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# Assessment of the protective potential of reinforcing steel in low carbon footprint concrete using electrical resistance corrosion monitoring

## Ocena właściwości ochronnych betonu o małym śladzie węglowym z zastosowaniem korozymetrii rezystancyjnej

*The paper presents the results of testing the protective properties of low carbon footprint concrete subjected to an accelerated carbonation process using electrical resistance corrosion monitoring. It was found that a significant reduction in the content of Portland clinker in the composition of low-carbon cement compared to Portland cement CEM I increases the progress of carbonation in concrete and, consequently, reduces its protective properties towards carbon steel. It was also found that the depth of carbonation and protective properties towards steel in low carbon footprint concrete is determined not only by the content of Portland clinker in the cement composition, but also by the activity of the main non-clinker components used.*

*Keywords: corrosion, carbonation, reinforcing steel, electrical resistance corrosion monitoring*

*W pracy przedstawiono wyniki badań właściwości ochronnych betonu o małym śladzie węglowym poddanego procesowi przyspieszonej karbonatyzacji z wykorzystaniem korozymetrii rezystancyjnej. Stwierdzono, że znaczne zmniejszenie zawartości klinkieru portlandzkiego w składzie cementu niskoemisyjnego w stosunku do cementu portlandzkiego CEM I zwiększa postęp karbonatyzacji w betonie i w konsekwencji zmniejsza jego właściwości ochronne stali węglowej. Stwierdzono także, że głębokość karbonatyzacji i właściwości ochrony stali w betonie o niskim śladzie węglowym uwarunkowane są nie tylko zawartością klinkieru portlandzkiego w składzie cementu, ale także aktywnością stosowanych nieklinkierowych składników głównych.*

*Słowa kluczowe: korozja, karbonatyzacja, stal zbrojeniowa, korozymetria rezystancyjna*

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## 1. Introduction

The reinforcing steel in concrete lies within a highly alkaline environment with a pH of 12.5 to 13.0. Under such conditions, a thin, 1 nm to 100 nm-thick passive layer consisting mainly of iron oxides $\gamma$-$Fe_2O_3$ and $Fe_3O_4$ [1] forms on the steel surface providing corrosion protection to the reinforcing steel [2]. Loss of passivation of the steel can occur due to neutralisation of the concrete cover caused by carbonation, which in the presence of moisture and oxygen results in the initiation of electrochemical corrosion processes. It is considered that corrosion processes of steel may start at a pH of as low as 11.8 when there is free access to oxygen, while in "normal" operating conditions of the structure it is assumed that these processes may already occur at a pH of 11. As emphasised in work [3], the above pH levels should be taken as indicative, since the initiation of corrosion and its course depend on many factors, mainly on concrete moisture and its temperature. For this reason, the pH of concrete alone cannot be a reference point for assessing its protective properties vis-à-vis the reinforcement, and it is necessary to measure the corrosion rate of the steel.

The reduction of $CO_2$ emissions from the Portland clinker production process makes it necessary to make greater use of cements with reduced Portland clinker content in the composition of concrete, which in domestic conditions is mainly replaced by limestone LL, fly ash V and granulated blast-furnace slag S [3, 4]. This measure results in a reduction in the alkalinity of the concrete. This is widely perceived as a durability issue, as it is recognised that reduced alkalinity can lead to accelerated carbonation and corrosion of reinforcing steel.

In the work presented in this paper, the protective properties of concrete on reinforcing steel have been determined using electrical resistance corrosion monitoring. Tests were conducted on reference concrete with Portland cement CEM I and low carbon footprint concretes formulated with low-alkalinity cements with a significantly reduced Portland clinker content (47 by weight of cement).

## 2. Object of the study

Concrete samples made with cements of the compositions given in Table 1 were prepared for the study. Three low-carbon cements containing 47% cement clinker were used, and Portland cement CEM I containing 95% Portland clinker was used as the reference cement. The composition of the concretes corresponded to the requirements of EN 206 [5] for exposure class XC4 (300 kg cement/$m^3$ of concrete mixture, $w/c$ = 0.55). Sand 0–2.0 mm and gravel aggregate of grain fractions 2–8 mm and 8–16 mm were also used.

