



A STUDY ON CARBONATION DEPTH PREDICTION FOR CONCRETE MADE WITH GBFS CEMENT AND FA ADDITION

BADANIE DOTYCZĄCE PROGNOZOWANIA GŁĘBOKOŚCI KARBONATYZACJI BETONU WYKONANEGO Z CEMENTU GBFS Z DODATKIEM FA

Maciej Lech^{1*}, Tomasz Juszcak², Jerzy Wawrzeniacyk¹
¹Kielce University of Technology, ²Grolman Poland

Abstract

This paper presents the results of the examination of accelerated carbonation of concrete mixes made with CEM III / A blast furnace slag cement and the addition of fly ash. The test program was developed using an experiment design with two factors: a water-binder ratio and a fly-ash / cement ratio. Carbonation depth measurements were carried out according to FprCEN/TS 12390-12 (CO₂ concentration = 4%, T = 20°C, RH = 55%). Associated tests were also carried out, including compressive strength, porosity, depth of absorption, water penetration depth, and capillary suction.

Analysis of the test results allowed us to determine the influence of binder composition on concrete carbonization depth under standard test conditions. The results show that the carbonation depth increases along with the increase in the W/B ratio and as a result of the increase in the fly ash content in the binder.

A mathematical model was developed to describe the carbonation process over time, which can predict the depth and rate of concrete carbonation. Furthermore, it was found that there is no close relationship between other properties tested (e.g. strength) and the depth of the carbonated concrete.

Keywords: concrete carbonation, carbonation model, carbonation accelerated testing, GBFS cement, FA addition

Streszczenie

W pracy przedstawiono wyniki badań przyspieszonej karbonatyzacji mieszanek betonowych wytworzonych cementem żużlowym wielkopieczowym CEM III/A z dodatkiem popiołu lotnego. Program badań został opracowany na podstawie projektu eksperymentu z dwoma czynnikami: stosunkiem wody do spoiwa oraz stosunkiem popiołu lotnego do cementu. Pomiar głębokości karbonatyzacji przeprowadzono zgodnie z FprCEN/TS 12390-12 (stężenie CO₂ = 4%, T = 20°C, RH = 55%). Przeprowadzono również powiązane testy, w tym wytrzymałości na ściskanie, porowatości, głębokości absorpcji, głębokości penetracji wody i ssania kapilarnego. Analiza wyników badań pozwoliła na określenie wpływu składu spoiwa na głębokość karbonatyzacji betonu w standardowych warunkach testowych. Wyniki wskazują, że wraz ze wzrostem stosunku W/B oraz zawartością popiołu lotnego w spoiwie wzrasta głębokość karbonatyzacji.

Opracowano model matematyczny do opisu procesu karbonatyzacji w czasie, który umożliwia przewidywanie głębokości i szybkości karbonatyzacji betonu. Ponadto stwierdzono, że nie ma ścisłego związku między innymi badanymi właściwościami (np. wytrzymałością) a głębokością betonu karbonatyzowanego.

Słowa kluczowe: karbonatyzacja betonu, model karbonatyzacji, przyspieszone badania karbonatyzacji, cement GBFS, dodatek FA

1. INTRODUCTION

Carbonation depth is a key parameter in the analysis of the service life of reinforced concrete structures and can well characterize the carbonation rate [1-4]. Research on the scope and rate of the carbonation process is of particular interest in the issues of steel reinforcement corrosion and concrete scaling resistance.

The wide range of factors that influence carbonation can be grouped into four categories consisting of mix composition, material properties, environmental factors, and serviceability conditions [5].

Information on the rate and carbonation depth can be obtained in different ways: (a) direct measurement of the carbonation depth on the structure, (b) accelerated carbonation testing with specimens from the structure (e.g. cores), (c) from reference data, if the concrete composition is known (e.g. the type of cement and the water-cement ratio) [6].

Much effort was made to describe the carbonation rate and depth with a variety of models. Czarnecki and Woyciechowski [7] presented a critical review of articles related to mathematical models of carbonation. Ekolu [5] presented a different approach to modeling the carbonation process. Generally, these models may be divided into different categories: empirical models, statistical models, and numerical models, simulation ones. Most of the models in the references are experiential and their mathematical expressions relate the depth of carbonation to the square root of time [1]. Czarnecki and Woyciechowski [7-9] found that in the case of concrete made with the addition of fly ash, the hyperbolic function gives a better description of the carbonation process. Although infinite in time, the carbonation process is limited in the space of concrete.

