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NON-INVASIVE TESTS OF HIGH PERFORMANCE CONCRETES IN THE CONTEXT OF THEIR APPLICATION IN UNDERGROUND CONSTRUCTION INDUSTRY

1. Introduction

Development in concrete technology has recently resulted in new generation concretes, including high performance concretes. New generation concretes are a response to the need of considering additional factors in investment processes, related to i.a. broadly understood the sustainable development, but principally they met with increasingly higher economic requirements set for the investments. Dynamic development of new generation concretes has also caused an important change to the investors' approach, and thus designers' approach to the term of structure durability. Recently, a new field in concrete design has been developed – durability technology [4]. Application of new generation concretes causes a significant increase to structure durability and their lifespan which can often be twice as long as that of regular concretes.

The increased use of new generation concretes has also been observed in the process of designing engineering facilities, both over ground and underground. This paper [1] proves that in reference to well casing, the application of high performance concrete may result in a relative reduction of casing cost by 36.3%. Furthermore, the reduced thickness of the casing results in its reduced volume and the volume of the breach, as well as cost of works related to the very laying of the concrete. Considering the higher material cost of HPC, the entire reduction of the cost of the concrete casing of a well can be estimated at the level of 15.00%.

Designing and analysing of the strength properties of high performance concretes is very dynamic, whereas standard PN-B-03264:2002 [8] regarding the design of reinforced concrete and compressed structures should consider only concretes with guaranteed strength not greater than $f^{G}_{c,cube}$ = 60 MPa (class B60). Together with Poland's accession to the European Union and the adjustment of Polish regulations to conform to the EU regulations, a new

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standard, PN-EN 206-1 [13] was introduced, defining strength of i.a. regular concretes. The currently applicable standard for designing reinforced concrete and compressed structures EN 1992-1-1 — Eurocode 2: *Design of concrete structures* [14] significantly extended the scope and application of concretes, up to concretes with a characteristic strength of 110 MPa and 115 MPa depending on sample type (class C110/115). For this reason, high performance concrete has found a broad application in such facilities as bridge structures, compressed elements, skyscrapers, underground facilities — tunnels and shafts.

Investors, as well as designers, when deciding to select high performance concrete, often consider the additional properties of this material, such as e.g. the quick increase in its strength. This property makes high performance concretes increasingly applied not due to their high strengths, but principally because of the possibility to carry out the investment in a much shorter time. The opportunity of earlier removal of boarding may in some cases shorten the investment process even by half, which largely compensates for additional costs of high performance concrete. However, in order to consciously assess the compression strength of concrete, it is necessary to perform a number of invasive tests and supplementary non-invasive tests. So far, there is no clear information on the course of this procedure in the case of non-invasive tests on high performance concretes. The modified recipe and properties of high performance concretes point to a different course of increase in strength in such concretes when compared to regular concretes.

The purpose of this paper is an attempt verify whether the existing standards and instructions allow for assessing the strength of hardened high performance concrete, including during its curing period. The term of the curing time is understood as the period where the engineer is carrying out a particular investment and must make the decision for example on disassembly of boarding. In the case of determining vast discrepancies in the HPC strength when using the recommendations of the binding standards and instructions, it would be justified to develop new principles regarding high performance concrete.

2. Previous interpretation of non-invasive HPC tests

Compression strength of concrete is one of the basic volumes to be determined during structure erection, when wishing to consciously manage the technological process and progress of concrete works. It is assumed that the most reliable information on concrete quality is obtained from samples prepared during facility construction or from core samples taken from an existing structure [5, 6].

Concrete strength in an existing structure has so far been determined in various ways, depending on the standard. In the 1960s, it was permitted to assess the compression strength of concrete on the basis of cut concrete blocks or cores sampled from the structure. In further standards, PN-B-06250:1975 [9] and PN-B-06250:1988 [10], it was permitted — in justified cases — to assess concrete strength on the basis of cores cut out from the structure. Standard applicable at the time, PN-B-01807:1988 [7], imposed additional an obligation to determine concrete strength using invasive an method on sampled cores, or non-invasive sclerometric method acc.

to PN-B-06261:1974 [11] and ultrasound method acc. to PN-B-06262:1974 [12]. At present, much more attention is paid to the issues of determining concrete strength in existing structures. In the European standard PN-EN 206-1:2003 [13], which has replaced PN-B-062250:1988 [10], it is clearly stated that concrete strength can be determined on core samples cut out from a structure, and additionally invasive tests of the structure can be performed.

