KONTRA 2022

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METHODOLOGY FOR MEASURING THE CARBONATION DEPTH OF CONCRETE – STANDARD AND NON-STANDARD ASPECTS

METODYKA POMIARU GŁĘBOKOŚCI KARBONATYZACJI BETONU – ASPEKTY NORMOWE I POZANORMOWE

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Abstract

Carbonation of concrete is a complex phenomenon, depending on many factors, including the heterogeneity of concrete, which results in an uneven carbonation front. The assessment of the depth of the carbonation front depends on the measurement technique adopted. The article summarizes the standard techniques for measuring the depth of carbonation and proposes an alternative measurement technique based on the measurement of the fields of the carbonated and noncarbonated surfaces, and then converting to the averaged depth of carbonation. For an example sample, the results obtained with different standard techniques and the proposed off-standard technique were compared.

Keywords: carbonation, research technique, carbonation front, cement concrete

Streszczenie

Karbonatyzacja betonu jest zjawiskiem złożonym, zależnym od wielu czynników, między innymi niejednorodności betonu, z czego wynika nierównomierny front karbonatyzacji. Ocena głębokości frontu karbonatyzacji zależy od przyjętej techniki pomiaru. W artykule podsumowano normowe techniki pomiaru głębokości karbonatyzacji oraz zaproponowano alternatywną technikę pomiaru opartą na pomiarze pól powierzchni skarbonatyzowanej i nieskarbonatyzowanej, a następnie przeliczeniu na uśrednioną głębokość karbonatyzacji. Dla przykładowej próbki porównano wyniki otrzymane różnymi technikami normowymi oraz zaproponowaną techniką pozanormową.

Słowa kluczowe: karbonatyzacja, technika badawcza, front karbonatyzacji, beton cementowy

1. INTRODUCTION

Carbonation is a physicochemical phenomenon occurring under the influence of carbon dioxide contained in the air. It is the most common mechanism of threat to the durability of reinforced concrete structures [1-4]. The phenomenon of carbonation takes place in any surface-unprotected concrete structure, since almost every building object is completely or partially immersed in an atmosphere whose component is CO_2 with a concentration sufficient to initiate and progress this process. Carbonation of concrete is a process with a complex, determined by many factors, course and equally complex impact on concrete and its properties [5-7]. The course of carbonation over time is associated with a number of factors of a material, technological and environmental nature. Concrete is a heterogeneous material and therefore the carbonation front does not have a linear waveform. Standard methods for determining the average carbonation front are

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differentiated algorithms. They differ in the way of taking into account the occurrence of aggregate grains on the front of carbonation line and local reductions of the carbonation front. They also differ in the number and location of measurement lines. Such differentiated approaches result in variability in the result of determining the average carbonation front, and at the same time is characterized by randomness of the results. The aim of this paper is to present an alternative method of measurement based on the determination of the surface of the noncarbonated area, and then convert it into an averaged carbonation depth and compare the obtained result with those obtained using standard measurement techniques.

2. STANDARDIZED TEST METHODS FOR CONCRETE CARBONATION

Current and previously standardized test methods of resistance to carbonation of concrete differ not only in the method of sample preparation (conditioning time, temperature, humidity, paraffin protection, size and shape of samples), the carbonation conditions (exposure time, CO_2 concentration, humidity) but also in the technique of measuring the carbonation range. The differences concern: the method of plotting the front line of carbonation (taking into account the grains of coarse aggregate, porous aggregatesa or air voids, rejection from corner measurements), the number of measuring points and their distribution and the accuracy of results presentation (Tab. 1).

Table 1. Comparison of selected standard methods for determining the depth of the carbonation frontline

