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Influence of low-clinker cements on the durability of reinforced concrete elements

Znaczenie cementów niskoklinkierowych w kształtowaniu trwałości elementów żelbetowych

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Abstract. This article analyses the suitability of low-clinker cements CEM IV/B (V) 42.5N LH/NA and CEM V/A (S-V) 42.5N LH/HSR/NA for concrete mixes resistant to corrosion caused by carbonation and chlorides other than from sea water (exposure classes XC4, XD1), as per EN 206. It presents the experimental results of the tests carried out in accordance with the current standards, including their analysis and the final conclusions. The performance of concretes containing low-clinker cements was found equivalent to the performance of the concretes containing the CEM II/B-V 42.5R HSR cement.

Keywords: concrete; durability; compressive strength; carbonation; migration of chloride ions; reinforced concrete structure.

Streszczenie. Artykuł zawiera analizę możliwości stosowania cementów niskoklinkierowych CEM IV/B (V) 42,5N LH/NA oraz CEM V/A (S-V) 42,5N LH/HSR/NA w betonach odpornych na korozję spowodowaną karbonatyzacją i chlorkami niepochodzącymi z wody morskiej (klasa ekspozycji XC4, XD1), wg PN-EN 206. Przedstawiono w nim wyniki badań przeprowadzonych zgodnie z aktualnymi normami, ich analizę oraz wnioski, które potwierdzają równoważne właściwości betonów z cementami niskoklinkierowymi z właściwościami betonów z cementem CEM II/B-V 42,5R HSR.

Słowa kluczowe: beton; trwałość; wytrzymałość na ściskanie; karbonatyzacja; migracja jonów chlorkowych; konstrukcja żelbetowa.

The selection of structural materials is based primarily on the capability of the structure to achieve the specified strength and durability within the required time frame. The requirements as to the properties and ingredients of concrete, one of the most popular construction materials, are specified most fundamentally in two standards used in Poland: EN 206+A2:2021-08 and PN-B-06265:2018-10. These requirements must be satisfied by any ready-mixed concrete manufacturer ever since concrete became a construction material. The provisions of these standards limit the application of certain low-clinker cements in specific exposure classes. That said, low-clinker cements and mineral admixtures are still becoming the materials of choice in the area of hydraulic binders in times when we strive to reduce CO_2 emissions and, more importantly, get the value of the clinker/cement ratio down to 0.60 by the year 2050 [1].

The influence of low-clinker binders on the durability of concrete structures and prospects for development of this material were the subject of various recently conducted research projects and comprehensive studies carried out in Poland [1-3] and in other countries [4-6]. The main objective was to evaluate the properties of concretes containing low carbon cements and find solutions to keep or even improve the performance of the structures built with them. Fitting in with this trend, this article tries to asses the prospects for using CEM IV/B (V) 42.5N LH/NA and CEM V/A (S-V) 42.5N LH/HSR/NA cements in exposure classes XC4 and XD1.

The conclusions presented herein are drawn directly from the comparison of the experimental results obtained on the tested concretes and on the reference concrete and considering the statistical analysis carried out within the framework of the equivalent concrete performance concept [7]. A combination of the above-mentioned elements of such assessment allowed a highly accurate determination that the resistance to harmful external factors of the analysed concretes is comparable to that of the reference concrete. Considering that EN 206 [7] allows using of the cements based on the equivalent concrete performance concept we can prove their adequacy for the applications otherwise excluded by the Table F.2 [8] also with uncertainty of evaluation of direct results. This approach yields a range of benefits to the ready-mixed concrete manufacturers, including reduction of the carbon footprint (i.e. CO_2) and thus care for the natural environment and also standardisation of production in terms of the type of cement used in the process and lower production cost.

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Description of the test method and the analysed cements

The purpose of this research was to analyse the durability of the concretes made with the use of low-clinker cements CEM IV/B (V) 42.5N LH/NA and CEM V/A (S-V) 42.5N LH/HSR/NA, compare the obtained results with the properties of the reference concrete containing CEM II/B-V 42.5R HSR cement which, as per Table F.2 of PN-B-06265 [8] may be used for XC and XD exposure classes. The applied cements feature (as per EN 197-1:2012[9]) a reduced content of clinker: 45 – 64% in the case of CEM IV/B (V) and 40 – 64% in the case of CEM V/A, and also a greater content of cementitious materials, including siliceous fly ash (V) and/ or ground granulated blast furnace slag (S). The following properties were analysed in order to properly determine their durability relevant properties:

● **mechanical strengt**h determined with the compressive strength test as per PN-EN 12390-3:2019-7 [10];

● **resistance to carbonation induced corrosion** (XC) determined with the accelerated method as per PN-EN 12390-12:2020-06 [11];

● **resistance to corrosion induced by chlorides other than sea water** (XD) derived from the determined chloride migration coefficient as per PN-EN 12390-18 [12].