Due to the fact that it is not always possible to sample a sufficient volume of material for the tests, e.g. due to weakening the structure (thin elements, cutting through bearing reinforcement, bearing beams), or difficulties in repair of the damage, non-invasive tests seem to be a necessary supplement of invasive tests. In the case of structures made of high performance concretes, there is, however, a problem with appropriate interpretation of the obtained measurement results.

Undoubtedly, the advantage of non-invasive tests, as the name implies, is the lack of damage to the structure. Lack of invasion into the building means that the tests are performed at the same place, which yields reliable results in the time function. Furthermore, diagnostics can be performed on high-risk elements of the structure, such as thin columns, or binding joists. Non-invasive tests are always performed on the produced element in the natural state, namely with initial or complete load.

There are many non-invasive methods that serve to test compression strength, but the most popular include sclerometric and acoustic methods.

Sclerometric method is based on hardness tests and is one of the most popular methods for controlling concrete quality. The most frequently used device for dynamic sclerometric tests is the Schmidt hammer, where strokes are caused with constant energy using a spring system. After the stroke, the hammer plunger bounces back to the specified height, which is determined at the scale by the "rebound number". The rebound number is therefore the measure of dynamic hardness of the tested material, which practically allows for direct finding of the empirical dependence between concrete strength f and the rebound number L in the form of:

$$f = f(L) \tag{1}$$

Such dependence is not the same for all concretes. Their nature depends on many parameters, starting from the composition of the concrete mix, and ending with moisture content and age of concrete tested. In literature on the subject, there are many correlation curves, the general nature of which is similar, yet the discrepancies are so vast that this does not allow for determining one, general regression curve for all concretes.

For practical reasons, in sclerometric tests, as well as in other non-invasive methods, the assessment of concrete strength is most frequently performed by calibration on the basis of core drillings to the limited range of strengths, using the predefined correlation dependence. In the case of sclerometric tests, PN-EN 13791:2008 [16] provides only for dependencies for regular concretes, in the following form:

$$f_L = 1.25 \cdot L - 23.0 \quad \text{for } 20 \leq L \leq 24 \tag{2}$$

$$f_L = 1.73 \cdot L - 34.5 \quad \text{for } 24 \leq L \leq 50 \tag{3}$$

A similar approach is observed in the provisions of PN-B-06262:1974 [12] and in the ITB instruction 210/1977 [3], where, as the most representative function for describing the dependence between the rebound number and regular concrete strength, the parabolic function was adopted in the form:

$$f_L = 0.041 \cdot L^2 - 0.914 \cdot L + 7.4 \tag{4}$$

It must be stressed that neither PN-EN 13791:2008 [16], nor PN-B-06262:1974 [12] consider high performance concretes in their analyses, and it is only the ITB instruction 210/1977 [3] that introduces additional coefficients to be used for adjusting the correlation curve, including i.a. concrete age. It must be additionally stressed that PN-B-06262:1974 [12] also permits the application of the function in the form:

$$f_L = a \cdot L + b \quad - \text{linear} \tag{5}$$

$$f_L = a \cdot e^{b \cdot L} \quad - \text{exponential} \tag{6}$$

$$f_L = a \cdot L^b \quad - \text{power} \tag{7}$$

where a, b, c — numerical factors.

In papers [17, 18], one can see the dependence between the rebound number and high performance concrete strength in the form of:

$$f_L = (0{,}9 \div 1.4) \cdot (0.041 \cdot L^2 - 0.914 \cdot L + 7.4) \tag{8}$$

It is, therefore, clear that this is an equation as with regular concretes multiplied by the adjustment factor equal to 0.9–1.4. Preliminary tests performed by the authors on high performance concretes have indicated that the values of the proposed factor are too low, and the proposed correlation curve does not correctly describe the increase in strength in such concretes.