No.	Standard	Carbonation conditions		Shape and method of sample preparation	Depth measurement method
1.	PN-EN 13295: 2005 Products and systems for the protection and repair of concrete structures – Test methods – Determination of resistance to carbonation [8]	Accelerated laboratory examination. The samples are treated with an atmosphere containing 1% CO_2 at $(21 \pm 2)°C$, humidity RH $(60 \pm 10)\%$.		In the case of paste, mortar or concrete with $D_{max} \le 10$ mm sample are beams of 40 mm x 40 mm x 160 mm size, in the case of concretes with $D_{max} > 10$ mm minimum sample dimensions are 100 mm x 100 mm x 400 mm. Before the test, storage under dry conditions for 14 days. Samples not protected by paraffin.	The depth of carbonation is measured by applying a phenolphthalein index to the surface of the fresh sample break. The same sample can be used several times to measure the increasing depth of carbonation over time, before each measurement a thin layer of the sample is removed. For each successive side, the length of the colour limit parallel to the edge of the sample shall be divided into four equal sections, thus determining the 5 measuring points. At each of these points, a measurement shall be made to the nearest 0.1 mm. When the carbonation front is broken with coarse aggregate, the carbonation line should be carried out through the aggregate, connecting the border on both sides of it. In places where there are voids in concrete or fragments of porous aggregate, a greater depth of carbonation may occur. If the values of the maximum carbonation cavity are less than 4 mm for concrete or 1.5 mm for mortar, the results may not be taken into account. If they are larger, the estimated maximum depth of carbonation shall be reported. The average carbonation result is determined with an accuracy of 0.5 mm.
2.	PN-EN 12390-10: 2019-02 Testing hardened concrete – Part 10: Determination of the carbonation resistance of concrete at atmospheric levels of carbon dioxide [9]	Carbonation in natural conditions	Carbonation under chamber conditions: concentration of CO_2 (0.040 ± 0.001) % The sample is stored under laboratory conditions $(T = (20 \pm 2)°C; RH = (65 \pm 5)\%)$ for (16 ± 2)h prior to the test.	The standard provides for the testing of rectangular samples with a length of at least 350 mm and shorter sides of at least 4 lengths of the maximum dimension of the aggregate grain. Samples not protected by paraffin.	The depth of the carbonation front is determined in 3 points for each of the walls of the sample. The length of the side of the sample should be divided into four equal parts and then measured in 0.25; 0.5 and 0.75 side lengths of the sample. The results shall be recorded to the nearest 0.5 mm. The average measurement result shall be given to the nearest 0.1 mm. When the carbonation front is broken with coarse aggregate, the carbonation line should be carried out through the aggregate, connecting the border on both sides of it. If the values of the maximum carbonation cavity are less than 4 mm, the results may be disregarded. If they are larger, the estimated maximum depth of carbonation shall be reported.
3.	PN-EN 12390-12: 2020-06 Testing hardened concrete – Part 12: Determination of the carbonation resistance of concrete – Accelerated carbonation method [10]	Accelerated laboratory examination. Before the test, the samples are conditioned in laboratory conditions for 14 days (temp from 18°C to 25°C, relative humidity from 50% to 65%). The measurement is made after 7, 28 and after 70 days of storage in the chamber at a temperature of $(20 \pm 2)°C$, with a humidity RH $(57 \pm 3)\%$ containing $(3.0 \pm 0.5)\%$ CO_2.		The standard provides for the testing of samples: 2 rectangular or 5 cylindrical with a length of at least 280 mm and shorter sides of at least 3 lengths of the maximum dimension of the aggregate grain or 8 cubic ones with a side length of at least 3 lengths of the maximum grain size. The reference sample size is 100 mm. Samples not protected by paraffin.	The depth of carbonation is measured at 3-5 points on each of the 4 surfaces of the prism, half of the cube or the dissected surface of the cylinder. To locate these points, the length of the edges should be divided into about 4 equal sections. The measurement shall be made with an accuracy of 0.5 mm. When the carbonation front is broken with coarse aggregate, the carbonation line should be carried out through the aggregate, connecting the border on both sides of it. If the values of the maximum carbonation cavity are less than 4 mm, the results may be disregarded. If they are larger, the estimated maximum depth of carbonation shall be reported. The average measurement result shall be given to the nearest 0.1 mm.

4.	PN EN 12390 – 12 Project valid from 2010 to 2020 [11]	The test proceeds as above with the exception of CO_2 concentration during the test, which should be (4.0 ±0.5)%.	Samples as above except for the possibility of securing two parallel sides with paraffin.	The measurement shall be as above, except for samples which have been secured with paraffin, in which case the measurement shall be made perpendicular to the unprotected walls of the sample. The design of the standard does not increase the number of measurements on one wall for protected samples, but at the same time requires 20 measurements for one sample.
5.	ISO 1920-12: 2015 Testing of concrete. Part 12: Determination of the carbonation resistance of concrete. Accelerated carbonation method [12]	Accelerated laboratory examination. The storage time in the carbonation chamber is 70 days. The samples are conditioned before the test for 14 days under laboratory conditions. In the chamber at (22 ±2)°C, at a humidity RH (55 ±5)% containing (3.0 ±0.5)% CO_2. In the case of locations in hot climates, the conditions in the chamber may change to the temperature (27 ±2)°C, with humidity RH (65 ±5)%. The depth of carbonation is measured on the 56th, 63rd and 70th day of storage in the chamber.	The test is carried out on 2 cubic or rectangular samples. The dimension of the samples in cross-section should be at least 100 mm and the length of the rectangular samples should be at least 400 mm. Before the test, two parallel walls may be paraffinized.	The depth of carbonation is measured at five locations on each wall where the sample has not been protected with paraffin or at 10 sites at each of the unsaffin-protected walls where the sample has been protected with paraffin. In order to locate the measurement points, divide the sides of the sample into 6 or 11 sections, respectively. The measuring points are the central points. The measurement shall be made with an accuracy of 0.5 mm.