Under natural conditions, the concrete is alternately dry and wet, and carbonation can continue into the concrete until the rewetting front reaches the current carbonation depth, so any subsequent cycle lasts longer. If concrete damping periods are too short, carbonation will not proceed and as a consequence the front will set at a constant level [7, 8].

With time of exposure, the rate of the carbonation process slows down, as carbon dioxide cannot reach the noncarbonated concrete layer. According to Fagerlund [10], the reason for this may be the diffusion of alkali from the interior of the concrete to the surface, which is opposite to the diffusion of CO₂.

An important problem for practice is to determine the correlations between accelerated and natural tests, which are needed to predict behavior in a real environment. A detailed discussion of this issue was presented by

Lollini and Redaelli [31]. The results of accelerated tests cannot be directly used to design the service life of an RC structure, since they do not take into account the real exposure conditions (such as, for instance, the actual relative humidity, temperature, wetting event) and the curing. The literature provides suggestions for calculation procedures intended for the extrapolation of accelerated test results to natural conditions [21, 22]. A general relationship between them cannot be assessed, since it is strongly affected by exposure conditions [5].

Many researchers have attempted to determine indicators on the basis of which the depth of carbonation could be reliably predicted [11, 12]. However, others believe that general indicators for potential durability, such as water porosity, gas permeability, and chloride diffusion, are not reliable in assessing the resistance of concrete to carbonation [13].

The most common attitude in concrete design and concrete durability control could be named a prescriptive approach. A typical example of this approach is the EN 206 standard [14]. For carbonation-induced corrosion, four classes are defined and described: XC1, XC2, XC3 and XC4. However, this attitude has many disadvantages, as it does not take into account the needs related to the development of up-to-date concrete technologies in terms of sustained development. Harrison [15] analyzed the behavior of hundreds of various concretes from the point of view of the rate and extent of carbonation. He concluded that in many cases the concretes had better parameters than expected, thus demonstrating from a practical and economical point of view the possibility of cheaper concrete production (higher water-cement ratio, less binder, and other cheap components).

In the case of contemporary concretes made with the use of unconventional materials (other binder than those specified in EN-206 [14], there is no information available on what concrete carbonation looks like under natural exposition conditions. Conclusions can be drawn mainly on the basis of the results of accelerated carbonation tests [16-18]. Under laboratory accelerated carbonation tests, testing is usually performed using significantly higher carbon dioxide concentrations to obtain results in possibly the shortest time. Concentrations are usually 3-4% [17, 18] and sometimes very high up to 10-50% [19].

A very important issue, in line with the sustainable development postulate, is the use of various mineral additives and the design of concretes taking into account their durability in a given environment. Therefore, the standard EN-206 introduces three

concepts for the use of additives: the k-factor concept [20], the equivalent concrete performance concept, the equivalent combination performance concept. The currently common reasoning related to the functioning of these concepts and their application (with examples) is presented in Report CEN/TR 16639: 2014 [23].

It is generally stated that, both technically and economically, the use of BFS or FA in concrete has many advantages. The results of the literature show that concretes with FA or BFS are more resistant to environmental loads such as chloride or sulfate attacks [24, 30]. On the contrary, they are often found to have a lower resistance to carbonation compared to Portland cement concretes [24]. Carbonation is clearly a key point to be analyzed for these kinds of material.

Partial replacement of OPC by BFS or FA alters thus the reaction kinetics and reaction degrees [19]. Previous research has already shown that the microstructure of BFS and FA concrete develops slower and the durability behavior is different from that of OPC concrete.

The calcium hydroxide (CH) content in BFS concrete is known to be drastically lower than that of ordinary Portland cement concrete. In the long term, BFS concrete tends to suffer more from carbonation attack due to its low alkalinity [25]. However, in terms of carbonation resistance, a general decrease in concrete behavior is observed when the cement clinker is replaced by type II additions. A work by Sisomphon and Frank [25] shows that the pozzolanic mixtures studied have a lower carbonation resistance and therefore also have a shorter induction period for carbonation. Rozière et al. [13] point out that from concrete mixtures made with the same water/binder ratio a negative effect of fly-ash can be deduced. Regarding blast furnace slag, Gruyaert et al. [19] conclude that carbonation coefficients increase as the replacement of cement by slag in concrete increases. Younsia et al. [24] also report huge differences in accelerated carbonation kinetics between water-cured and air-cured concretes, especially in the case of concretes with blast furnace slag.

Carbonation coefficients increase as the replacement of cement by slag in concrete increases. The carbonation resistance of BFS concrete is poor and although curing for longer times (up to 3 months) increases the resistance, performance remains low, especially for cement replacement levels of 70% and above [19].