Analogical interpretation of test results is performed in the case of applying the ultrasound test method. In the case of such tests, PN-EN 13791:2008 [16] also provides for correlation dependence exclusively for regular concretes, in the following form:

$$f_V = 62.5 \cdot V^2 - 497.5 \cdot V + 990 \quad \text{for } 4.0 \text{ km/s} \leq V \leq 4.8 \text{ km/s} \tag{9}$$

In PN-B-06261:1974 [11] and in the ITB instruction 209/1977 [2], as the most representative function describing the dependence between the velocity of ultrasound wave V and regular concrete strength, the function was adopted in the form:

$$f_V = 2.39 \cdot V^2 - 7.06 \cdot V + 4.2 \quad \text{for } V = 2.4 \div 5.0 \text{ km/s} \tag{10}$$

Neither PN-EN 13791:2008 [16], PN-B-06261:1974 [11], nor ITB instruction 209/1977[2] consider high performance concretes or concrete age in their analyses.

In the literature on the subject, one can see the correlation dependencies for various types of concrete for the ultrasound method, including for high performance concretes. Some of them, similarly as in the case of the sclerometric method, were obtained by multiplying by the dependence factor specified for regular concretes.

Previous experience in the area of applying non-invasive methods in high performance concretes gives grounds for assuming that the methods for interpreting the results, as proposed in the current standards and instructions, yield underestimated results and do not consider the age of concretes tested.

3. Non-invasive tests of HPC

The purpose of the tests performed was to determine the possibility of applying non-invasive methods in tests of high performance concretes and to estimate compression strength on the basis of relevant regression curves. The tests were carried out according to the recommendations of standards and sectoral instructions. After the measurement of the rebound number and the trip time of ultrasound impulse, controlled destruction of the samples took place.

PN-EN 12390-1:2001 [15] permits the performance of non-invasive tests on cores sampled from structures and laboratory-made cylindrical, cuboid, or cubic samples. The tests involved 16 cubic samples with dimensions 150×150×150 mm, made of the same concrete mix. The basis for the study was formed by the recipe of the concrete mix presented in Table 1, developed on the basis of data from the literature.

TABLE 1
Recipe for high performance concrete mix

Content of particular components per m^3 of the mix	
Cement CEM I 42.5	500.0 kg
Water	160.0 dm^3
Sand 0/2 mm	575.0 kg
Diabase aggregate 2/8	1 224.0 kg
Silica fume	51.6 kg
Superplasticizer	7.5 kg

Invasive and non-invasive tests with the sclerometric and ultrasound method were performed after day 3, 7, 14, 21 and 28 of curing. Each time, 3 samples were subjected to destruction. The obtained results of the invasive tests in particular time periods have been presented in Figure 1. On the basis of the tests, it can be stated that the increase in compression strength of the concrete analysed on days 7–28 was close to linear. Sample results from day 3 of curing were characterised with vast discrepancy, hence they were neglected for further considerations.

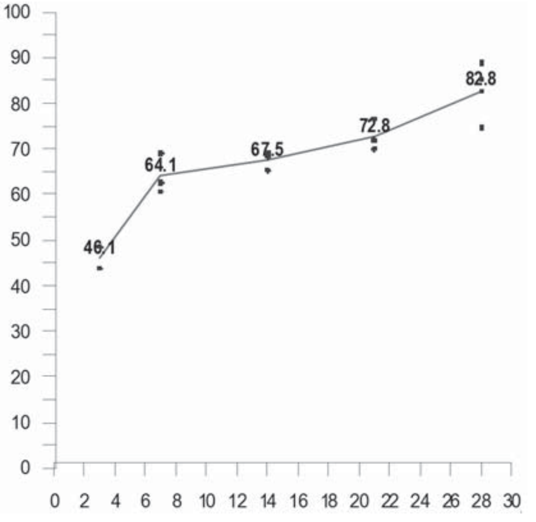

Fig. 1. Increase in mean compression strength of HPC specified on cubic samples

The analysis of non-invasive tests, both sclerometric and ultrasound, was performed with a simplified method, based on the correlation of relevant base curves. The approximate method, according to the European standard, can be applied for at least 9 result pairs (1 pair of results comprises results from invasive and non-invasive tests) and does not consider concrete age. Therefore, for the purpose of reducing the probability of error, results of tests from day 7, 14, 21 and 28 of concrete curing were used.

