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Effect of carbonation on non-destructive strength and durability assessment of limestone based concrete

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ABSTRACT

For the condition assessment and determination of residual bearing capacity of existing concrete structures, strength and durability related properties of the reinforced element are of high importance. Assessment of these properties can be performed by (i) destructive testing of drilled cores and testing the extracted samples in lab environment for compressive strength evaluation and determination of carbonation depth and (ii) indirect methods by using non-destructive techniques such as rebound hammer, ultrasonic pulse velocity tester, resistivity meter and air permeability meter.
The experimental program is conducted on concrete slabs of different strength classes intended for various exposure classes according to EN206, based on a limestone aggregate matrix where different amounts of CEMI and CEMIII (260-340 kg) and alternating w/c-ratios (0.40-1.00) were used. The plates were tested at the age of 90 days and the test program was repeated at the age of 5.5 years, after exposing the elements in a sheltered outside environment to natural carbonation, in order to evaluate the effect of carbonation on the mechanical and durability related properties.
Best fit correlations between the output of these different techniques were established by means of regression analysis. By using UPV and air permeability testing devices the strength and carbonation coefficient can be obtained non-destructively. Furthermore, the effect of age (i.e. carbonation) on the established correlation curves and predictive models is clearly noticeable.

Keywords: Strength assessment, durability assessment, non-destructive testing, carbonation

1. INTRODUCTION

For characterization of existing concrete structures, insight in the strength and durability related properties are necessary in order to come to an adequate expert judgement and repair strategy (Hobbs *et al.* (2007)). By means of (i) time-consuming and labour-intensive destructive testing of drilled cores and testing in lab environment and/or (ii) indirect methods by using non- or semi-destructive techniques on site, as an alternative. In this study, an experimental program was conducted on concrete slabs with an approximate age of 5.5 years, intended for various exposure classes (variation in W/C-ratio, cement type and cement content), based on a limestone inert matrix, and frequently used for Belgian applications. These slabs were intensively investigated, both in 2014 (results discussed in Craeye *et al.* (2017)) and 2019, by means of destructive testing (compressive strength tests and determination of carbonation rate), and non-destructive techniques (the rebound hammer, the ultrasonic pulse velocity tester, the Wenner probe for concrete resistivity and the air permeability tester). Best fit correlations between the output of these different techniques were established. The effect of age (e.g. carbonation) on the established predictive models is being evaluated.

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By measuring the propagation speed of ultrasound waves through the material, the concrete quality is investigated. A high pulse velocity will result in a good quality concrete and, therefore, a higher compressive strength and more durable material can be expected. In this study, only ultrasonic techniques were used to determine to ultrasonic pulse velocity (direct transmission), according to EN 12054-4. The main influencing parameters on the output of the UPV are the type, content and hardness of the aggregates, the presence of cracks/voids in the structure and the moisture content of the concrete (Breysse (2012)). The W/C-ratio also affects the readings in pulse velocity. Furthermore, relative humidity also influences the output. The pulse velocity might increase up to 5% between dry and saturated test specimens, according to Solís-Carcaño *et al.* (2008).

The rebound hammer measures the rebound of a spring-loaded mass impacting on the surface of a concrete sample or structure, generating the rebound number, according to EN 12504-2. The higher this number, the harder the surface, indicating a high concrete compressive strength. A correlation exists between the compressive strength of standard cubes and the rebound number obtained by the hammer. However, this correlation is not universal and has to be modified for different devices, different concrete mixes or different conditions of testing. The condition of the surface has a high influence on the readings. Furthermore the type and the hardness of the aggregate and the carbonation degree, as it increases the surface hardness of the concrete, will have a big influence on the rebound number (Kim et al. (2009)). The influence of carbonation on the rebound number varies considerably according to the strength level but the effect of carbonation on the strength evolution is negligible for medium and high strength concrete.