## 3. Experimental

Electrical resistance corrosion monitoring was used to assess the protective properties of concretes made from low-carbon cements towards the embedded reinforcing steel [6]. This method makes it possible to monitor the corrosion loss of the metal under operat-

**Table 1. Composition of tested cements**
**Tabela 1. Skład badanych cementów**

| Cement type | Component content [% by weight] | | | |
| --- | --- | --- | --- | --- |
| | clinker component CEM I | ground granulated blast furnace slag | silica fly ash | limestone |
| | K (K + Rᵃ) | S | V | LL |
| CEM I 42.5 R | 95 (100) | – | – | – |
| CEM III/A 42.5N-LH/HS/NA | 47 (50) | 50 | – | – |
| CEM (50K-30S-20LL) | 47 (50) | 30 | – | 20 |
| CEM (50K-50V) | 47 (50) | – | 50 | – |

ᵃ Portland clinker with setting time regulator.

ing conditions. The principle of operation of resistance sensors is related to the change in resistance of the measuring elements $\Delta R$ as a result of the decrease in their cross-sectional area $\Delta S$ due to corrosion, according to the equation:

$$\Delta R = \frac{\rho L}{\Delta S}, \qquad (1)$$

where:

$\Delta R$ – measured electrical resistance of the sensor [$\Omega$],

$\rho$ – resistivity of steel equal to $14.3 \times 10^{-8}$ [Wm],

$L$ – length of the measuring element (fixed) [m],

$\Delta S$ – cross-sectional area – area dependent on corrosion progress [$m^2$].

As the exposure time progresses, the resistance of the sample increases, according to equation (1), due to the loss of cross-section $\Delta S$. Measurements can be taken at arbitrary time intervals, allowing the corrosion progress to be monitored continously and the corrosion progress rate to be determined. Corrosion sensors of type ER-10/0.5-FC were used in the tests. The sensors were fixed in specially prepared 130 × 180 × 170 mm moulds. The moulds contained a steel rod to which the corrosion sensors were glued in such a way that, in the moulded concrete sample, the corroding element of the sensor was located 30 mm from the edge of the sample. This was done to reproduce the thickness of the 30 mm-thick reinforcement cover provided in EN 1992-1-1 [7, 8] for construction class S4 and environmental exposure class XC4. The moulds thus prepared were filled with the concrete mixture in two layers and compacted using a vibrating table. The day after concreting, the specimens were removed from the moulds and then immersed in water at 20℃ ±2℃. On the 7th day after concreting, the specimens were removed from the water and left in air-dry conditions in the laboratory (temperature: 20℃ ±2℃, humidity: 40–60%), where they matured for an assumed time of 90 days. After this time, the first corrosion measurement was taken (initial measurement). Corrosion measurements were carried out using a portable ATLAS 1001 COR corrosion meter, shown in Fig. 1a. A view of the test piece with the corrosion sensor is shown in Fig. 1b.

Since natural carbonation of concrete occurs very slowly and over a long period of time (several or several years), it was therefore decided to accelerate the process. For this purpose, the
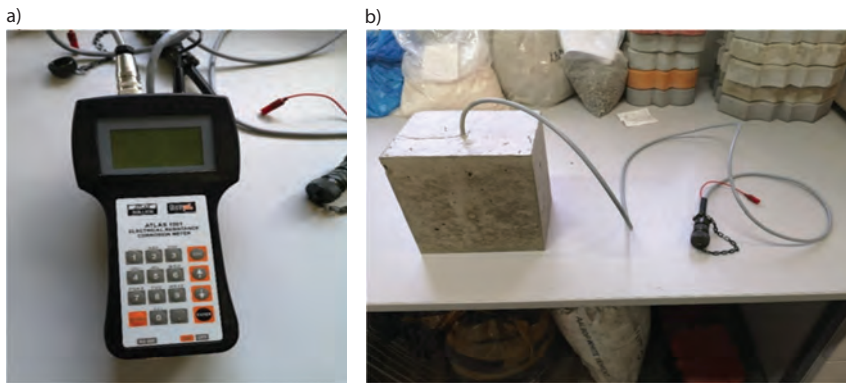
a) b)



