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Practical application of the concept of equivalent concrete performance

Praktyczne zastosowanie koncepcji równoważnych właściwości użytkowych betonu

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Abstract. The paper presents a method of assessing the equivalent performance properties of concretes intended for use in exposure classes XC2 or XC4, made based on the relatively newly introduced CEM II/C-M (W-LL) 32.5R cement. The guidelines indicated in the technical report CEN/TR 16639 were used for the assessment of equivalent properties of both concretes. In the current legal situation, the use of CEM II/C cement, among others, for concrete of exposure class XC4, is possible of the PN-B-06265:2022-08 standard only after confirming its suitability by analyzing equivalent performance properties resulting from nature of the operating conditions. The essence of verification using equivalent performance properties of concrete is based on the comparison of the properties of reference concrete based on the solution recommended for use in a given exposure class to the properties of test concrete based on a new cement solution in terms of the assumed characteristics appropriate for the designed applications. The project included reference concretes made using CEM II/B-V 32.5R cement meeting the minimum composition criteria for exposure classes XC2 or XC4, and the tested concretes were concretes made using CEM II/C-M (W-LL) 32.5R cement.
Keywords: concrete; cement; equivalent concrete performance; low-clinker Portland composit CEM II/C; durability of concrete.

Streszczenie. W artykule przedstawiono sposób oceny równoważnych właściwości użytkowych betonów przeznaczonych do stosowania w klasach ekspozycji XC2 lub XC4, wykonanych na bazie nowo wprowadzonego na rynek cementu CEM II/C-M (W-LL) 32,5R. Do oceny wykorzystano wytyczne wskazane w raporcie technicznym CEN/TR 16639. W obecnej sytuacji prawnej użycie cementu CEM II/C m.in. do betonów klasy ekspozycji XC4 jest możliwe w świetle normy PN-B-06265:2022-08 jedynie po potwierdzeniu przydatności w drodze analizy równoważnych właściwości użytkowych wynikających z charakteru warunków eksploatacyjnych. Istota weryfikacji za pomocą równoważnych właściwości użytkowych betonu polega na porównaniu właściwości betonu referencyjnego rekomendowanego do zastosowania w danej klasie ekspozycji z właściwościami betonu testowego, zawierającego oceniany cement. Jako referencyjne przyjęto betony wykonane na cemencie CEM II/B-V 32,5R spełniające minimalne kryteria składu w przypadku klas ekspozycji XC2 lub XC4, a analizowane były betony wykonane na cemencie CEM II/C-M (W-LL) 32,5R.
Słowa kluczowe: beton; cement; równoważne właściwości użytkowe betonu; niskoklinkierowe cementy portlandzkie CEM II/C; trwałość betonu.

In the cement industry, recent years have been a period of intense search for solutions to reduce CO_2 emissions, driven by two fundamental factors – ecological and economic. The former results from the policy adopted at the European level to limit the negative impact of greenhouse gases on disastrous climate change.The latter is due to the rapid galloping increase in the costs of CO_2 emission rights. The basic effect of the cement industry's activities, which directly impact the recipient of the products, is the constant reduction in the offer of high-clinker CEM I cements that are being increasingly replaced by „low-emission" cements with a high content of non-clinker main components. These solutions, apart from the obvious ecological effect, involve new challenges related to ensuring the expected properties of concrete in terms of strength, but also durability and technology [1].

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From the point of view of the concrete manufacturer, who must ensure the functional properties defined by the customer (and imposed by the structure designer), the expansion of the market offer of various types of cement does not mean that it is possible to use every available cement in every intended application.This applies in particular to the resistance of concrete to the expected environmental conditions, i.e. exposure classes specified in the PN-EN 206 [2] and PN-B-06265 [3] standards. Restrictions in this respect are included in chapter 5.1.1 of the PN-EN 206 standard, which allows only the use of „constituents with established suitability for the particular intended use of the concrete". Although the general suitability of cement is recognized in relation to the PN-EN 197-1 [4], PN-EN 14216 [5] and PN-EN 197-5 [6] standards, it is clearly stated that „where general suitability is established for a constituent, this does not indicate suitability in every intended use of the concrete and for every concrete composition". Therefore, in order to correctly select the right cement for a specific application from cements with established general suitability, the PN-EN 206 standard in chapter 5.2.2 recommends to take into account:

● implementation of concrete works;
● purpose of concrete;
● curing conditions (e.g. heat treatment);
● environmental conditions to which the structure will be exposed (exposure classes XC, XD, XS, XF, XA);
● potential reactivity of the aggregate with alkalis contained in the components.

Due to the need to ensure the durability of the structure expected in the design, the national supplement to PN-B-06265:2022-08 [3] specifies in Annex F (in tables F2, F3 and F4) the areas of application of cements in particular exposure classes.