The results of the compressive strength test were used to evaluate the concrete with respect to the design strength class, using for this purpose the preliminary acceptance criteria as per the Appendix A to PN-EN 206 [7]. As regards the carbonation depth and the chloride migration coefficient a statistical analysis was carried out within the framework of the equivalent concrete performance concept to determine the influence of the reduce content of clinker and the increased content of the supplementary cementitious materials on the permeability of concrete.

Durability of concretes containing low-clinker cements

The durability of concrete incorporated into the structure may be considered representative of the capability of the structure to retain its performance properties throughout the design service life. Reinforced concrete structures are deemed to have lost durability when a risk of corrosion of the reinforcement has been identified, i.e. when concrete has lost its highly alkaline pH, which used to protect the reinforcement, due to the carbonation process progressing from the outer surfaces. A decrease in the pH value below 11.8 weakens the skin that protected the steel by passivation, thus highly increasing the risk of corrosion. This process is yet accelerated by ion chlorides, which, at higher concentrations, may quite often start the process before the level of pH 11.8 has been reached. To address this risk, the manufacturers of cement, chemical admixtures and the ready-mixed concrete itself are searching for solutions to increase the resistance of concrete to penetration by CO_2 and chloride ions. As a quite popular solution, the concrete mix is enriched with type II additions which lower its permeability.

In the research described in this article the mixes were specified for XC4/ XD1 exposure classes. Each of the mixes under analysis contained the same percentage of the respective fractions of aggregate, the same amount of cement and the same water/cement ratio in the respective exposure classes.

The test results are given in Table 1 below. The tested mixes fell in the assumed consistency ranges of class S3 and class S4 with the air void content below 3.5%.

Table 1. Properties of tested concrete mixtures
Tabela 1. Właściwości badanych mieszanek betonowych

Description	Reference mix	Tested mixes	
Cement type	CEM II/B-V 42,5 R HSR	CEM IV/B(V) 42,5 N LH/NA	CEM V/A(S-V) 42,5N LH/HSR/NA
Concrete designation – exposure classes	R2 – XC4, XD1	TD1 – XC4, XD1	TD2 – XC4, XD1
Consistency – slump in mm after 10 min	150	170	155
Air content [%]	2,0	1,8	2,4

Compressive strength results. Compressive strength was determined on the specimens cured for 28 and 56 days in water at the temperature of 20 ± 2°C. The results are shown in Table 2. The value of f_{ck} + 6 MPa was taken as the strength class acceptance criterion as in the initial testing (Appendix A to PN-EN 206 [7]). Accordingly, it was established that the reference concrete achieved the specified strength class after 28 days of curing while among the tested concretes, the specimens containing the CEM IV (TD1) and CEM V (TD2) cements satisfied the C30/37 requirements after 56 days of curing and this should be the time of evaluation and declaration of conformance.

Table 2. Compressive strength of the tested concretes
Tabela 2. Wyniki wytrzymałości na ściskanie analizowanych betonów

Description	Reference mix	Tested mixes	
Cement type	CEM II/B-V 42,5 R HSR	CEM IV/B(V) 42,5 N LH/NA	CEM V/A(S-V) 42,5N LH/HSR/NA
Concrete designation – exposure classes	R2 – XC4, XD1	TD1 – XC4, XD1	TD2 – XC4, XD1
The minimum strength class of concrete	C30/37	C30/37	C30/37
28-day compressive strength [MPa]	43,0	38,2	39,7
Average 56-day compressive strength [MPa]	52,5	45,2	48,7

Carbonation test results. The carbonation test was carried out after 56 days of curing the concrete in water at a temperature of 20 ± 2°C and 14 days of conditioning in air-dry environment as per the test method [11].The comparative analysis of the analysed concretes considered the average carbonation depth (d_k) after 70 days of testing in the environmental chamber at a temperature of 20 ± 2°C, 57 ± 3% RH and 3.0 ± 0.5% concentration of CO_2. Fig. 1 gives the carbonation test results for the analysed concretes.