Fig. 1. Corrosion measurement set-up: a) ATLAS 1001 COR corrosion resistance meter, b) test piece with corrosion sensor

Rys. 1. Zestaw do pomiarów korozymetrycznych: a) korozymetr rezystancyjny ATLAS 1001 COR, b) element próbny z czujnikiem korozymetrycznym
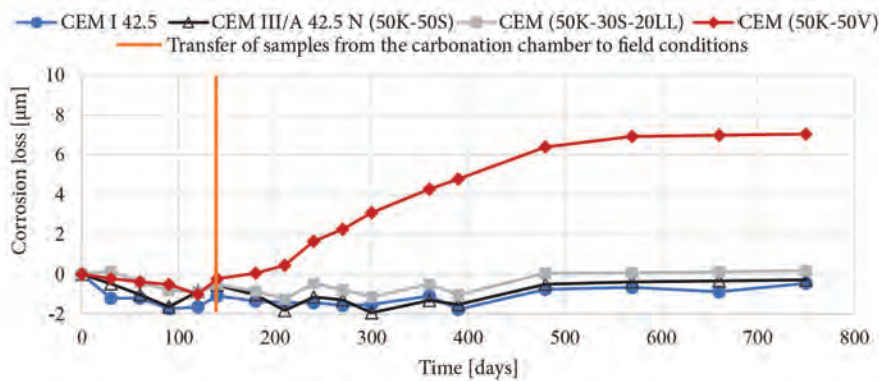


Fig. 2. Mean corrosion measurement results of XC4 concretes ($c = 300$ kg, $w/c = 0.55$) made with CEM I 42.5, CEM III/A 42.5 N (50K-50S), CEM (50K-30S-20LL) and CEM (50K-50V) cements

Rys. 2. Średnie wyniki pomiarów korozymetrycznych betonów XC4 ($c = 300$ kg, $w/c = 0,55$) wykonanych z cementów: CEM I 42,5, CEM III/A 42,5 N (50K-50S), CEM (50K-30S-20LL) i CEM (50K-50V)

concrete samples were placed in a carbonation chamber ($CO_2$ concentration: 4.0% ±0.5%, temperature: 20°C ±2°C, relative humidity: 55% ±5%). The exposure time in the chamber was 140 days, i.e. twice the time from the procedure in EN 12390-12 [9]. After the end of exposure in the carbonation chamber, the concrete samples were placed in field conditions (unprotected samples exposed to the weather). For the first year, corrosion measurements were taken monthly, while in the second year of exposure, they were taken quarterly. After 2 years of exposure, one sample from each type of concrete was broken to visually assess the corrosion sensors and to measure the extent of carbonation. The extent of carbonation was determined in a simplified manner using the Rainbow Test indicator. The measurement is similar to the measurement of carbonation depth by the phenolphthalein method according to EN 12390-12 [9]. The Rainbow Test preparation is a composition of marker fluids allowing identification of selected pH reactions, i.e. from 5 to 13 [10]. In the present analysis, only pH ≤7, pH = 9 and pH ≥11 were considered, while the extent of carbonation was assumed to be the staining of the concrete between green (pH = 9) and purple (pH = 11).

## 4. Corrosion measurement results

Fig. 2 shows the average results (from 3 samples) of corrosion measurements of the tested concretes over a period of 2 years, where the first (reference) result comes from measurements immediately before the samples were placed in the carbonation chamber and was taken as 0 µm. The vertical orange line in the figures indicates the moment when the concrete samples left the carbonation chamber (140 days) and were transferred to field conditions with full environmental exposure. The negative results of the corrosion loss measurements can be associated with the specificity of the methodology used and the presence of an isolated compensating system in the sensor. It can be concluded that an increase in the sensor cross-section (negative values) indicates the absence of corrosion of the steel.