■ table F2 contains cements conforming to the PN-EN 197-1 [4] or PN-B-19707 [7] or PN-EN 197-5 [6];
■ table F3 contains CEM II-A,B,C-M cements conforming to the PN-EN 197-1 [4] or PN-B-19707 [7] or PN-EN 197-5 [6];
■ table F4 contains cements conforming to the PN-EN 14216 [5].

For cements included in these tables (already available or potentially available on the market), the acceptable scope of their use in a given exposure class is marked with the letter „X", while the requirement to confirm the suitability of this type of cement in a given exposure class is marked with the letter „O". The general criterion for such a division of cements is the result of long-term experience of their use in individual exposure classes. CEM I cement is undoubtedly dedicated to all types of environmental conditions, but the greater the content of main components other than clinker and/or the greater the number of their combinations, the greater the limitations. It is worth paying attention to the nature of these restrictions. In the previous version of the national supplement (PN-B-06265:2018-10 [8]), the letter „O" in the tables of Annex F meant „not applicable", while the current standard [3] „requires confirmation of suitability". Resigning from the categorical exclusion of the use of certain cements in specific exposure classes basically translates into the possibility of using any cement in any environmental conditions, provided, however, that its suitability in these specific applications is confirmed in accordance with standard procedures – for example by methods of equivalent concrete performance. The logic of this approach results from the fact that the marking of cement with the letter „O" in the appropriate tables does not result from the bad experiences with its use in a given environment, but rather from the lack of sufficient positive evidence confirming the required durability of concrete in specific conditions. In such a case, it is then necessary to individually confirm the requirements for a specific concrete recipe – and this is the task of the concrete manufacturer in the case of designed concrete, or of the recipe owner (e.g. contractor, investor, raw material supplier, etc.) in case of prescribed concrete.

With the expansion of the market portfolio of new types of cement, many publications presenting research results appear [e.g. 2], especially in the context of assessing their impact on durability. Such information, of course, expands general knowledge about new products, but does not replace the obligation for the concrete manufacturer to carry out proof of equivalent concrete properties in preliminary tests of concrete when indicated by standard restrictions.

The article presents an analysis of the possibility of providing such proof according to the proposal presented in the PN-EN 206 standard [2]. The authors used the results of a fairly extensive research program regarding new possibilities of using cements from the CEM II/C-M group, presented in the publication [10].

Method of assessment equivalent properties of concrete

A method to accept a given cement in its intended use (expected exposure class XC, XS, XD, XA, XF, XM), for which standard provisions (tables F2, F3 and F4 in Annex F of PN-B-06265 [3]) require confirmation of suitability, is to use the recommendations formulated in note No. 1 to the above-mentioned tables – „Cements that are not intended for use in given exposure classes (...) may be used after confirming the possibility of their application with methods related to assessment and comparison of performance (point 5.2.5.3 or 5.2.5.4 of PN-EN 206+A2:2021-08)". In these chapters, the PN-EN 206 standard [4], as well as its current national supplement PN-B-06265 [5], provide general principles of the concept of these two proposed methods, and to obtain more detailed information, they refer to the provisions of the CEN technical document TR 16639 [11].

The rules of the equivalent concrete performance concept (ECPC) in the case of the use of special additives and special cements, the origin and characteristics of which are precisely defined and documented, allow for changes in the requirements regarding:

● minimum cement content;
● maximum water/cement ratio.

It is then necessary to check whether the operational properties of the concrete, in particular those related to resistance to environmental conditions, are equivalent to the properties of the reference concrete, in accordance with the requirements for a given exposure class. The concept should only be applied when using cements compliant with PN-EN 197-1 or PN-EN 197-5, together with mineral additives.

On the other hand, the principles of the equivalent performance of combinations concept (EPCC) allow for a specific set of combinations of cement compliant with PN-EN 197-1 or PN-EN 197-5 and an additive (or additives) with established suitability, which may be fully included in the requirements specified for concrete regarding:

■ maximum water/cement ratio;
■ minimum cement content.

The methodology of this method includes three basic elements:

● identification of the type of cement, compliant with the European Standard and having the same or similar composition as the assumed combination;
● assessment of whether concretes containing such a combination have similar strength and durability, taking into

account a specific exposure class, as concretes containing an identified type of cement,

● introduction of production control that will ensure the definition and implementation of these requirements for concrete containing the appropriate combination.