The effect of the slag dosage ratio on the carbonization depth of high-performance concrete (water-binder ratios of 0.25-0.35) is small, and the carbonation depth ratio does not increase significantly with the change

of the mixed quantity significantly; dosage increased from 45% to 60%, the carbonation depth increases slightly, which shows that the influence of changing the slag dosage on the carbonation performance of concrete is very small [11].

Carbonation makes BFS concrete more vulnerable to scaling under the combined load of frost attack and de-icing salts, compared to ordinary Portland cement mixtures [30]. As appears from Deja [26], Giergiczny et al. [27], Wawrzeńczyk [28], the increased content of BFS in the binder results in the deterioration of the structure of the air pores, thus deteriorating the resistance to concrete scaling.

This article presents the results of accelerated carbonation tests of concretes made with CEM III/A blast furnace slag cement and the addition of fly ash. Therefore, the influence of two material factors (GBSF and FA) with a potentially negative impact on the course of the carbonation process was analyzed. The aim was to develop mathematical models to predict the depth of carbonation and the rate of carbonation depending on the binder composition and the water-binder ratio.

2. MATERIALS AND METHODS

2.1. Materials

The following materials were used in the testing:

- CEM III/A 42.5N blast furnace cement,
- silicone fly-ash,
- crushed limestone grit of 2-8 mm and 8-16 mm,
- plasticizer or superplasticizer.

The characteristics of cement and fly ash are presented in Table 1. Cement contains 50% slag.

Table 1. Results of the analysis of cement and fly ash

Parameter	Unit	Cement	FA
Humidity	%		0.3
Loss on ignition	%	2.99	3.54
Insoluble particles	%	0.59	16.6
Silica (SiO ₂)	%	26.67	52.0
Alumina (Al ₂ O ₃)	%	5.6	21.8
Iron oxide (Fe ₂ O ₃)	%	2.28	7.1
Calcium oxide (CaO)	%	53.83	4.32
Magnesium oxide (MgO)	%	3.85	2.48
Sulphur trioxide (SO ₃)	%		0.57
Sodium oxide (Na ₂ O)	%	0.28	1.15
Potassium oxide (K ₂ O)	%	0.79	2.70
Sodium oxide (Na ₂ O) eq	%	0.8	2.93
Cl ⁻	%	0.064	0.006
Disposable calcium oxide (CaO)	%		0.08
Blaine	cm ² /g		2.963
Density	g/cm ³		2.05
x'	µm		66.75

2.2. Testing program

The testing program was developed using experimental planning theory. In this examination, a bifactor 9-point experimentation plan was applied. This attitude allows us to determine the relationship between the examined characteristic (Y) and the composition factors ($X1, X2$) as a regression function in the form of a quadratic polynomial:

$$Y = a0 + a1 \cdot X1 + a2 \cdot X2 + a11 \cdot (X1)^2 + a22 \cdot (X2)^2 + a12 \cdot X1 \cdot X2 \quad (1)$$

The function could be visualized in the form of a contour or a 3D plot. This provides the possibility of a graphical presentation and identification of the relationship between the feature being examined and composition factors (water-cement ratio and fly-ash percentage).

The following investigated factors were adopted:

- water-to-binder ratio (W/B), code name $X1$,
- fly-ash additive content in relation to cement (FA% = FA/C), code name $X2$,

The coded values are to be:

- $X1 = (W/B - 0.55) / 0.10$; $X1 \in \langle -1, +1 \rangle$,
- $X2 = (FA/C - 0.15) / 0.15$; $X2 \in \langle -1, +1 \rangle$, respectively.

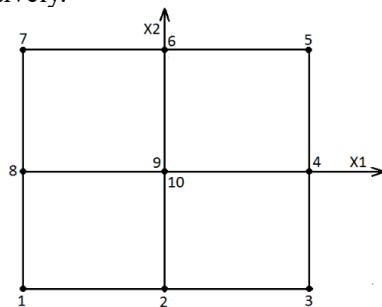


Fig. 1. Experimental planning scheme

The experimental planning scheme is shown in Figure 1. The coded and natural planning matrix is shown in Table 2.

Table 2. Planning matrix

Ref.	X1	X2	W/B	FA%
1	-1	-1	0.45	0
2	0	-1	0.55	0
3	1	-1	0.65	0
4	1	0	0.65	15
5	1	1	0.65	30
6	0	1	0.55	30
7	-1	1	0.45	30
8	-1	0	0.45	15
9	0	0	0.55	15
10	0	0	0.55	15

The characteristics examined were the following:

- concrete compressive strength, f_c ;
- carbonation depth, d_k ;
- porosity, p ;
- water absorption, n_w ;
- water penetration depth, D_p ;
- capillary suction, n_{cap} .