Measuring concrete resistivity on site can be performed in various ways. It is often measured with a Wenner probe consisting of four equally spaced point electrodes that are pressed onto the concrete surface, which makes the technique entirely non-destructive. Results show that there is no appropriate relationship between surface resistivity and strength, generally due to different mechanisms support compressive strength and electrical resistivity. Consequently, it is not recommended to use surface resistivity as an indicator for evaluation of compressive strength (Ramezanianpour *et al.* (2011)). Nevertheless, the electrical resistivity of concrete is an important parameter, e.g. used to describe the corrosion rate of reinforced concrete elements for durability assessment. This parameter is related to the water content, the cement type, the W/C-ratio of concrete and the hydration degree. Environmental conditions such as relative humidity and temperature also affect the resistivity of the concrete matrix.

Several researches have shown that the coefficient of air permeability k_T correlates quite well with other standardized durability related tests (Jacobs *et al.*, 2009, Torrent et al., 2012). For instance, carbonation depth of concretes after 500 days of natural exposure correlates well with their k_T values measured at 28 days: higher air permeability leads to higher carbonation rate. These concretes have W/C-ratios in the range 0.26-0.75 and are made with CEM I (except few mixes to which 5-8% silica fume was added). Furthermore, according to (Neves *et al.* (2015)), a reliable correlation exist between the carbonation rate and the coefficient of air permeability, of which the linear scale factor depends on the type of cement that is being used. As such this non-destructive method can be used to update the residual service life of an existing concrete structure.

2. MATERIALS AND METHODS

2.1. Concrete composition

The study was initiated in 2013, with the casting of 14 non-reinforced slabs using 7 concrete mixtures with strength classes varying from C12/15 up to C50/60. For each mix two slabs (600 x 100 x 100 mm³) were cast and tested (destructive compressive strength and various non- or semi-destructive techniques, as mentioned in (Craeye et al., 2017)). The composition of these mixtures is given in Table 1. These concrete mixtures are frequently applied in Belgium for different exposure classes. Limestone aggregates are used (max. grain size 22 mm), except for mixture C25/30 (which used porphyry 8 mm). Blends of three different cement types are selected: Portland CEM I 52.5R and blast furnace slag CEM III/A 42.5N – CEM III/B 42.5N. The W/C-ratio varies from 0.40 up to

1.00, the cement content from 260 kg/m³ up to 340 kg/m³ depending on the required exposure classes.

Once this original research project was finished in 2014 (results available and discussed in Craeye *et al.*, 2017), the slabs were stored in an unconditioned but sheltered outside environment (no direct exposure to rain). Temperature and relative humidity were not registered, moisture level and saturation degree were not monitored during storage.

For this research study, the slabs are tested at an approximate age of 5.5 years. Note that the test program will be repeated in 2023-2024 to evaluate the effect of age and carbonation of concrete with age of 10 years.

Table 1 Concrete composition in different strength classes

Strength class	Exposure Class	Slump W/C	Aggregates Max. grain size	Cement Min. content
C12/15	X0	S4 1.00	Limestone 22 mm	CEM III/B 42.5N LH SR LA 260 kg/m³
C20/25	XC2	S3 0.60	Limestone 22 mm	CEM III/B 42.5N LH LA 280 kg/m³
C25/30	XC3-XF1	S3 0.55	Porphyry 8 mm	CEM III/B 42.5N LH LA 280 kg/m³
C30/37	XC4-XF1	S3 0.50	Limestone 22 mm	CEM I 52.5R + CEM III/B 42.5N LH LA 300 kg/m³
C35/45	XC4-XD3-XF4	S3 0.45	Limestone 22 mm	CEM III/A 42.5N LA 320 kg/m³
C40/50	XC4-XD3-XF4	S3 0.40	Limestone 22 mm	CEM I 52.5R + CEM III/A 42.5N LA 320 kg/m³
C50/60	XC4-XD3-XF4	S4 0.40	Limestone 22 mm	CEM I 52.5R + CEM III/A 42.5N LA 340 kg/³

2.2. Selection of testing methods

Out of each slab 7 cores (diameter 100 mm, height 100 mm) are drilled to perform compressive strength and carbonation tests. To determine the actual compressive strengths of the concrete slabs, 3 cores are tested per slab, according to EN 12504-1. The core strength is converted into the equivalent cube compressive strength ($f^*_{ccub150}$) by means of a shape factor (averaged value of 1.05, NBN B15-001).