As can be seen from the principles of both concepts established and described in the standard – equivalent concrete performance ECPC and equivalent performance of combinations EPCC, the mere confirmation of this „equivalence" does not consist in a verbal statement of the „similarity" of the assessed material set in a given concrete recipe in relation to the adopted pattern as meeting the requirements in terms of strength and durability. What is needed is the specific material evidence resulting from both theoretical analyzes and research results, for which the assessment of compliance with the criteria is confirmed by statistical analysis. The basis of obtaining such evidence is the technical document CEN/TR 16639 [11], which provides principles and methods of conduct, as well as examples resulting from current practice used in some European countries. This document also discusses quite extensively the principles of the concept of the k coefficient, along with the method of determining it in a specific material set of a given recipe, which may be useful in the analyzed case of a cement-additive combination, and this, in turn, is needed in the use of the concept of the equivalent performance of combinations (EPCC).

In the current situation of introducing an increasing number of different types of multi-component cements into industrial production, the presented principles of both ECPC and EPCC concepts will be frequently used tools, allowing to potentially claim the applicability of a given cement in the selected exposure class. Attention should be paid to two more aspects of using the concept of equivalent performance properties. In both methods, both indicators – the maximum water/cement ratio and the minimum cement content can be corrected, but only in relation to the limit values of the concrete composition specified in tables F.1 in the PN-EN 206 and PN-B-06265 standards. In turn, in both methods it is noted that they concern the use of cements in accordance with PN-EN 197-1 or PN-EN 197-5, and an additive (or additives) with established suitability (i.e. fly ash in accordance with PN-EN 450-1 [12], class 1 silica fume in accordance with PN-EN 13263-1 [13], ground granulated blast furnace slag in accordance with PN-EN 15167-1 [14], optionally fillers (e.g. limestone powder) in accordance with PN-EN 12620 [15]). Of course, this limitation cannot be treated generally, but only in relation to concretes compliant with PN-EN 206 + PN-B-06265. In the case of other cements or additives with a suitability determined on the basis of other documents (European Technical Assessments or National Technical Assessments), the current legal system should provide for the introduction of concrete of such composition as a single use of a construction product, and of course a National Declaration of Performance cannot be issued in relation to the standard set of PN-EN 206 + PN-B-06265.

Properties of compared cements

From the extensive testing program of three cements from the CEM II/C-M group related to the CEM II/B-V cement presented in publication [3], the results obtained forthe CEM II/C-M (W-LL) 32.5 R cement were selected for analyzes to demonstrate the application of the equivalent concrete performance concept. The basic properties of the compared cements are presented in Table 1, while the possible areas of their application in concrete depending on the environmental conditions (PN-B-06265 [3] – Table F1 for CEM II/B-V and Table F2 for CEM II/C-M (W-LL)) are listed in Table 2. The visible standard limitations prompt an attempt to answer the question whether it is possible to extend the possible applications of CEM II/C-M (W-LL) cement and whether the tests performed so far are sufficient for this purpose [2].

Table 1. Basic properties of the compared cements
Tabela 1. Podstawowe właściwości porównywanych cementów

Property	Type of cement	
	CEM II/C-M (W-LL) 32.5R	CEM II/B-V 32.5R (reference)
Initial setting time [min]	330	220
Final setting time [min]	390	280
Water demand [%]	29.2	31.0
Specific surface [cm^2/g]	5230	4330
Compressive strength:		
after 2 days [MPa]	14.1	16.7
after 28 days [MPa]	43.5	40.2
Standard clinker content (K) [%]	50 – 64	65 – 79

Table 2. Scopes of use of compared cements according to PN-B-06265 [3]
Tabela 2. Obszary zastosowania porównywanych cementów wg PN-B-06265 [3]

Type of cement	Exposure class					
	XC	XS	XD	XF	XA	XM
CEM II/B-V	XC1 – XC4	XS1 – XS3	XD1 – XD3	XF1 – XF2	XA1 – XA3	XM1 – XM3
CEM II/C-M (W-LL)	XC1 – XC2	○	○	○	○	○

The research program [10] was established in such a way that the recipes for a given exposure class XC2 or XC4 were composed for standard limit values maximum w/c ratio and minimum cement content (Table 3). Therefore, for a given exposure class, the compositions of both concretes (with CEM II/C-M cement and with CEM II/B-V cement) were identical. They could only differ slightly in the amount of added plasti-

Table 3. Recommended limit values for the composition of concrete according to PN-B-06265 [3]
Tabela 3. Zalecane wartości graniczne dotyczące składu betonów wg PN-B-06265 [3]

Exposure class	Minimum strength class of concrete	Maximum w/c ratio	Minimum cement content [kg/m^3]
XC2	C16/20	0.65	280
XC4	C25/30	0.55	300

cizer, which was to ensure the same consistency. With the assumed a research program, the goal was fully achieved – it was easy to answer the question whether the newly offered CEM II/C-M cement is „better" or „worse" compared to the already well-known CEM II/B-V cement, commonly used on the market.