Of the concretes tested, steel corrosion was only observed in the case of the low carbon footprint concrete made with CEM(50V-50K) ash cement containing 50% fly ash V (Fig. 2). The other concretes were characterised by a lack of corrosion of the reinforcing steel over the 2-year period studied.

In order to verify the corrosion loss measurement results obtained, one of the samples from each type of concrete was split and the corrosion sensors were extracted. A visual assessment clearly confirmed the results recorded by the corrosion method. The steel of the corrosion sensor placed in the low carbon footprint concrete made of CEM ash cement (50K-50V) was covered with corrosion products (rust) practically over its entire surface (Fig. 3). The sensors removed from the other concretes remained intact without any signs of corrosion (Fig. 3).
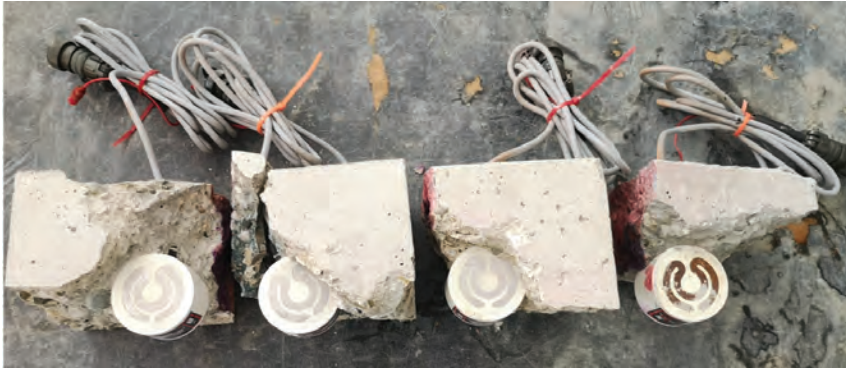
Fig. 3. Corrosion sensors extracted from low carbon footprint cement concrete (from left): CEM I 42.5 R, CEM III/A 42.5 N (50K-50S), CEM (50K-30S-20LL), CEM (50K-50V)

Rys. 3. Czujniki korozymetryczne wyciągnięte z betonu o niskim śladzie węglowym wykonane z cementu (od lewej): CEM I 42,5 R, CEM III/A 42,5 N (50K-50S), CEM (50K-30S-20LL), CEM (50K-50V)
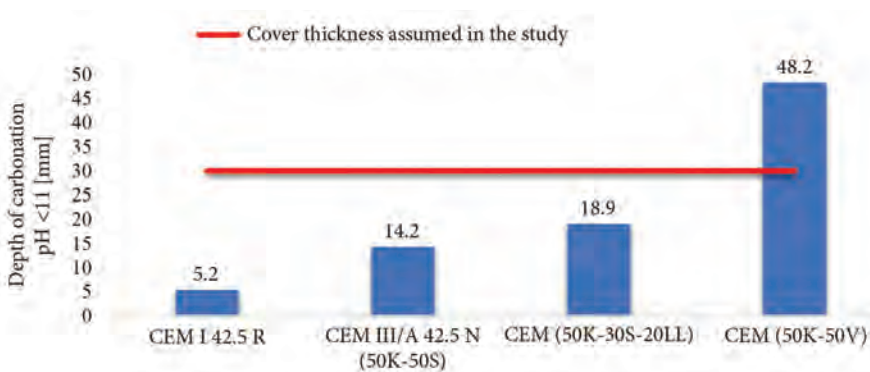


Fig. 4. Extent of the carbonation front of the tested concretes causing depassivation of the reinforcing steel (pH <11)

Rys. 4. Zasięg frontu karbonatyzacji badanych betonów powodujący depasywację stali zbrojeniowej (pH <11)