3. CARBONATION DEPTH MEASUREMENT TECHNIQUE USING ALKALINE INDICATORS

All discussed standard methods are based on qualitative chemical analysis. The basis of this method are chemical indicators for assessing the reaction of concrete, which change coloration at a certain pH limit. A number of different alkaline indicators can be used to determine the course of the pH limits in concrete.

The natural pH of concrete is approx. 12.5÷13.0 and this is the level that ensures the passivating effect of the coating in relation to the reinforcement. It is considered that already lowering the pH below 11.0 is the beginning of the threat of corrosive processes in reinforcement, and pH values at the level of 9,0÷10,0 are considered to be the limits below which the protective capacity of the coating is lost [1]. In measurement practice, mainly four types of indicators are used: phenolphthaleic ("deep purple test", pH limit value = ~8.5), timolophthaleic (limit pH = ~10.5), timolophenolphthaleic (limit pH = ~9.5) and the so-called "rainbow test", which allows to identify at the turn of the sample the approximate pH range in the interval every 2 (i.e. approximate pH limits = 12, 10, 8) [1, 13-15]. The rainbow indicator is used in the diagnosis of operated structures, and the interpretation of the result is often difficult, due to the blurred boundaries of color zones and the smooth transition of one color into another with a change in pH at the depth of concrete. In the analyzed standard methods, phenolphthalein is used. As a result of using this indicator, clearly outlined color areas are obtained (an uncarbonated purple zone with a pH of < 8.5 and a carbonated zone of uncolored concrete). The border of these two zones is clearly outlined, which allows to plot a clear front line of carbonation.

4. PROPOSAL FOR AN ALTERNATIVE MEASUREMENT TECHNIQUE

Cement concrete is a heterogeneous material, and the standard methods for determining the average depth of carbonation are based on point measurements, including different numbers of measurements depending on the standard. The greater the number of measuring points, the more accurate the result can be obtained. The proposed new measurement technique is based on the adoption of an infinite number of measurements, which is possible by measuring the total area of the sample (A_{tot}) and measuring uncarbonated area (A_{ns}), followed by conversion to the averaged depth of carbonation (d) according to formula:

$$d = \frac{\sqrt{A_{tot}} - \sqrt{A_{ns}}}{2} \qquad (1)$$

where:
A_{tot} – area of total specimen cross – section,
A_{ns} – area of noncarbonated zone.

The proposed measurement technique involves measurement by the method of image analysis at the sample break after the application of phenolphthalein.