Test results of the compressive strength of concretes, listed in Table 4 and presented in the charts in Figure 1, clearly indicate that with the concretes containing CEM II/C-M (W-LL) cement achieve higher strength values after 7, 28 and 56 days of curing, compared with the reference CEM II/B-V cement. The opposite effect was observed only in the case of 2-day strength, but this means that in the initial stage of hydration, the process occur at a lower rate. However, this fact is not disqualifying, as this property (two-day strength of concrete) is not subject to compliance assessment, but only affects the technological conditions of construction works (removal of formwork and supports, structure loading, maintenance time). The remaining characteristics describing the development of strength over time, especially in the case of 28-day and 56-day strength, as related to the assignment of concrete to the appropriate class, clearly indicate that CEM II/C-M (W-LL) cement performs better, compared to CEM II/B-V.

Table 4. Compressive strength of the tested concretes
Tabela 4. Wyniki wytrzymałości na ściskanie badanych betonów

Exposure class	Compressive strength class	Type of cement	Compressive strength [MPa]			
			f_{c2}	f_{c7}	f_{c28}	f_{c56}
XC2	C16/20	CEM II/C-M (W-LL) 32.5R	5.1	13.6	24.3	29.5
XC2	C16/20	CEM II/B-V 32.5R	6.6	11.4	19.5	26.6
XC4	C25/30	CEM II/C-M (W-LL) 32.5R	8.9	21.3	35.2	43.0
XC4	C25/30	CEM II/B-V 32.5R	9.3	17.9	27.3	33.7

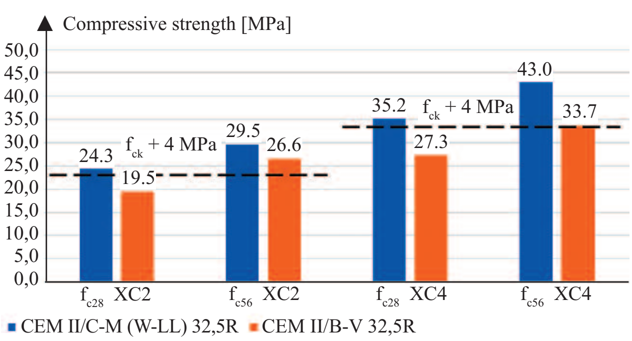


Fig. 1. Comparison compressive strength of concretes after 28 and 56 days of curing
Rys. 1. Porównanie wytrzymałości na ściskanie betonów po 28 i 56 dniach dojrzewania

However, the problem in the analysis of the results of the implemented research program remains in the fact that its basic assumption was that the reference concrete should obtain the C16/20 strength class in the XC2 exposure class and, respectively, C25/30 in the XC4 exposure class. Meanwhile, sufficient strength values were not obtained for the adopted concrete compositions (maximum w/c value and minimum amount of cement in the appropriate exposure classes) to qualify them to the required classes after 28 days of curing

Table 5. Assessment of the compressive strength of concrete after 28 and 56 days in relation to the minimum compressive strength classes appropriate for individual exposure classes according to PN-B-06265
Tabela 5. Ocena wytrzymałości na ściskanie betonów po 28 i 56 dniach w odniesieniu do minimalnych klas wytrzymałości na ściskanie właściwych dla poszczególnych klas ekspozycji wg PN-B-06265

Exposure class	Minimum class of compressive strength	Assessment of compressive strength opf concrete with:	
		CEM II/C-M (W-LL) 32.5 R	CEM II/B-V 32.5 R
after 28 days			
XC2	C16/20	YES	NO
XC4	C25/30	YES	NO
after 56 days			
XC2	C16/20	YES	YES
XC4	C 25/30	YES	NO

(Table 5). In the case of 56-day strength, the reference concrete meets the criteria of the required C16/20 class in the XC2 exposure class, but does not meet the C25/30 condition in the XC4 exposure class (Table 5). If the research program was extended to include the testing and assessment of 90-day compressive strength, knowing the trends in the development of strength of concretes with cements containing silica fly ash, concrete with the assumed composition would certainly achieve average strength, allowing it to meet the C25/30 class criterion required for the XC4 exposure class. However, as in this case there is no hard evidence in the form of a test result after 90 days of curing, theoretical analyzes cannot be considered as sufficient proof of meeting the criteria of the required concrete class. The situation is different in the case of concrete containing CEM II/C-M (W-LL) cement, which meets the strength class criteria after only 28 days of curing in both exposure classes.