2.3. Testing Methods

Concrete mixes were prepared in a laboratory forced mixing device. The sequence of dosing of the components was as follows: dry components, portion of batch water and admixture, and remaining portion of water. The amount of plasticizing admixture was dosed as much to obtain the consistency of S3. The total mixing time was approximately 4 minutes. Once consistency was measured, test samples were prepared as follows:

- 15 cm side cubic samples to test compressive strength and water penetration (9 samples),
- 8×8×35 cm beam samples to test carbonation (3 samples),
- 100 mm side cubic samples to determine water absorption, capillary suction, and porosity (6 samples),

All samples were stored for up to 28 days in water at 20°C. Compressive strength tests were performed after 28 and 90 curing days according to the PN-EN 12390-3 standard.

Porosity characteristics tests were carried out using 100 mm side cubic samples. The samples were soaked with water for 7 days and their weight and volume were determined using the hydrostatic method. The samples were dried to constant weight at 105°C for 48 hours. The samples were placed in an airtight container, air was evacuated by vacuuming and then the sample container was gradually filled with degassed water by heating to 60°C. The samples remained in the container with water for the next 48 hours and then their mass was determined. On the basis of the results obtained, the mass and volume water absorption and the porosity p as volume water absorption under vacuum were calculated.

Capillary suction tests were performed using a single 15×15×5 cm sample cut from a cubic sample, once the depth of penetration of the water was tested. The samples were stored under laboratory ambient conditions ($T = 20^\circ\text{C} \pm 2^\circ\text{C}$ and $\text{RH} = 65\% \pm 5\%$) up to 4 weeks. The side faces of the samples were coated with a resin. The samples were placed on a sponge base in a bath tub filled with water, with the water level 5 cm above the face of the lower sample. Samples were taken from the tub, dried with a rag, and sample weights were determined. These tests were repeated in periods for 8 days.

Capillary suction tests were performed on a $15 \times 15 \times 5$ cm sample cut from a cubic sample after testing the depth of penetration of the water. The samples were stored under laboratory conditions ($T = 20^\circ\text{C} \pm 2^\circ\text{C}$ and $\text{RH} = 65\% \pm 5\%$) for up to 4 weeks. The side surfaces of the samples were painted with resin. The samples were placed in a bath of water on a sponge cushion so that the water level was 5 mm above the bottom surface of the sample. The samples were taken from the bath, wiped with a cloth, and weighed. These tests were repeated periodically until day 8.

Concrete carbonation tests were carried out using the accelerated method, as prescribed by FprCEN/TS 12390-12 [17], and applying a special chamber equipped with the following systems:

- temperature control system with the temperature control range of $16 \div 30^\circ\text{C}$ ($\pm 1^\circ\text{C}$);
- humidity control system with the humidity control range of $30 \div 90\%$ ($\pm 1\%$ RH);
- constant level carbon dioxide concentration control system with the control range of $0 \div 5\%$;
- gas transmission system inside the chamber (air circulation);

- recording system of the chamber's inside conditions measurements results.

The testing chamber and control panel views are shown in photo 1.

The test samples were cured for 28 days in water and then for another 14 days in air at a temperature of $18\text{-}25^\circ\text{C}$ and a relative humidity of $50\text{-}65\%$. After this period, a petroleum wax coat was applied to the top and lower faces of the sample and two front walls. The two other sample faces were left in a natural condition, and carbonized layer depth measurements were made. Subsequently, the prepared samples were placed in the airtight carbonization chamber equipped with a forced air flow system, with a carbon dioxide concentration of $4.0\% \pm 0.5\%$, temperature of $20^\circ\text{C} \pm 2^\circ\text{C}$ and a relative humidity of $55\% \pm 5\%$. Samples were arranged in the chamber to make free air flow around carbon dioxide-saturated faces possible. The carbonation depth examination was carried out five times using three concrete beam samples after 14, 28, 42, 56, and 70 days of storage inside the carbonation chamber. After determined time beam samples were broken to obtain some 50 mm thick pieces (photo 2). The remaining portion of the beam