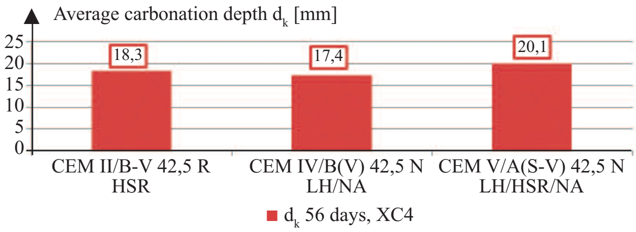

Fig. 1. The average carbonation depth d_k [mm] in the tested concretes, determined after 56 days of curing for the exposure class XC4

Rys. 1. Średnia głębokość karbonatyzacji d_k [mm] w badanych betonach, oznaczona po 56 dniach dojrzewania w przypadku klasy ekspozycji XC4

The carbonation depth of the concrete containing CEM IV/B(V) 42.5N LH/NA cement was lower than the carbonation depth obtained for the reference concrete and the concrete containing the CEM V/A(S-V) cement.While the carbonation front of the concretes containing CEM V/A(S-V) concretes was the most extensive, there was only 1.8 mm difference of carbonation depth in relation to the reference concrete. Therefore, it can be concluded that the use of the tested cements CEM IV/B(V) and CEM V/A(S-V) does not necessitate increasing the depth of concrete cover for the given exposure classes.

Chloride ion migration testing. The non-steady state migration of chloride ions was tested in the case of curing in water after 28 and 56 days for all the analysed compositions and after 90 days for the concrete containing CEM V/A cement. Three cylindrical specimens were prepared from each mix, adapted to the dimensions of d = 100 mm and h = 50 ± 2 mm. The test duration ranged from 24 to 96 h and a constant voltage of 30 V was applied. The comparative analysis of the durability of the analysed concretes took into account the average chloride migration coefficient depending on the average chloride ion penetration depth, average temperature of both test solutions during the test, applied voltage, specimen height and duration of the test.

The results of the experiments are presented in Fig. 2. In addition ageing factor (AF) was determined for the CEM V concrete, which indicates the magnitude of the effect of the curing length on the magnitude of chloride migration.

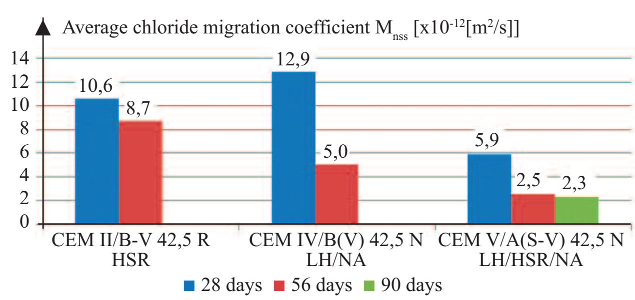

Fig. 2. Comparison of chloride migration coefficients of the analysed concretes at different ages (28, 56 and 90 days)

Rys. 2. Porównanie współczynników migracji jonów chlorkowych z analizowanych betonów w różnym czasie dojrzewania (28, 56 i 90 dni)

In the case of 28 day old specimens, the substitution of cement at a 1:1 ratio increased the chloride ion migration rate in the CEM IV concretes and decreased it considerably in CEM V concretes, as compared to the reference concrete. Conversely, after 56 days the value of the chloride migration coefficient tends to decrease in the tested concretes. This means a much better performance of the tested concretes, as compared to the CEM II concrete. In the case of CEM V concretes, extending the curing time to 90 days yet slowed down the inward migration of chlorides (Fig. 2).

The value of AF determined on the basis of chloride migration over time (Figure 3) at 0.85 (exponent of the power function) indicates a strong correlation between the permeability of concrete expressed by the susceptibility to chloride migration and the period of time of curing in water.

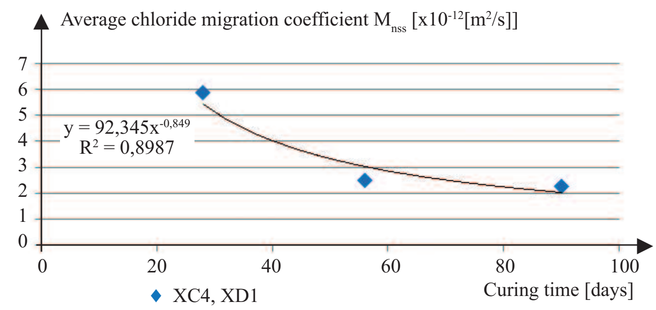

Fig. 3. Determination of the ageing factor (AF) for the CEM V/A (S-V) concrete

Rys. 3. Wyznaczenie wskaźnika ageing factor (AF) betonu z cementem CEM V/A (S-V)

Durability assessment – statistical analysis. For a reliable assessment of the influence of low-clinker cements on the durability of concrete a statistical analysis was carried out based on the provisions of CEN/TR 16639 [13]. This tool was used to compare the determined properties of the concretes containing tested cements with the properties of the reference concrete. The factors taken into consideration included, beside the average result for the *n* number of specimens, also a number of specimens (n), standard deviation for the obtained individual results and the limit values of T_j in relation to the assessed durability aspect (j) derived from CEN/TR 16639 [13].