When comparing the effectiveness of a new product in relation to the obtained strength, it can be stated that the scope of the research only confirms the trend, but is not a sufficient proof of equivalent properties. However, it is sufficient as a preliminary test for the analyzed concrete compositions. These recipes, for which strength parameters are obtained after more than 28 days, require redefining the deadline for obtaining the class (56 or 90 days) with full consequences – that is, full information for the recipient of the concrete, who must predict how to proceed with the maintenance of the concrete during curing and the possibility of dismantling the formwork and loading the constructed structure (information on the equivalent time for strength assessment should be included in the sales and technical documents). The second way to solve this problem is to develop and evaluate new concrete recipes with a lower w/c ratio and/or a larger content of cement than the limit values for given exposure classes. Then, it would be possible to provide proof of the equivalent performance of the concrete.

Figure 2 presents the results of the tests on the depth of water penetration under pressure for both concretes cured for 28 days, in relation to the predicted exposure classes. Similarly to the strength assessment, concretes containing CEM II/C-M (W-LL) showed a greater resistance to water ingress than

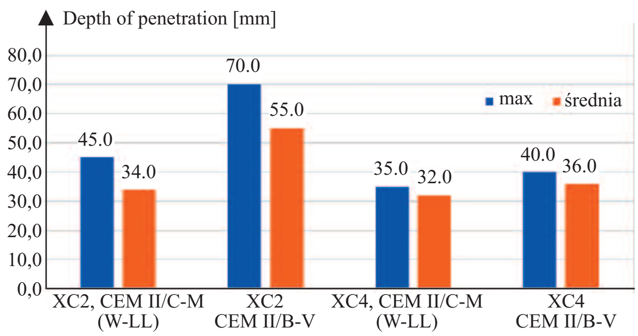
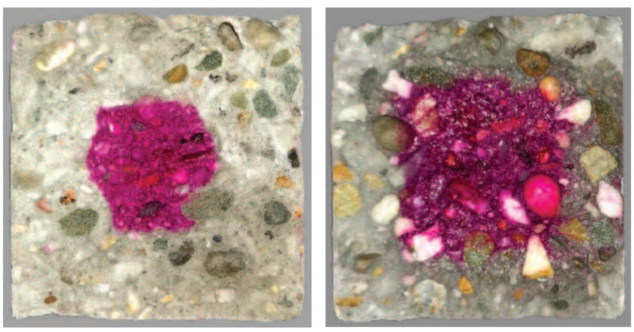


Fig. 2. Depth of water penetration into concretes under pressure
Rys. 2. Wyniki badania głębokości penetracji wody pod ciśnieniem

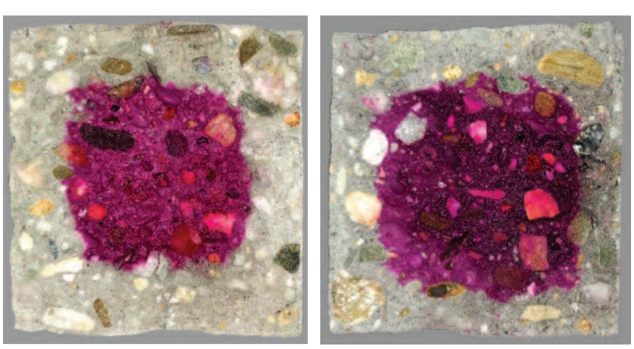
those containing CEM II/B-V cement. Based on the results, in general, they can be considered as „better", but they should not be assessed for equivalent concrete properties precisely because they do not meet the criteria of the minimum strength class of reference concrete after 28 days of curing in given exposure classes.

The third assessed property of the compared concretes was their resistance to carbonation, which is particularly important forthe XC exposure class group. Tests of concretes designed for application in the XC2 exposure class were basically intended to confirm the assumptions (Table 3) regarding the approval of the use of CEM II/C-M (W-LL) cement in this exposure class. However, tests of concretes intended for exposure class XC4 were to confirm the suitability of this cement in such application due to standard restrictions in this area (Table 3).



CEM II/B-V 32.5R CEM II/C-M (W-LL) 32.5R

Photo 1. View of concrete samples meeting the minimum composition criteria for exposure class XC2 after testing for resistance to carbonation
Fot. 1. Widok próbek betonów odpowiadających składem minimalnym kryteriom klasy ekspozycji XC2 po badaniu odporności na karbonatyzację



CEM II/B-V 32,5R CEM II/C-M (W-LL) 32,5R

Photo 2. View of concrete samples meeting the minimum composition criteria for exposure class XC4 after testing for resistance to carbonation
Fot. 2. Widok próbek betonów odpowiadających składem minimalnym kryteriom klasy ekspozycji XC4 po badaniu odporności na karbonatyzację