Prior to the drilling the slabs are tested non-destructively: ultrasonic pulse velocity (via direct transmission), air-permeability, surface resistivity, and rebound hammer tests are executed, according to EN 12504-2, SIA 262/1, AASHTOT277 and EN 12504-4 respectively. The location of the tested area on the slab are identical for each test and the same procedure is followed for each slab to minimise measuring artefacts.

The depth of carbonation (or the carbonation coefficient) is determined on 1 core per slab, according to EN 14630, using a 1% phenolphthalein solution.

3. RESULTS AND DISCUSSION

3.1. Strength assessment

In Figure 1 the results of the individual tests on both slabs per strength class are given and compared to the results obtained in 2014. There is a time difference of 5.5 years in between the 2014 and 2019 results. In general, there is a slight decrease in strength, except for C20/25. Lower strength loss was observed for the lower strength classes: 1.3% and 4.9% for C12/15 and C20/25, while for C30/37-C35/45-C40/50-C50/60 the decrease is 20.9%-9.0%-4.4%-8.4% respectively. As the slabs were stored in a sheltered outdoor environment, variation in saturation degree and frost exposure might explain the decrease in strength.

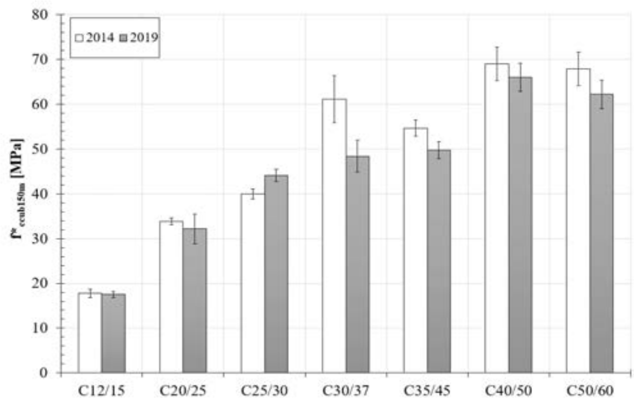

Figure 1. Equivalent cube compressive strength

The output of the equivalent cube compressive strength results is linked to the test results of the ultrasonic pulse velocity (direct transmission), the rebound hammer measurements and the air permeability measurements, as shown in Figure 2, Figure 3 and Figure 4. Note that the results of 2014 are only presented by means of the dotted line: the depicted data points and corresponding correlation line are representing the 2019 data.

Linear regression analysis is performed the obtain the best fitting curve between destructive and non-destructive test, and the reliability of the correlation of one method specifically, is quantified by means of the coefficient of determination (R^2-value) and the standard deviation (shown in the graphs). A linear correlation exists between cube compressive strength and the ultrasonic pulse velocity and compressive strength and the rebound number, with comparable correlation R^2 of 0.726 and 0.701 respectively. Compared to the 2014 study (dotted line), there is a noticeable drop in R^2 (0.957 for the rebound number, 0.886 for the ultrasonic pulse velocity): measurements on concrete surfaces that were subjected to environmental effects, have a significant lower linear coherence compared to tests performed on young concrete. It is known that carbonation has an effect on strength-hardness correlation (Kim *et al.*, 2009) which is also identified in this study. There is a noticeable shift in the correlation in between the 2014 and 2019 correlation curve (Figure 2, Figure 3). Furthermore, the difference in between the correlation provided by the provider of the supplier and the one obtained in this research is noticeable. For a given strength, the rebound number increases due to carbonation, and this effect is more prominent for higher strength classes. Comparable conclusions can be drawn regarding the correlation in between strength and ultrasonic pulse velocity. However, the effect of carbonation is less prominent. Furthermore, the compressive strength is inversely proportional with the air permeability (Figure 1c)): increasing the permeability of matrix leads to a decrease in strength. A good correlation is found in this project, R^2 equals 0.822.