Figure 2 presents results of invasive tests of the samples analysed and the results of the performed analysis of strength estimation from sclerometric tests using the simplified method, according to recommendations of PN-EN 12390-1:2001 [15]. The figure presents base curve described with equation (3) and results of its scaling in the form of:

$$f_L = 1.73 \cdot L + 1.75 \tag{11}$$

Due to the fact that the base curve (3), according to the assumptions of the standard analysed, is the bottom envelope of compression strength, Figure 2 additionally presents the correlated form of the equation describing bottom envelope of the strength of concrete analysed in the form of:

$$f_L = 1.73 \cdot L - 3.47 \tag{12}$$

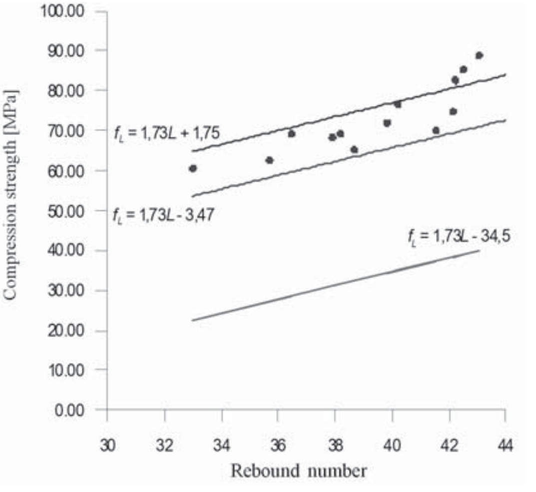

Fig. 2. Diagrams of dependence of actual strength of cubic samples made of HPC on the rebound number, acc. to PN-EN 12390-1:2001 [15]

Analogical analysis were performed using the recommendations of PN-B-06262:1974 [12] and ITB instruction 210/1977 [3]. Figure 3 presents base curve described with equation (4) and results of its scaling in the form of:

$$f_L = 2.12 \cdot (0.041 \cdot L^2 - 0.914 \cdot L + 7.4) \tag{13}$$

It must be stressed that the value of a correlation factor equal to 2.12 is the average value of the obtained correlation factors on particular days of curing. The values changes in the range 1.96–2.50.

Figure 3 also presents the dependence taken from papers [17, 18] (equation 8), where maximum value of the correlation factor amounts to 1.4.

On the basis of the analyses performed, it can be determined that the proposed base functions contained in the standards describe the actual strength of concrete analysed in an unsatisfactory manner, in particular as regards the dependence contained in PN-B-06262:1974 [12]. Therefore, an additional analysis was performed, considering other regression functions when estimating compression strength of the concrete. The results of this analysis have been presented in Table 2.

TABLE 2

Results of regression of the dependence between compression strength and the rebound number

Function type	Function form	R^2 Value
Linear	$f_L = 2.43 \cdot L - 22.91$	0.73
Parabolic	$f_L = 0.229 \cdot L^2 - 15.19 \cdot L + 314.04$	0.79
Exponential	$f_L = 19.392 \cdot e^{0.033 \cdot L}$	0.76
Power	$f_L = 0.691 \cdot L^{1.267}$	0.75

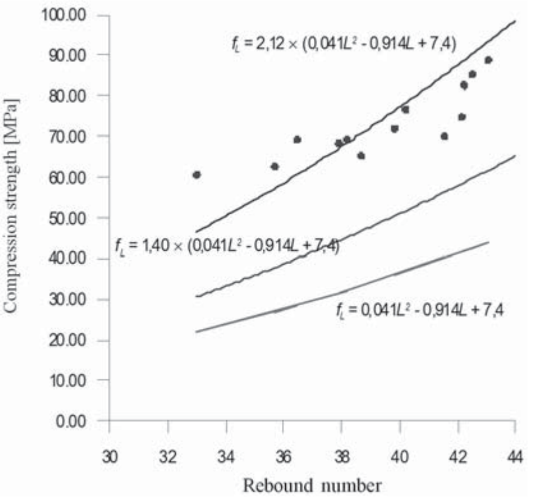

Fig. 3. Diagrams of dependence of actual strength of cubic samples made of HPC on the rebound number, acc. to PN-B-06262:1974 [12] and ITB instruction 210/1977 [3]

The analysis performed indicates that the dependence between compression strength of the concrete on the obtained rebound number is best reflected by the parabolic function. This confirms the assumptions of PN-B-06262:1974 [12], whereas the form of the function is slightly different than the one proposed by the standard.