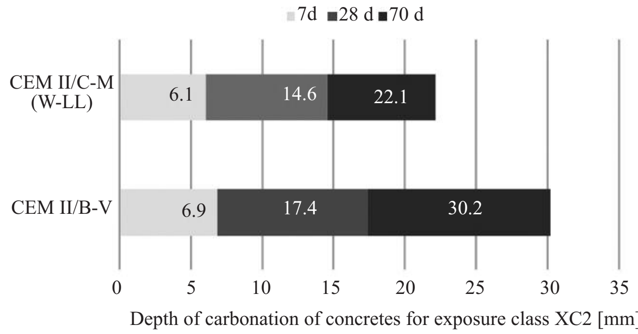
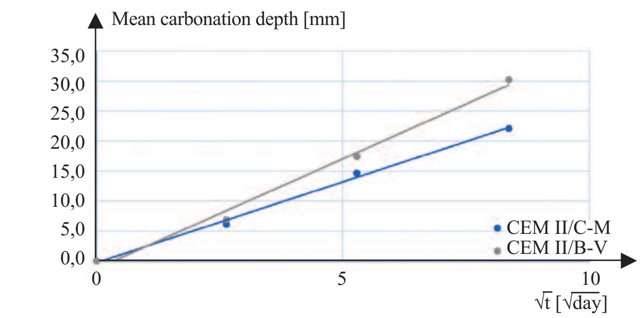


Fig. 3. Depth of carbonation of concretes made of CEM II/B-V or CEM II/C-M(W-LL) cement, meeting the composition criteria for exposure class XC2, after 7, 28 and 70 days of exposure to CO_2
Rys. 3. Głębokość karbonatyzacji betonów wykonanych na CEM II/B-V oraz CEM II/C-M(W-LL), spełniających kryteria składu w przypadku klasy ekspozycji XC2, po 7, 28 i 70 dniach oddziaływania CO_2



Composition for the selected exposure class – type of cement	Carbonation rate constant K_{AC} [mm • $d^{-0,5}$]
XC2 – CEM II/B-V 32.5R	3.66
XC2 – CEM II/C-M(W-LL) 32.5R	2.69

Fig. 4. Comparison of the speed of the carbonation process of concretes in exposure class XC2 and the carbonation rate constant K_{AC} [mm·$d^{-0,5}$] determined on the basis of the obtained results
Rys. 4. Porównanie szybkości przebiegu procesu karbonatyzacji betonów w klasie ekspozycji XC2 oraz stałej szybkości karbonatyzacji K_{AC} [mm·$d^{-0,5}$] wyznaczonej na podstawie uzyskanych wyników

The effect of the impact of CO_2 in the climatic chamber on concrete samples after 56 days of curing, according to the standard procedure PN-EN 12390-12 [16] and using phenolphthalein as an indicator, are presented in the Photos 1 and 2. In turn, in Figure 3 and 4, the results of tests on the depth of carbonation and the rate of the carbonation process for concrete with minimum composition criteria for exposure class XC2 are summarized. For concretes meeting the composition criteria for class XC4, the results are presented in Figure 5 and 6.

The comparison of the results allows us to generally determine a greater depth of carbonation and a faster carbonation process of the reference concrete, containing CEM II/B-V cement. There is also a clear tendency for both types of concrete, according to which the carbonation depth and the rate of the carbonation process decrease with an increase in the amount of cement used and a decrease in the w/c ratio. This translates into

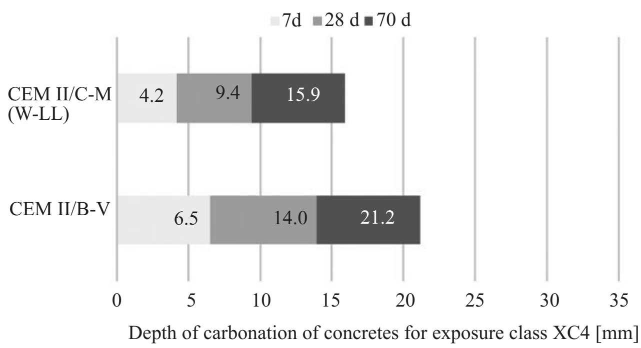
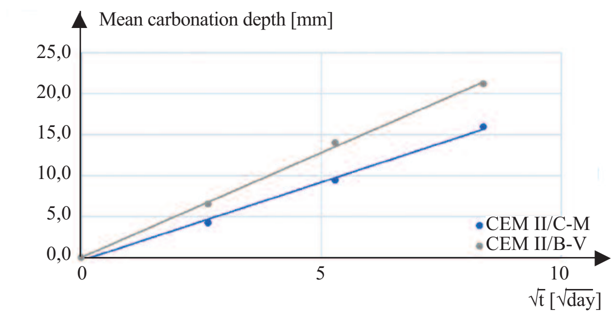