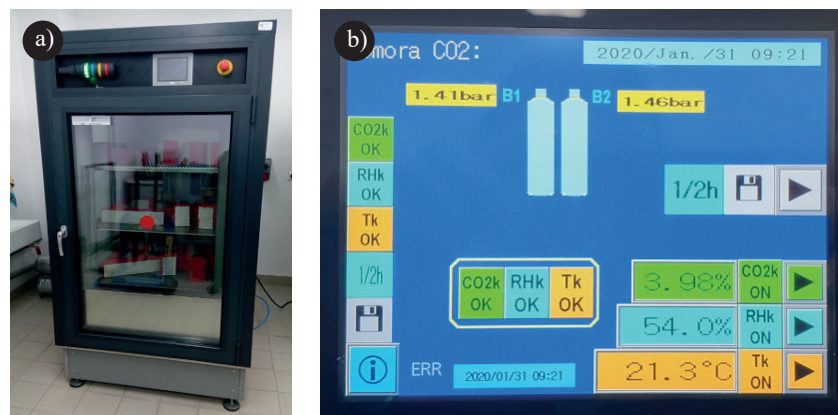


Photo 1. Views of the chamber (a) and control panel (b)

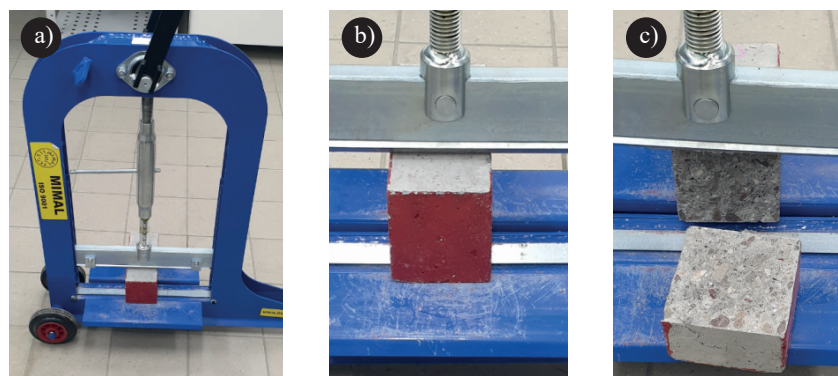


Photo 2. Method of preparing the samples for examination: (a) block splitter to break a sample, (b) breaking face perpendicular to nonprotected surfaces, (c) broken sample view

was protected as described above and placed in the chamber until the next examination date.

A phenolphthalein solution was sprayed on the surface of the fresh fracture of the sample, which causes the color of the concrete surface to change to a violet color. After about 60 minutes, the samples were photographed. The carbonation depth was determined by taking measurements on photographs using the *NIS-Elements* software. First, each photograph was calibrated. The arrangement of the measuring lines on the break surface is shown in Figure 2. Measurements were made at five points on one surface with an accuracy of 0.1 mm, which means a total of 10 measurements on one sample. The carbonation depth for a given sample is the average result. For each series of concrete, the mean value of the carbonation depth and the standard deviation were calculated, taking into account the results obtained on 3 samples. Based on the statistical test, it was checked whether there were outliers (gross errors). Where such occurred, they were ignored in the calculations of the final dk value for a given concrete tested.

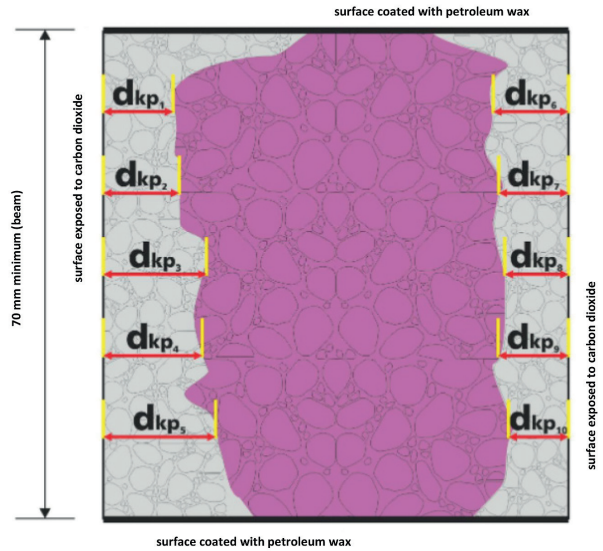


Fig. 2. Arrangement of the measuring points in the beam break

3. TEST RESULTS ANALYSIS

The results of the carbonation depth and accompanying examinations of the tested concretes are shown in Table 3.

