially split and a silver nitrate solution is sprayed on to one of the freshly split sections. The chloride penetration depth can then be measured from the visible white silver chloride precipitation, after which the chloride migration coefficient can be calculated from this penetration depth.

In this experimental program the test method slightly deviates from the standard procedure: the chloride load was applied to the cured surface and not to a sawed surface.

The RCM-method is used as part of the DuraCrete methodology in order to determine the chloride migration coefficient (\(D_{RCM}\)) of concrete. In real life, the process of the penetration of chloride ions into a concrete will take many years but with help of an external potential that is applied axially across a concrete test specimen, with the RCM-test method (see figure 3) chloride ions will be forced to migrate into the concrete in several hours or days, depending on the resistance of the concrete test specimen. That is the reason why it is called the ‘Rapid’ Chloride Migration Method.

In figure 4 the values of the chloride migration coefficient (mortar) for the three different curing methods are shown. These values are evaluated based on the previous mentioned variables (time and type of cement):

- As expected, the RCM value at 84 days is lower than the value at 28 days. Due to the ongoing hydration the mortar has at later age a larger resistance against the ingress of chlorides.
- The RCM values of mortar with CEM III/B are lower than the RCM values of mortar made with CEM I, especially in case of the water cured mortar.

Comparison of the results of mortar based on the CEF is presented in figure 5. The declination of the CEF for the unsealed mortar is visible, especially for mortar made with CEM III/B.
In case of the water cured concrete the difference is less obvious. The CEF for CEM I is larger than 1, whereas the CEF for CEM III/B is smaller than 1.

In figure 6 the values of the chloride migration coefficient for concrete are shown.

– As expected, the RCM values at 84 days is lower than the value at 28 days, but this is only the case of the sealed and water cured concrete. In case of the unsealed curing method the RCM value becomes slightly higher.
– In case of the sealed and water curing method the RCM values of concrete made with CEM III/B are lower than the values of concrete made with CEM I. In case of the unsealed curing method the RCM value is slightly higher.

Comparison of the results of concrete based on the CEF is presented in figure 7. It is obvious that the CEF for the unsealed concrete is much higher, especially for concrete made with CEM III/B.

In case of the water cured concrete the difference is less obvious. The CEF for CEM I is larger than 1, whereas the CEF for CEM III/B is smaller than 1.

Comparison of the results of concrete and mortar shows that the RCM values of concrete than the RCM values of mortar.

6  WATER PENETRATION

The second test method which is considered to be capable to investigate permeation properties of cover concrete is the water penetration test. This test is prescribed in EN 12390-8 and consists of the application of water under pressure to the surface of hardened concrete, see figure 8. The specimen is then split and the depth of penetration of the water front is measured.

In this experimental program the test method slightly deviates from the standard procedure: the pressure was applied to the cured/trowelled surface and
the average penetration depth was measured. Measuring the average penetration depth is done because the penetration could be strongly influenced by the local conditions.

In figure 9 the values of the average penetration depth are presented for the three different curing methods. These values are evaluated based on the previous mentioned variables:

- The values of penetration depth compared in time do not differ to a large extent.
- The penetration depths of CEM III/B are lower than the penetration depths of CEM I in case of the sealed and water curing method. In case of the unsealed curing method the penetration depth is almost equal.

Comparison of the results based on the CEF is presented in figure 10.

It is obvious that the CEF for the unsealed concrete is much higher, especially for concrete made with CEM III/B.

In case of the water cured concrete the difference is less obvious. The CEF for CEM I is larger than 1, whereas the CEF for CEM III/B is smaller than 1.

7 DISCUSSION RESULTS

The experimental program leads to the following evaluations and discussions:

- The results shows that the RCM values of concrete are lower than the RCM values of mortar. An explanation could be that concrete has a lower volume of paste, which is responsible for the transport of liquids/ingress of chlorides.
- The results of both the RCM and the water penetration test shows that concrete made with CEM III/B is more sensitive for curing than CEM I. An explanation could be that the hydration of CEM III/B is slower, therefore the time available for evaporation is longer. This leads to more moisture loss and less water available for hydration.
- The results of both the RCM and the water penetration test shows that water curing for concrete made with CEM I is less effective than the sealed curing method. An explanation could be that calciumhydroxide (Ca(OH)₂) forms a larger part of the paste structure in case of CEM I. Water curing leads to dissolving of calciumhydroxide (Ca(OH)₂) and therefore to a coarser pore structure than in the sealed curing method.
- The results of both the RCM and the water penetration test shows that water curing for concrete made with CEM III/B is more effective than the sealed curing method. An explanation could be that the hydration of blast furnace slag requires more water than available in the sealed condition. Water curing applies this extra water, therefore a denser pore structure develops.

8 CONCLUSIONS

- Curing has a major influence on the permeability characteristics of the surface concrete and consequently on the concrete durability.
- Concrete made with CEM III/B is more sensitive for curing than CEM I.
- From the curing methods applied the sealed curing method guarantees the most dense pore structure in case of CEM I.
- In case of CEM III/B the water curing method guarantees the most dense pore structure.

ACKNOWLEDGEMENT

This work is part of an ongoing research project. In the future the modeling will be extended by three dimensional flow simulations through the generated and hydrated microstructure. The research project is financially supported by a Casimir grant from...
the Netherlands Organisation for Scientific Research (NWO).

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