The influence of carbonation process on concrete bridges and durability in Estonian practice

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Abstract. Concrete as one of the most widely used construction material in building industry, has considerable implementing in bridge engineering due to its extensive number of effective technical characteristics. However, according to exploitation environment, there are substantial factors such as aggressive liquids (e.g. deiced salts, sulfates, etc), rapid temperature alterations and the increasing rate of CO₂ to take into account predicting actual retained service life of concrete structure and the need of repairmen to increase the lifespan of the bridge. According to several measuring, concentration of atmospheric CO₂ is reported linearly increasing and is modeled to appear as exponential increase in the next decade. This environmental influence leads to accelerated carbonation process of concrete and brings up the importance of its potential untimely degradation mechanism. Hence, the main aim of this research is to give an analyzed overview of the carbonation depths of selection of 11 concrete bridges in Estonia built in the period of 1976-2007 and their relation with compressive strength of concrete. In addition to in situ tests, laboratory research was performed to understand natural carbonation rate and compressive strength relations of concrete.

1. Introduction

Carbonation of concrete is considered as inevitable chemical process of Ca(OH)₂ as an active alkali content of concrete and CO₂ as a consistently increasing environmental factor [1]. During the last decade the increase of CO₂ content is observed above 10% and according to latest research and simulation mechanisms it is expected to increase rapidly [2]. It is commonly understood that during carbonation process pH value of concrete decreases form highly alkali content (pH above 12) to weakly alkali content with a pH value of 8 or below it.

In a context of reinforced concrete, this intensified reaction implies the rebar corrosion that concludes with decreasing service life of built structure. However, carbonation process of concrete is chemically most active while the relative humidity (RH) is between 50…70%. Above RH of 70% the moisture content in capillary pores restrains the gas diffusion. Based on surveys depth of concrete carbonation can reach above 15 mm at 60% RH after 16 year exploitation and remain around 0 mm at 100% of RH [3]. Another issue is the open pore radius of concrete structure, according to research pore radius above 32 nm increased the carbonation coefficient significantly [4]. In generally service life of a reinforced concrete bridge structure is generally designed from 50 to 100 years, although degradation features are noticed already in the first decade of a lifespan [5]. Hence in favorable conditions depth of concrete carbonation can reach to concrete cover during lifespan and terminate the designed service life. As in general, one of the most important characteristic of concrete is...
compressive strength. Therefore the relation between carbonation depth and compressive strength is taken under examination. Although the main focus of this article is to understand the carbonation depth of exploited reinforced concrete bridges built from 10 to 40 years ago. To differentiate the rate of CO₂ and its influence on carbonation depth, highway and urban area structures were taken into survey in field tests. Parallel tests were performed in laboratory to measure CO₂ influence on concrete designed according to EN 206, Annex F recommendations [6]. Additionally an early structure formation of concrete at 60% and 90% of RH and its influence on compressive strength and carbonation depth in natural carbonation rate was measured.

2. Experimental work

2.1. Field tests
The field tests (in situ) were carried out in two different intervals – highway bridges were tested in 2015 autumn and urban area bridges in 2016 spring. All structures were visually inspected prior to testing to select the most influenced areas. In every construction the selected areas were in two different heights – first 30...50 cm from the bottom of abutment and second approximately 170 cm from the bottom. The idea of the heights difference is to present the variation of the carbonation process in one component. To be clear, then on every structure there were six different measurement areas. Rebound number as implied compressive strength and carbonation depth was performed according to standards EVS-EN 12504-2:2012 and EVS-EN 14630:2006 respectively [7, 8].