Table 3. Average concrete properties results

Ref.	Compressive strength		Carbonation depth					Water penetration	Water absorption	Porosity	Capillary suction
	f_c -28 MPa	f_c -90 MPa	d_k -1 mm	d_k -2 mm	d_k -3 mm	d_k -4 mm	d_k -5 mm	D_p mm	η_w %	P %	n_{cap} g/m ²
1	62.0	67.9	2.7	4.0	4.9	6.2	6.0	9	3.3	8.6	1187
2	49.0	55.6	5.0	7.5	8.2	10.3	10.5	14	3.8	10.2	2359
3	41.4	47.2	6.4	9.1	10.3	12.6	12.9	14	4.4	11.7	2531
4	34.6	43.9	8.2	10.4	13.0	15.4	16.3	24	4.5	11.6	2500
5	30.1	38.1	9.7	13.0	16.0	18.4	19.2	20	4.8	12.6	3234
6	40.5	46.1	7.3	9.6	11.3	13.6	14.3	14	4.1	10.5	3078
7	58.5	66.6	5.3	7.5	8.3	9.6	10.8	14	3.2	8.2	1000
8	58.2	65.8	4.7	6.5	7.2	8.7	9.3	10	3.4	8.7	1266
9	47.2	54.8	6.0	8.7	9.6	11.4	12.1	12	3.9	10.0	1734
10	47.9	55.7	6.4	8.3	10.1	11.9	11.9	10	4.0	10.2	1484

3.1. Carbonation depth and concrete composition relations

The influence of concrete composition on the depth of carbonation was analyzed by determining the relationships in the regression function form of the $d_{ki} = f(X1, X2)$. Regression functions in the form of incomplete quadratic polynomials (higher-

order components turned out to be irrelevant) were determined using the *Design Expert 8* software. The a_i regression and the R correlation coefficients for specific examination dates (measurements 1 through 5) are shown in Table 4.

Table 4. The regression coefficients a_i and R for the function $d_{ki} = f(X1, X2)$

Regression coefficients	Examination ref.				
	d_k-1	d_k-2	d_k-3	d_k-4	d_k-5
a0	6.17	8.46	9.89	11.81	12.31
a1	1.93	2.42	3.15	3.64	3.72
a2	1.37	1.58	2.03	2.10	2.46
a12	0.17	0.10	0.57	0.62	0.36
R	0.98	0.97	0.99	0.99	0.99

The contour plots 3 and 4 show examples of dependencies. As appears from the comparative analysis of those plots, the carbonation depth depends on both the water-to-binder ratio (W/B) and the fly-ash (FA) content in the binder. The lower the W/B ratio, the concrete is more watertight, and thus the carbonation depth is lower. Increased fly-ash content at a given W/B ratio results in higher porosity and larger carbonation extend.

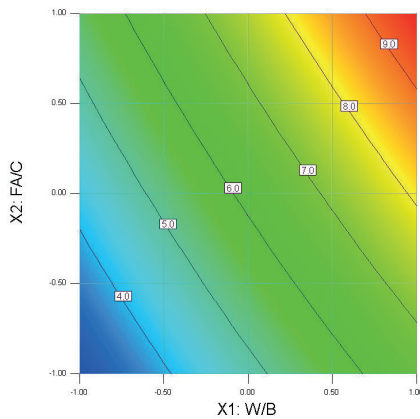


Fig. 3. Influence of concrete composition on the depth of carbonation d_k-1 after 14 days of exposure in the CO_2 chamber

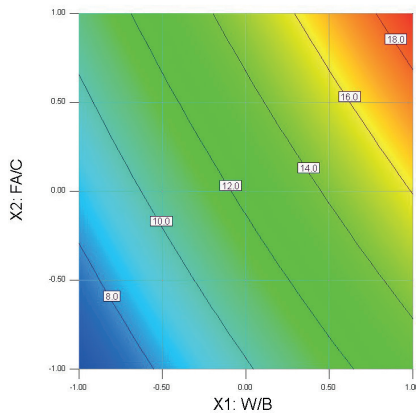


Fig. 4. Influence of concrete composition on the depth of carbonation of d_k-5 after 70 days of exposure in the CO_2 chamber

3.2. Relation between carbonation and hardened concrete properties

The interactions found between the specific properties determined for the tested concretes are illustrated in Figure 5 as a matrix chart. Relations shown on the graph indicate the presence of quite good correlations; however, these are not sufficiently close correlations that could be a basis for determining the carbonation depth. Neither the ‘volume-related’ characteristics, such as water absorption n_w and porosity p , nor the ‘surface-related’ characteristics, such as D_p water pressure penetration depths and capillary suction n_{cap} , create sufficiently good indicators of carbonation ratios.