## 5. Depth of carbonation and corrosion of steel

Table 2 shows the results of a simplified distribution of pH in the concrete samples tested. The smallest extent of carbonation (5.2 mm) was characterised by concrete made from Portland cement CEM I 42.5 R (reference cement). For concretes with a small carbon footprint (47% Portland clinker in the composition), the carbonation progression was 14.2 mm in the blast cement CEM III/A 42.5 N and 18.9 mm when using the multicomponent cement CEM (50K-30S-20LL). The carbonation front of the cement matrix, lowering the pH below 11, exceeded a depth of 30 mm only in the

case of concrete with a small carbon footprint made with CEM ash cement (50K-50V; Fig. 4). The results obtained from the measurement of the depth of concrete carbonation coincide with the results obtained from the corrosion measurements – where concrete neutralisation occurred to a depth greater than 30 mm, steel corrosion and associated corrosion cavities (rust formation) occurred.

The results confirm the important role of Portland clinker in shaping the carbonation resistance of low carbon footprint concretes (made from cements with low Portland clinker content). The concretes, made from the low carbon footprint cements CEM III/A 42.5 N (50K-50S) and CEM (50K-30S-20LL), were able to provide an adequate level of corrosion protection for the reinforcing steel, despite a 48% lower proportion of Portland clinker, compared to Portland cement CEM I 42.5 R. The results obtained confirm the conclusions presented in works [11, 12], namely that when selecting the main non-clinker components for low-carbon cement, emphasis must be placed on their activity and influence on the shaping of concrete properties, and on improving concrete tightness (strength) by lowering the water/cement ratio in concrete.

## 6. Conclusion

The results presented in the paper showed that low carbon footprint concrete made from low-carbon cements containing 47% Portland clinker showed lower resistance to carbon dioxide-induced

**Table 2. Distribution of pH in concrete for exposure class XC4 ($c$ = 300 kg, $w/c$ = 0.55) determined with the Rainbow Test**
**Tabela 2. Rozkład odczynu pH w betonach w klasie ekspozycji XC4 ($c$ = 300 kg, $w/c$ = 0,55) oznaczony preparatem Rainbow Test**

| Cement | Share of Portland clinker [% by weight of cement] | Depth of carbonation progression – pH distribution [mm] | | |
|---|---|---|---|---|
| | | pH ≤7 | pH = 9 | pH ≥11 |
| CEM I 42.5 R | 95 | 0.0–4.1 | 4.1–5.0 | >5.2 |
| CEM III/A 42.5 N (50K-50S) | 47 | 0.0–10.4 | 10.4–13.8 | >14.2 |
| CEM (50K-30S-20LL) | | 0.0–17.3 | 17.3–18.2 | >18.9 |
| CEM (50K-50V) | | 0.0–44.7 | 44.7–47.2 | >48.2 |

corrosion (carbonation resistance) than reference concrete made from CEM I 42.5 R Portland cement.

The depth of concrete carbonation of low carbon footprint concretes depends on the composition of the low carbon cements. The results show that in concretes containing blast furnace cement CEM III/A (50% ground granulated blast furnace slag) and multicomponent cement with CEM (30S-20LL), the extent of carbonation was about three times greater than in the reference concrete (Fig. 4). In the composition of the CEM II (S-LL) multicomponent cement, the synergistic effect resulting from the use of LL limestone – an ingredient with a much higher fineness compared to Portland clinker and granulated blast-furnace slag – is also important, thereby resulting in a higher tightness of the cement matrices [11, 12]. The tightness of concrete can also be significantly increased by lowering the water/cement ratio (*w/c*) in concrete [11, 12]. However, in concrete with CEM cement (50K-50V), the range of carbonation was almost ten times greater than in the reference concrete and this concrete has very limited protective properties towards reinforcing steel. This is due to the lower activity of fly ash relative to that of ground granulated blast furnace slag.

*CRediT authorship contribution statement*

**Michał Tałaj:** Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing.

**Maciej Batog:** Formal analysis, Investigation, Project administration, Resources, Validation, Writing – original draft, Writing – review & editing.

**Tomasz Jaśniok:** Conceptualization, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

**Zbigniew Giergiczny:** Conceptualization, Formal analysis, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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