2.2. Description of field test dataset
To confirm the presence of carbonation process in real situation field tests for 11 existing road bridge abutments were carried out. To emphasise the effect of CO₂, different bridges were selected. Since time is the main variable that influences carbonation process then the main ground for the selection was to group bridges with different age. The second purpose was to investigate bridges in different environmental conditions – on highway, where pollution rate is lower, and in urban areas, where pollution rate is higher. As a result there are 11 different bridges with age between 10-41 years (Table 1). Although the concrete strength class of tested elements wasn’t the main factor of selection, it still has effect on the compression strength and is added to describe the data.

| Structure name | Construction year | Location | Designed concrete class (EVS-EN 206) |
|----------------|-------------------|----------|-------------------------------------|
| Kahala I       | 1977              | Highway  | C25/30                              |
| Kahala II      | 1977              | Highway  | C25/30                              |
| Kopli          | 1976              | Urban    | C25/30                              |
| Kuusalu I      | 1989              | Highway  | C25/30                              |
| Kuusalu II     | 1989              | Highway  | C25/30                              |
| Võidujoooksu   | 1988              | Urban    | C35/45                              |
| Kärevere 3     | 1999              | Highway  | C35/45                              |
| Kärkna         | 2000              | Highway  | C35/45                              |
| Raudtee        | 1998              | Urban    | C25/30                              |
| Körveküla      | 2006              | Highway  | C35/45                              |
| Smuuli         | 2007              | Urban    | C30/37                              |

2.3. Laboratory tests
Laboratory tests were performed to evaluate characteristics of concrete during early formation phase (90 days) while the concrete develops its nearly constant structure. Concrete mixes were designed
according to EN 206, Annex F recommendations and calculated according to absolute volume principle and Bolomey formula [6]. Target of the concrete class was set to C30/37 with a slump class S3 (100-150)mm and the cement quantity is rather over dimensioned due to considerably high water cement ratio (0.55). Additionally lower water cement ratios (0.50 and 0.45) were formed from initial designed mix reducing water to compare capillary void effect on compressive strength according to environmental RH content (60% or 90%) and carbonation depth of concrete during time. The mix details of concrete are presented in Table 2. Compressive strength specimens were arranged according to EVS-EN 12390-2:2009, for carbonation depth (70x70x280) mm specimens were applied. Compressive strength was tested according to EVS-EN 12390-3:2009 [9, 10]. Carbonation depth was measured after cut slabs from prism specimen and EVS-EN 14630:2006 principles applied [8].

Table 2. Mix details of concrete.

| Material                  | Quantity (kg/m³) |
|---------------------------|------------------|
| Cement (CEM I 42.5N)      | 460              |
| Sand 0-4                  | 540              |
| Gravel 2-8                | 336              |
| Gravel 8-16               | 784              |
| Water                     | 253              |

3. Results and discussion

Average results of compression strength with standard deviation of every bridge are shown in Table 3. It is clear that carbonation as a process exists and also concrete strength has increased in comparison to initial strength. As a result, in some cases the results of compression strength were discarded because of too high standard deviation or carbonation depth. If looking into values, then Raudtee viaduct has more than 10 mm higher value of carbonation depth than others. The reason for substantially higher value could be explained by the location – the viaduct passes thoroughfare with dense traffic and abutments are next to road. These values are excluded from further investigation.

Table 3. Average results of every structure.

| Name of structure | Designed compression strength (MPa) | Average compression strength (MPa) | Stdev of compression strength (MPa) | Average carbonation depth (mm) | Stdev of carbonation depth (mm) |
|-------------------|-------------------------------------|-----------------------------------|-----------------------------------|-------------------------------|---------------------------------|
| Kahala I          | 25.00                               | 44.42                             | 4.67                               | 6.03                          | 4.81                            |
| Kahala II         | 25.00                               | 34.50                             | 3.00                               | 4.17                          | 1.46                            |
| Kuusalu I         | 25.00                               | 49.97                             | 7.37                               | 5.12                          | 1.77                            |
| Kuusalu II        | 25.00                               | 47.50                             | 3.64                               | 3.55                          | 1.23                            |
| Kärevere 3        | 35.00                               | 54.52                             | 3.73                               | 3.57                          | 0.89                            |
| Kärkna            | 35.00                               | 42.75                             | 6.12                               | 3.67                          | 1.18                            |
| Körveküla         | 35.00                               | 41.92                             | 2.44                               | 3.50                          | 0.98                            |
| Kopli             | 25.00                               | 37.00                             | 1.22                               | 5.90                          | 1.37                            |
| Võidujooksu       | 35.00                               | 52.10                             | 1.76                               | 3.68                          | 0.82                            |
| Raudtee           | 25.00                               | 31.50                             | 2.68                               | 16.12                         | 3.52                            |
| Smuuli            | 30.00                               | 47.25                             | 4.33                               | 1.98                          | 0.29                            |
Comparing measured result to minimal environmental requirement for protective layer of concrete reinforcement in EVS-EN 10080:2006, where minimal allowed layer thickness is 10 mm, then only Raudtee viaduct has passed the value [11]. Taken into account that in most cases the minimal layer thickness is above 35 mm, none of the tested bridges have critical level of carbonation, though 40 years of exploitation has reached in some cases.