The result is deemed to pass the comparative evaluation if the calculated value of T_j exceeds the limit values of T_j = 1.440 (n = 4) for the carbonation depth of T_j = 1.533 (n = 3) for the chloride migration coefficient. The outcome of the statistical analysis is presented in Tables 3 and 4.

Table 3. Statistical evaluation of the equivalent performance properties for carbonation depth determined on 56-day old concretes

Tabela 3. Ocena statystyczna równoważnych właściwości użytkowych w przypadku głębokości karbonatyzacji oznaczonej na betonach dojrzewających 56 dni

Reference concrete	CEM II/B-V 42,5R HSR	T_j	Condition	
Tested concretes	CEM IV/B(V) 42,5N LH/NA	4,757	T_j > 1,440	Pass
	CEM V/A(S-V) 42,5N LH/HSR/NA	3,136		Pass

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Table 4. Statistical evaluation of the equivalent performance properties for chloride migration determined on 28-day and 56-day old concretes
Tabela 4. Ocena statystyczna równoważnych właściwości użytkowych w przypadku migracji jonów chlorkowych oznaczonej na betonach dojrzewających 28 i 56 dni

Reference concrete	CEM II/B-V 42,5R HSR	T_j (28 days)	T_j (56 days)	Condition	
Tested concretes	CEM IV/B(V) 42,5N LH/NA	1,616	10,279	T_j > 1,533	Pass
	CEM V/A(S-V) 42,5N LH/HSR/NA	13,073	14,545		Pass

The statistical evaluation clearly shows that the durability related performance properties of the concretes containing CEM IV/B(V) and CEM V/A(S-V) can be considered equivalent to the properties of the reference concrete containing the CEM II/B-V cement.

Final conclusions

The above described results of the experimental research demonstrate that the concretes containing CEM IV and CEM V cements despite a reduced content of clinker can still reach the limit values of the durability criteria, showing properties comparable to the reference concrete.The statistical analysis carried out as part of this study confirmed the applicability of the equivalent concrete performance concept for the qualification of concrete specifications based on low-clinker cements. The analysis of the durability related parameters of concrete showed that:

■ The concretes containing pozzolanic cement CEM IV as a substitute for CEM II cement can achieve C30/37 strength class after 56 days of curing and showed the lowest carbonation among the tested concretes. As regards the chloride migration coefficient, even though the result exceed the level obtained for the reference concrete, the statistical analysis showed resistance to penetration by chlorides equivalent to the concrete containing the flyash Portland cement CEM II.

■ The concrete containing blended cement CEM V as a substitute for the flyash Portland Cement CEM II achieved the specified strength of C30/37 class after 56 days of curing and with a greater than the other concretes carbonation it showed the highest resistance to penetration by chloride ions. In the case of CEM V concrete, the statistical analysis showed that despite the carbonation depth greater by 1.8 mm this property is equivalent to the resistance to CO_2 penetration showed by the reference concrete.

■ The value of the ageing factor AF of the concrete containing blended cement CEM V derived from the chloride migration coefficient clearly indicates a strong correlation between the chloride ion migration rate and curing time. This is additionally confirmed by the decrease of the chloride migration coefficient M_{nss} with the increase in the time of curing the specimens in water.

■ With the same content of cement and the same w/c ration the resistance of concrete to carbonation and penetration by chloride ions will depend primarily not only on the percentage of calcium hydroxide with CO_2 capturing properties, the quantities and types and additives to concrete but also on the properties of the concrete mixture, including in particular the influence of the air void content and structure in hardened concreteon the transport of aggressive agents.

■ It has been established, based on the experimental data, that low-clinker cements can be used successfully in the concretes specified for exposure classes XC and XD. Now, the development efforts should focus on ensuring the development of strength at lower temperatures as in the standard conditions the tested concrete achieved the strength class C30/37 only after 56 days of curing.

■ Substitution of the flyash cement CEM II with the low--clinker cement described in this article at a 1:1 rate allows to decrease the clinker factor CF and thus the CO_2 emission by ca. 17% in the case of CEM IV and by ca. 24% in the case of CEM V.

■ When pozzolanic cement CEM IV/B(V) 42.5 N LH/NA is specified for exposure classes XC4 and XD1 particular attention should be paid during production to ensure the specified mixture composition as regards the quantity and quality of cement, w/c ratio and air void content.

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