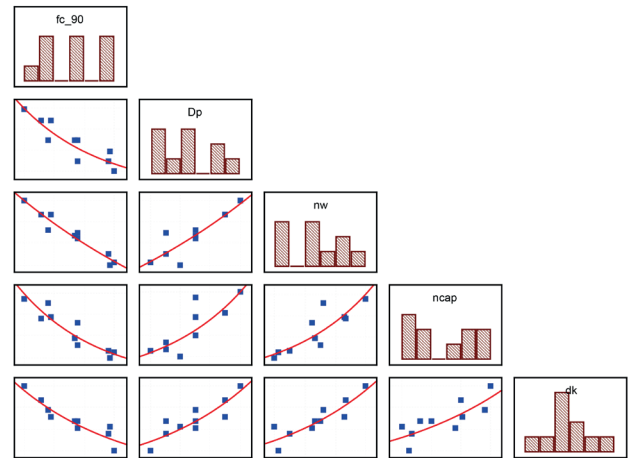


Fig. 5. Matrix diagram illustrating relations between concrete properties

The relationship between the depth of carbonation d_k and the strength of the concrete $fc-28$ and various percentages of FA ash are presented in Figure 6.

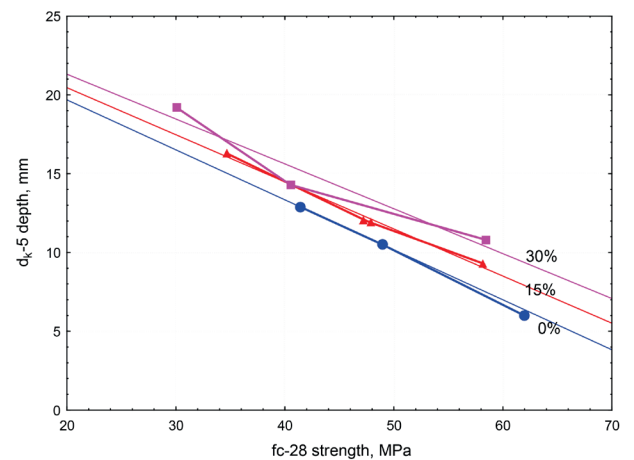


Fig. 6. Relation between the depth of carbonation of d_k and the concrete strength of $fc-28$ and the different percentages of FA ash content

It could be seen that the higher the strength, the lower the depth of carbonation. However, no simple linear relationship is clear. A trend line shift related to the fly ash content is visible: a higher fly ash content with the same concrete strength results in an increased carbonation depth, which could be explained by modifications in the concrete porosity structure.

3.3. Carbonation depth and exposure time relations

The relationship between carbonation depth d_k and exposure time to carbon dioxide in the carbonation chamber is shown in Figure 7. In standard time, the depth of the d_k ranged from 6.0 mm to 12.8 mm for the CEM III concrete, from 9.3 mm to 16.3 mm with a 15% fly ash content and from 10.8 mm to 19.2 mm with a 30% ash content.

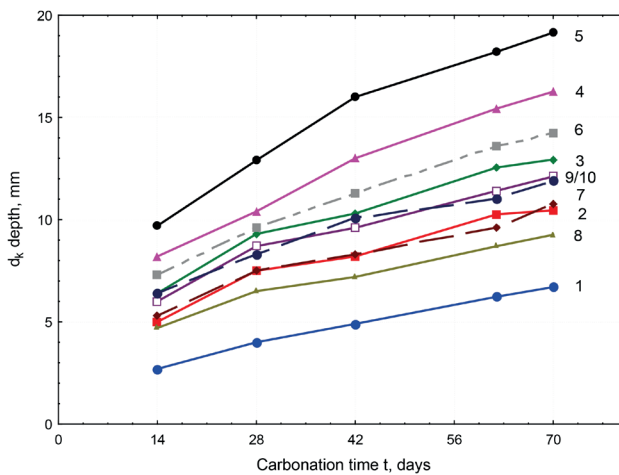


Fig. 7. Relation between the depth of carbonation of d_k and the exposure time in the CO_2 chamber

3.4. General carbonation model

The following results from the graph shown in Figure 7:

- The deeper the carbonation depth after 14 days, the higher the depth in the later period.
- The depth of carbonation after 14 days depends on the concrete composition (W/B, F/A%) that was manifested in the contour plot no. 8.
- The growth rate of the carbonation depth dk depends not only on the exposure time t but also on the concrete composition.
- Analysis of the relation d_k and the exposure time relation indicated the function $d_k(t) = a + K \cdot \sqrt{t}$ describes this relation in the best for a specific concrete.