Onward results are presented from every sample area to include the deviation of every measurement. Results of every measurement can be seen in Figures 1 and 3-5. The distributions of carbonation depth measurements for single measurement are widely spread (Figure 1) for highway structures. The reason for wide distribution could be linked to the quality of measurements and changing properties of concrete.

![Figure 1. Measured carbonation depth.](image)

Average and maximum values confirm previous research results that carbonation is a temporal process and carbonation depth is higher in older structures [12]. Although overall results show that there aren’t big differences in urban and highway areas, but trend shows that potential carbonation process is slightly higher in urban areas and it appears with older structures. The reason of comparatively similar results could be explained by the weather condition of Estonia, where suitable relative humidity (50...70%) for activated carbonation process appears approximately three months in a year, similarly effect marked in previous research [13].

According to parallel laboratory tests, results presented in Figure 2, it is evident that carbonation is a very slow process but applicable conditions in present – RH 60%, high capillary porosity with water cement ratio of 0.55 carbonation depth of concrete can reach up to 3 mm after 2 month exploitation. However with higher RH content such as 90% and low water cement ratio (0.45) carbonation depth of concrete is steadily near to 0 mm. Although it seems that carbonation depth will reach its constant value after 70 day exploitation in natural carbonation conditions, but most likely will continue the process in time as seen in field tests. Commonly accelerated carbonation exploitation is applied in laboratory tests due to slow progress in time to reveal its effect on concrete but within this study only natural carbonation was used to maintain the comparability of field tests. That causes the seemingly constant carbonation depth of concrete after short period measuring even with high water cement ratio and applicable environmental conditions with RH in the range of 50-70%.
Figure 2. Laboratory tests and carbonation depth in formation period.

Figure 3. Changes in compression strength during exploitation.

The distribution of measured compression strength for single measurements are more widely spread (Figure 3) than carbonation measurements. The reason of additional uncertainty is the measurement methodology of sclerometer, which allows maximum deviance of 6.5% from average value. Comparing to initial nominal compression strength values with test results it can be said that concrete is getting stronger within time. Due to the fact that initial values aren’t directly measured and there were 4 different concrete classes under investigation, further discussion of compression strength temporal changes is obviated.

Figure 4. Annual average carbonation rate in comparison to age of structure.
Presuming that fresh concrete was not carbonated and dividing measurement results with the age of structure brings the process rate in forth. Contrary to total measured carbonation depth, where older structures had higher results, annual rates are higher in younger structures. The regression between age and annual carbonation change is notable in both areas. This could be described by two factors connected to $\text{CO}_2$. Firstly it’s due to nature of carbonation process where $\text{CO}_2$ enters into concrete through exposed voids. Secondly the fact those in last decades the content of $\text{CO}_2$ has increased due to higher level of motorization.

![Figure 5](image.png)

**Figure 5.** Relation between the average annual changes of compression strength and carbonation depth.

According to annual changes of different properties, the regression can be determined between compression strength and carbonation is in urban areas, but missing in highways. Linear regressions in both areas are still positive, which means that higher carbonation rate links to higher strengthening rate.

4. Conclusions
To clarify the correlation between $\text{CO}_2$ and carbonation in real situation, field tests were carried out to determine concrete carbonation depth and compression strength. Results show that newer bridges have lower total results, but yearly growth of carbonation and compression is higher. Unfortunately there is only weak correlation between carbonation and compression strength changes, because no tests have been carried out during construction and it is impossible to determine initial compression strength afterwards.

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