As the resistivity meter is not designed for strength estimation, the measurements cannot be related to each other. In comparison with the 2014 study, it appears that the surface resistivity of the concrete slabs increased over a period of 5.5 years which can be linked to an increase in hydration degree and a decrease in saturation level (moisture content).

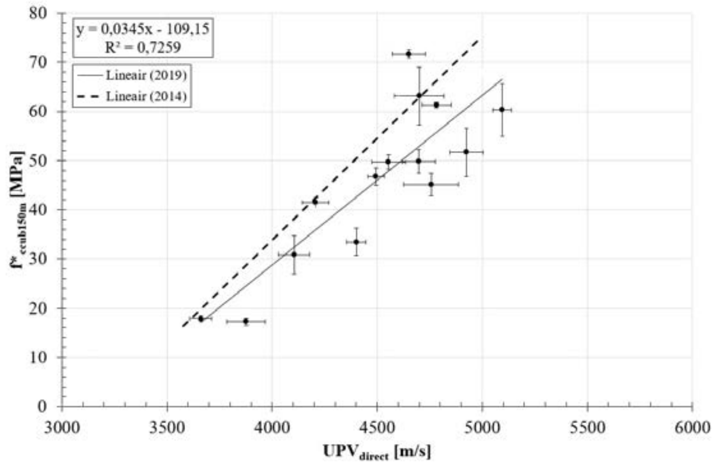

Figure 2. Correlation $f^*_{ccub150m}$-ultrasonic pulse velocity

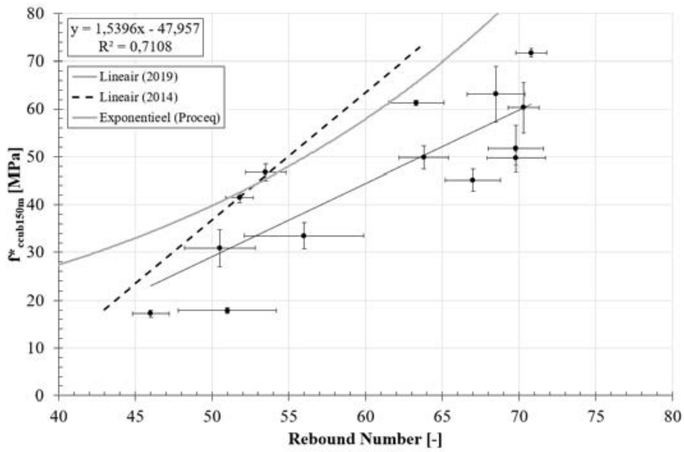

Figure 3. Correlation $f^*_{ccub150m}$-rebound number

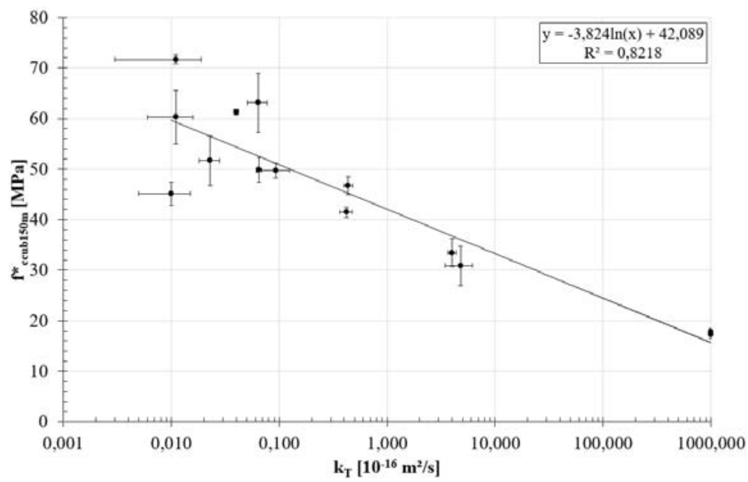

Figure 4. Correlation $f^*_{ccub150m}$-air permeability