The proposal for an algorithm for calculating the field of noncarbonated and carbonated areas was placed in Figures 1-3. It should be emphasized that the proposed method is not universal and is applicable only in the case of testing laboratory samples. It cannot be used in the case of testing forgings of structures elements.
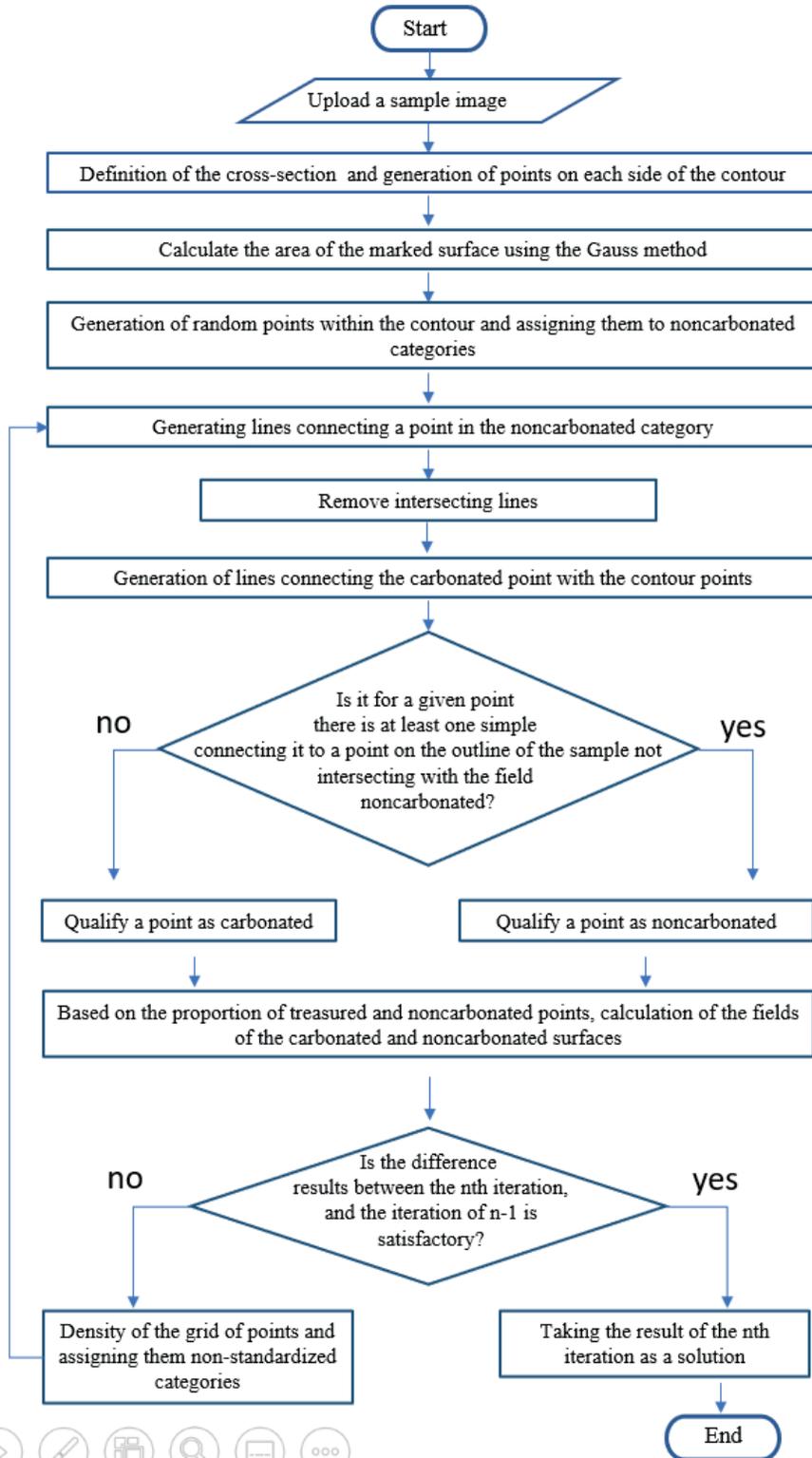