Fig. 5. Depth of carbonation of concretes made of CEM II/B-V or CEM II/C-M(W-LL) cement, meeting the composition criteria for exposure class XC4, after 7, 28 and 70 days of CO_2 exposure
Rys. 5. Zestawienie głębokości karbonatyzacji betonów wykonanych na CEM II/B-V oraz CEM II/C-M(W-LL), spełniających kryteria składu dla klasy ekspozycji XC4 po 7, 28 i 70 dniach oddziaływania CO_2



Composition for the selected exposure class – type of cement	Carbonation rate constant K_{AC} [mm • $d^{-0,5}$]
XC4 – CEM II/B-V 32.5R	2.56
XC4 – CEM II/C-M(W-LL) 32.5R	1.92

Fig. 6. Comparison of the speed of the carbonation process of concretes in exposure class XC4 and the carbonation rate constant K_{AC} [mm·$d^{-0,5}$] determined on the basis of the obtained results
Rys. 6. Porównanie szybkości przebiegu procesu karbonatyzacji betonów w klasie ekspozycji XC4 oraz stałej szybkości karbonatyzacji K_{AC} [mm·$d^{-0,5}$] wyznaczonej na podstawie uzyskanych wyników

a greater resistance to carbonation of the concretes with CEM II/C-M (W-LL) cement.

However, the answer to the question whether the presented analyzes of the carbonation resistance of concretes can be used to prove the equivalent performance properties of the assessed concretesis analogous to the previously presented assessment of strength or resistance to water penetration under pressure: they cannot, due to the failure to meet the requirements of the minimum strength class of the reference concrete after 28 days of curing.

Assumptions and necessary corrections for the assessment of equivalent performance of concretes

Despite the reservations expressed in the previous chapter, regarding the formal possibilities of applying the assessment of equivalent performance of concrete on the basis of the research program carried out, the procedure for such an analysis is presented below on the example of two tested properties, i.e. resistance to water penetration under pressure and resistance to carbonation. The argument should begin with the fact that the basic assumption of the research program, i.e. the minimum required compressive strength classes of reference concrete in the XC2 and XC4 exposure classes, determined after 28 days of curing, was not met. Therefore, two possible solutions can be considered. The first is to redesign the concrete in such a way as to achieve sufficient strength specific to the required exposure class by reducing the w/c ratio and/or increasing the amount of cement. Then, for these new recipes, the entire research program should berepeated. The second method is to change the definition of the strength class, referring not to 28-day compressive strength, but to 56-day or even 90-day strength (for the XC4 class). Therefore, the study should be extended to consider the 90-day compressive strength. The second solution is an „against the grain" deduction path – somewhat dangerous from a practical point of view. The recipient, unaware of the definition of the class after 90 days of curing, may not cooperate properly in the process of placing, maintaining and protecting the cured concrete. The concrete may therefore never achieve its designed properties.

Regardless of the above inaccuracies in the assumptions of the research program [3], the obtained test results were used to illustrate the procedure for assessing the selected equivalent functional properties, compiled in Tables 6 and 7. Using the guidelines of the technical report CEN/TR 16639 [11], the T_j coefficient was calculated in relation to the assessed aspect of durability „j".

$$T_j = \frac{\left[m_r - \frac{m_t}{1+0{,}01 d_j}\right]}{s/\sqrt{n}} \tag{1}$$

where

$$s = \sqrt{\left\{s_r^2 + \frac{s_t^2}{\left(1+0{,}01 d_j\right)^2}\right\}} \tag{2}$$

and:
m_r – the average test result for n samples of the reference concrete;
m_t – the average test result for n samples of the test concrete;
s_r – the standard deviation of the mean value for the reference concrete;
s_t – the standard deviation of the mean value for the test concrete;
n – the number of samples;
d_j – the limit value of the durability aspect j, as shown in Table 3 in CEN/TR 16639 [11]).

Table 6. List of parameters for an exemplary assessment of equivalent performance properties of concretes with CEM II/C-M(W-LL) 32.5R cement in relation to concretes with CEM II/B-V 32.5R cement (based on CEN/TR 16639) in terms of resistance to water penetration
Tabela 6. Zestawienie parametrów do przykładowej oceny równoważnych właściwości użytkowych betonów z cementem CEM II/C-M (W-LL) 32.5R w odniesieniu do betonów z cementem CEM II/B-V 32.5R (na podstawie CEN/TR 16639) w zakresie odporności na penetrację wody

Exposure class	Water penetration depth [mm]					
	test concrete (containing CEM II/C-M (W-LL) 32.5R cement)			reference concrete (containing CEM II/B-V 32.5R cement)		
XC2	45	29	27	70	45	50
	m_t = 33.7 s_t = 9.9			m_r = 55,0 s_r = 13.2		
	s = 15,2					
	T_j = 3.31 > $T_{j,lim(n=3)}$ = 1.533					
XC4	35	31	29	40	34	32
	m_t = 31.7 s_t = 3.1			m_r = 35.3 s_r = 4.2		
	s = 4.8					
	T_j = 3.94 > $T_{j,\ lim(n=3)}$ = 1.533					