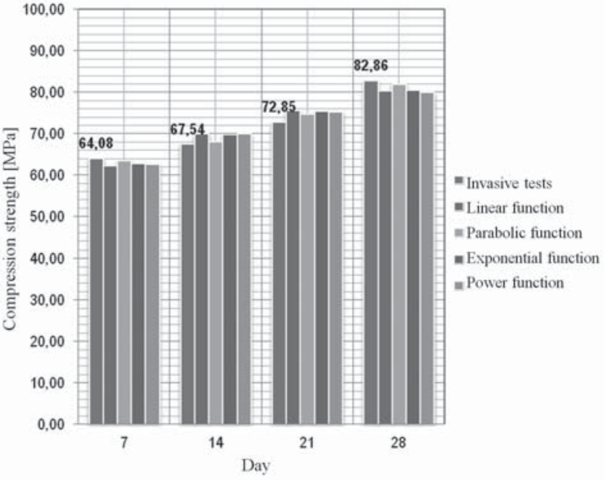

Fig. 4. Diagrams of dependence between actual strength of cubic samples made of HPC and the rebound number, acc. to regression function from Table 2

Figure 4 also presents the level of adjustment of the functions analysed on consecutive days of concrete curing. It must be stressed that the proposed function in the form:

$$f_L = 0.229 \cdot L^2 - 15.19 \cdot L + 314.04 \tag{14}$$

best describes the actual compression strength of the samples also on consecutive days of concrete curing.

Figure 5 present results of invasive tests of the samples analysed and results of the performed analysis of the strength estimation from ultrasound tests using the simplified method, according to recommendations of PN-EN 12390-1:2001 [15]. The figure presents base curve described with equation (9) and results of its scaling in the form of:

$$f_V = 62.5 \cdot V^2 - 497.5 \cdot V + 1040.8 \tag{15}$$

Due to the fact that the base curve (9), according to the assumptions of the standard analysed, is the bottom envelope of compression strength, Figure 5 additionally presents the correlated form of the equation describing bottom envelope of the strength of concrete analysed in the form of:

$$f_V = 62.5 \cdot V^2 - 497.5 \cdot V + 1030.9 \tag{16}$$

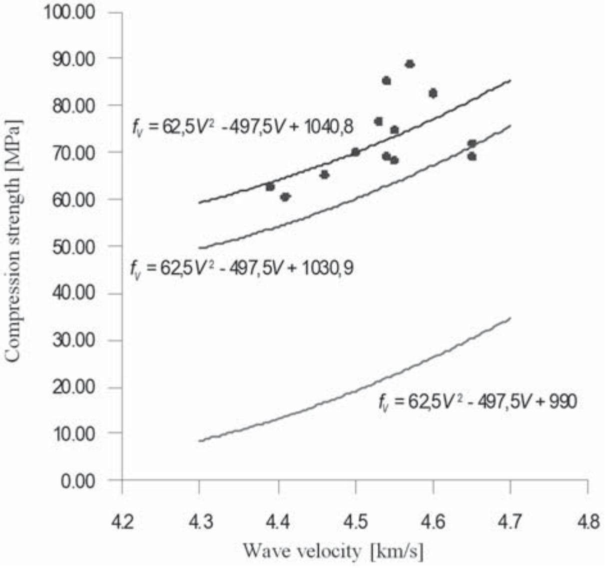

Fig. 5. Diagrams of dependence of actual strength of cubic samples made of HPC on the wave velocity, acc. to PN-EN 12390-1:2001 [15]

Analogically as in the case of sclerometric tests, an additional analysis was performed using the recommendations of PN-B-06261:1974 [11] and ITB instruction 209/1977 [2]. Figure 6 presents base curve described with equation (10) and results of its scaling in the form of:

$$f_V = 3.4 \cdot (2.39 \cdot V^2 - 7.06 \cdot V + 4.2) \quad (17)$$

Figure 6 also presents the dependence taken from papers [17, 18], developed for high performance concretes, in the form:

$$f_V = 2.7 \cdot (2.75 \cdot V^2 - 8.12 \cdot V + 4.8) \quad (18)$$

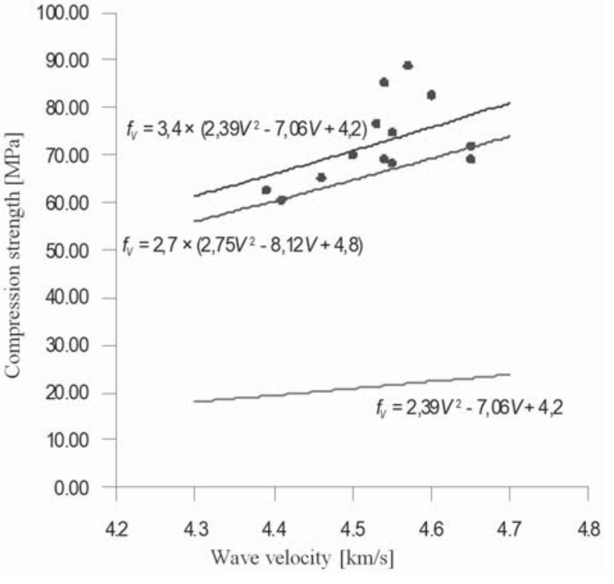

Fig. 6. Diagrams of dependence of actual strength of cubic samples made of HPC on the wave velocity, acc. to PN-B-06261:1974 [11] and ITB instruction 209/1977 [2]

On the basis of the analyses performed, it can be determined that the proposed base functions contained in the standards, similarly as in the case of the sclerometric tests, describe the actual strength of the concrete analysed in an unsatisfactory manner. Therefore, an additional analysis was performed, considering other regression factors when estimating compression strength of the concrete. The results of this analysis have been presented in Table 3.

TABLE 3

Results of regression of the dependence between compression strength and wave velocity

Function type	Function form	R^2 Value
Linear	$f_V = 57.18 \cdot V - 186.57$	0.28
Parabolic	$f_V = -554.98 \cdot V^2 + 5076.1 \cdot V - 11530$	0.48
Exponential	$f_V = 1.776 \cdot e^{0.817 \cdot V}$	0.31
Power	$f_V = 0.259 \cdot V^{3.724}$	0.32

The analysis performed indicates that the dependence between compression strength of the concrete on the wave velocity, similarly as in the case of the sclerometric tests, is best reflected by the parabolic function. This confirms the assumptions of both PN-EN 12390-1:2001 [15] and PN-B-06261:1974 [2], whereas the form of the function is slightly different than the one proposed by the abovementioned standards.

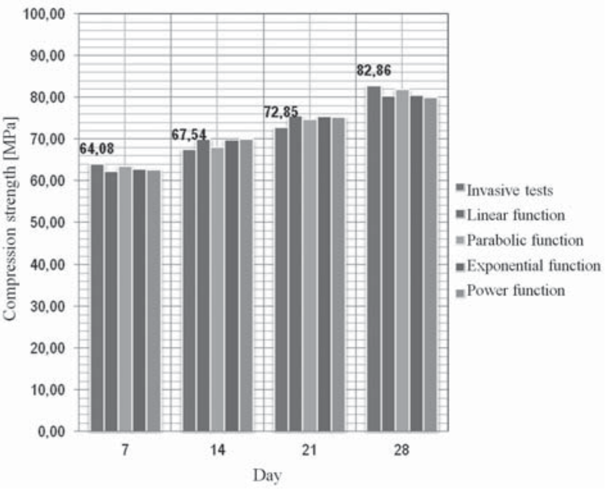

Fig. 7. Diagrams of dependence between actual strength of cubic samples made of HPC and wave velocity, acc. to regression function from Table 3

Figure 7 also presents the level of adjustment of the functions analysed on consecutive days of concrete curing. It must however be stressed that, similarly as in the case of the sclerometric tests, parabolic function best describes the actual compression strength of the samples also on consecutive days of concrete curing.

4. Summary

As a result of the tests performed and their analysis, the following observations were made and the following conclusions were drawn:

1) In sclerometric tests, a much better correlation of results is obtained when applying the proposed regression curves, yet worse results are yielded by the methods considering the factor related to concrete age. The fact was confirmed that the reading of the rebound number depends on material age. However, the values of factors related to the age of regular concretes do not correspond to the HPC analysed.
2) In the ultrasound tests, a much better correlation of the results is obtained when applying the proposed regression curves. Similarly as in the case of sclerometric tests, the parabolic function best describes the actual compression strength of the samples also on consecutive days of concrete curing.

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