The generalized function describing the relation of the depth of $dk(t)$ and the factors examined shall be composed of two sections:

$$d_k\left(\frac{W}{B}, FA\%, t\right) = f\left(\frac{W}{B}, FA\%\right) + g\left(\frac{W}{B}, FA\%\right) \cdot \sqrt{t} \quad (2)$$

The functions $f()$ and $g()$ in the form of polynomials were adopted. The calculations of the regression coefficients were carried out using the *Statistica* software, and the following relations were obtained for natural values.

$$d_k\left(\frac{W}{B}, FA\%, t\right) = 0.709 - 0.126 \cdot \frac{W}{B} - 8.02 \cdot FA\% + 22.417 \cdot \frac{W}{B} \cdot FA\% + \left(-1.71 + 4.203 \cdot \frac{W}{B} + 1.258 \cdot FA\%\right) \cdot \sqrt{t} \quad (3)$$

The comparison of the measured dk with calculated values of the $d_k()$ function is shown in Figure 8.

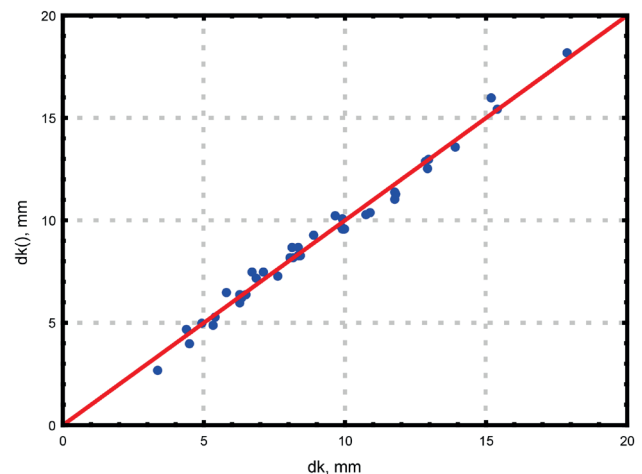


Fig. 8. Relation between measured d_k and calculated values $d_k(t)$ function

3.5. Carbonation rate

The k carbonation rate was determined graphically by transforming Figure 7. The average carbonation depth at each exposure time was plotted against the square root of the exposure time in days, and linear regression was performed through the points according to the classical formula:

$$d_k = a + K \cdot \sqrt{t} \quad (4)$$

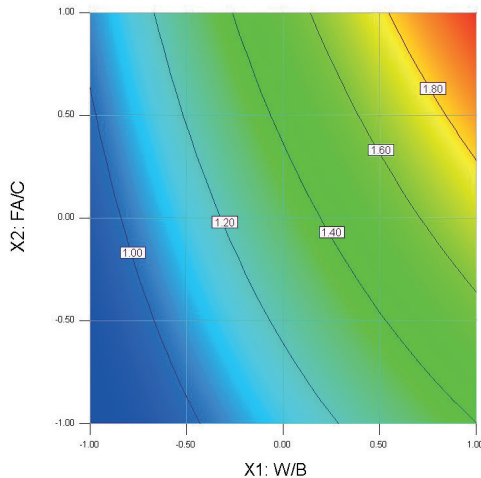


Fig. 9. The relationship between the carbonation rate index K and factors $X1$, $X2$ examined

The slope of the linear function illustrates the K carbonation rate index. Carbonation rates varied from 0.8 to 2.0 mm/day^{0.5} for the tested concretes. The relationship between the carbonation rate K and the factors examined $X1$, $X2$ is shown in Figure 9. The contour line arrangement shows that the carbonation rate depends on both the W/B ratio and the amount of $FA\%$ fly-ash additive. Therefore, it is

similar to the contour line arrangement illustrated in Figures 3 and 4.

4. CONCLUSIONS

This article presents the results of accelerated carbonation tests of concretes made with CEM III / A blast furnace slag cement and the addition of fly ash. Therefore, the influence of two material factors (GBSF and FA) with a potentially negative impact on the course of the carbonation process was analyzed.

The results of the test are as follows:

1. The carbonation depth increases with increasing the water-binder W/B ratio and as a result of increasing the fly-ash content in the binder.
2. It was found that there is no close relationship between other properties tested (for example, strength) and the depth of carbonated concrete.
3. The mathematical model of carbonation over time that can predict the depth of carbonation. Analysis of the relation d_k and exposure time relation indicated the function $d_k(t) = a + K \cdot \sqrt{t}$ describes this relation in the best for a specific concrete.
4. It was found that the concrete carbonation rate K is not a constant value as it depends on both the W/B ratio and the fly-ash content in the binder.

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