Table 7. List of parameters for an exemplary assessment of equivalent performance properties of concretes with CEM II/C-M(W-LL) 32.5R cement in relation to concretes with CEM II/B-V 32.5R cement (based on CEN/TR 16639) in terms of resistance to carbonation depth

Tabela 7. Zestawienie parametrów do przykładowej oceny równoważnych właściwości użytkowych betonów z cementem CEM II/C-M (W-LL) 32.5R w odniesieniu do betonów z cementem CEM II/B-V 32.5R (na podstawie CEN/TR 16639) w zakresie głębokości karbonatyzacji

Exposure class	Carbonation depth[mm]							
	test concrete (containing CEM II/C-M (W-LL) 32.5R cement)				reference concrete (containing CEM II/B-V 32.5R cement)			
XC2	22.69	21.24	20.77	20.88	33.29	30.35	27.09	29.28
	23.64	22.50	22.06	22.79	30.70	31.00	28.65	31.42
	$m_t = 22.07$		$s_t = 1.02$		$m_r = 30.22$		$s_r = 1.88$	
	$s = 2.04$							
	$T_j = 18.39 > T_{j,lim(n=3)} = 1.345$							
XC4	16.78	17.00	13.70	15.90	23.01	19.91	19.67	20.50
	19.00	15.92	14.53	14.63	23.06	21.37	19.68	22.54
	$m_t = 15.93$		$s_t = 1.69$		$m_r = 21.22$		$s_r = 1.48$	
	$s = 1.97$							
	$T_j = 12.81 > T_{j, lim(n=3)} = 1.345$							

Using this tool, the obtained values of the water penetration depth (Table 6) and carbonation depth (Table 7) obtained for the tested concretes were compared to the appropriate reference concretes. The analysis, in addition to a direct comparison of the mean values for „n" samples (n = 3 for water penetration depth tests and n = 8 for carbonation depth tests), also takes into account the standard deviations of both data sets. In the calculation of the statistical coefficient T_j, the limit value d_j of the assessed aspect (j) was assumed (depth of water penetration (j) or depth of carbonation (j) as an aspect of durability), equal to +30%. Due to the lack of a criteria for penetration depth of pressurized water in the CEN/TR 16639 guidelines, the d_j value was adopted as analogous in the assessment of carbonation, chloride migration and frost resistance in the presence of de-icing agents. Finally, in the compared pairs of concretes developed for exposure classes XC2 and XC4, the statistical coefficient T_j for the water penetration depth is greater than the established limit value $T_{j,lim}$ for the set of „n" results (Table 8). This means that in terms of these aspects of durability, the evaluated formulations with CEM II/C-M (W-LL) cement can be considered equivalent to those with CEM II/B-V cement. For these analyzes to be considered valid, it should be noted once again that the criteria must be met for all concrete properties declared by the manufacturer, starting with the strength class.

Table 8. Limit values $T_{j,lim}$ according to CEN/TR 16639

Tabela 8. Wartości graniczne $T_{j,lim}$ wg CEN/TR 16639

Number of test results (n)	Limit value $T_{j,lim}$
3	1.533
4	1.440
5	1.397
6	1.372
7	1.356
8	1.345
9	1.337
10	1.330
11	1.325
12	1.321

Summary

The article presents an exemplary proof of equivalent performance of the assessed concrete, prepared with the use ofa new market product – CEM II/C-M (W-LL) cement, showing how the statistical tools proposed in the CEN/TR 16639 technical report [11] can be applied based on a case study. Selected test results obtained from a broader research program, the aim of which was the comparative analysis of several new cements, related to the reference concrete with CEM II/B-V cement, were used in the analyses. While the comparison of the same properties of concretes characterized by the same composition, but containing different cements, quite simply indicated that the use of CEM II/C-M (W-LL) cement gives a beneficial effect in terms of each tested feature (compressive strength, resistance topenetration of water under pressure, resistance to carbonation), the statistical credibility of this thesis requires clear and specific grounds for the analyses. First of all, the standard against which the equivalence of properties is determined must demonstrate compliance with all of the standard requirements set out forthe analyzed exposure class. Only then can the evaluation tool presented in the CEN/TR 16639 technical report be used. In the event of even a partial non-compliance, which is the case in the example presented in the article, the results of such tests are an important contribution to general knowledge, but cannot constitute conclusive proof of the equivalent performance of the new solution, compared to the reference evaluated in a prior use.

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