Fig. 1. Algorithm for determining the carbonated and noncarbonated area based on the sample image
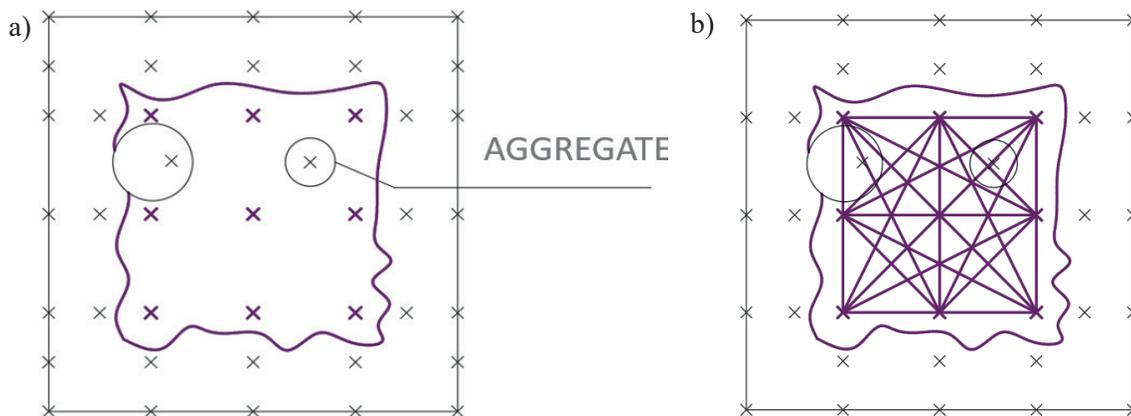
Fig. 2. Schematic of the algorithm: a) generation of random points to which the category of the noncarbonated is assigned, b) the lines connecting the noncarbonated points are generated
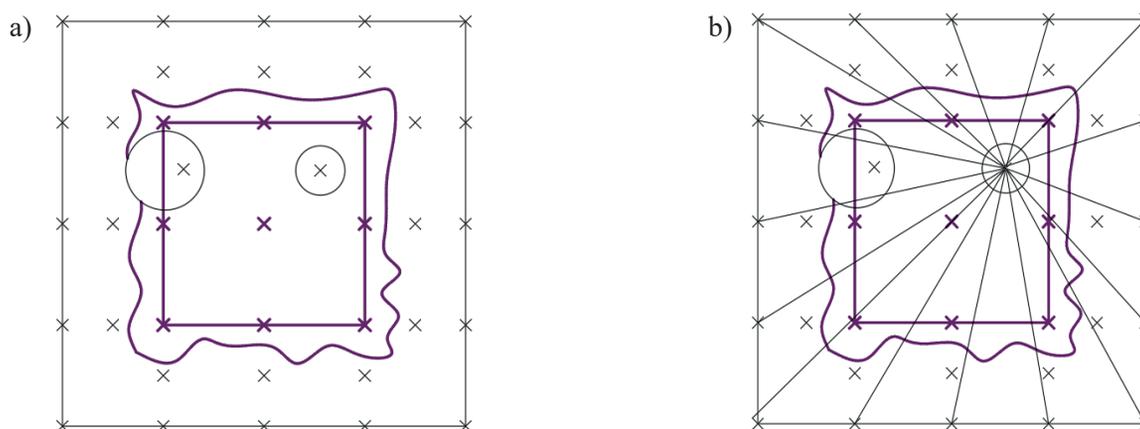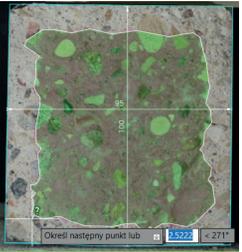

Fig. 3. Schematic of the algorithm: a) removal of intersecting lines, b) generation of lines connecting carbonated points to contour points

5. COMPARISON OF THE RESULT OF THE STANDARD AND ALTERNATIVE MEASUREMENT

As part of the comparison of the results of the depth of the carbonation front obtained using the measurement techniques described in the analyzed standards for the sample image after the carbonation test, image analysis was carried out. The carbonation depths were measured in accordance with the standards and the average carbonation depth was determined in accordance with the proposed algorithm. The results of the standard measurements are summarised in Table 2. After applying the discussed algorithm, the following results were obtained: total sample cross-section area (A_{tot}) equal to 9441 mm^2, noncarbonated area (A_{ns}) equal to 5539 mm^2 (Tab. 2) After applying the formula (1), an average depth of the carbonation front of 11.4 mm was obtained.

Comparing the measurement results with three standard methods (Table 2) and a new method using image analysis, it can be concluded that all methods give a comparable final result, i.e. in the range from 10.4 mm to 11.5 mm. The result of the image analysis method is the closest to the result obtained by the PN-EN12390-10 method, which assumes the most even distribution of measuring points along the edges of the sample. Statistical confirmation of the convergence of results obtained by different methods would require measurements on a larger population of samples, which at the current stage of research was not planned. Previous analyses suggest that the convergence of the image analysis method and the standard methods will be very high.

Table 2. Measurement of carbonation depth using standard methods: PN-EN 12390-10: 2019-02, PN-EN 12390-12: 2020-06 and PN EN 12390-12, ISO 1920-12: 2015 and proposed method

	PN-EN 12390-10: 2019	PN-EN 12390-12: 2020-06	ISO 1920-12: 2015	Proposed method
Sample image with unlabeled measurement lines or area				
Measurement	11.5 mm	10.8 mm	10.4 mm	11.4 mm

6. SUMMARY

The method of measuring the depth of carbonation presented in the article is a certain improvement in standard procedures. In the point measurement, performed with a linear measure, the precision of the person making the measurement is of great importance, but also the interpretation of the local course of the boundary line between the purple noncarbonated area and the gray carbonated area. The analysis of the consolidated image proposed in the new method is the most representative way of averaging the measurement. The simplicity of processing the photo and obtaining the result based on the proposed algorithm significantly speeds up and facilitates the study. The authors are aware that the key aspect of the representativeness of the method is the method of taking the photo of the sample break, including especially the angle of the lens axis relative to the plane of the fracture, which should be 90 degrees. Despite this caveat, the new method seems interesting and should be evaluated by statistical methods and then described in the form of a detailed measurement procedure.

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