The effect of cement and aggregate type and w/c ratio on the bound water content and neutron shielding efficiency of concretes

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**Highlights**

- Bound water content in concrete varies depending on cement and aggregate type.
- Bound water content in concrete is independent from w/c ratio.
- No relation between hydrogen input from bound water and neutron shielding was found.
- Neutron shielding efficiency can be modified by cement and aggregate change.

**Abstract**

Modeling studies of the effect of cement type, aggregate type and w/c ratio on the bound water amount and shielding properties against neutron ionising radiation of concretes are presented. The change of cement or aggregate type had an significant influence on the bound water amount and neutron linear attenuation coefficient (NLAC) calculated in Monte Carlo N-Particle Transport Code. The multiple regression analysis for the dependent variable NLAC suggested no correlation between w/c ratio and examined parameter. Data gained in ionic chamber implies an influence of cement type on the concrete shielding properties.

**1. Introduction**

Shielding concrete technology is primarily used in facilities where protection must be ensured for individuals and devices against the ionising neutron and gamma radiation produced by radioactive materials, or as a result of particle collisions in accelerators. In the case of gamma radiation, shielding with appropriate material density [1,2] is considered a sufficient protective barrier. Due to the different speeds at which neutrons move, neutron radiation interacts with atomic nuclei either through dispersion or absorption [3].

In order to analyse and interpret neutron flows, the Boltzmann neutron transport equation must be solved. However, solving this equation requires adopting certain simplifications and using numerical techniques [4]. The MERC SF-N computer program was recently developed for calculating removal cross-sections for fast neutrons transmitted through homogeneous structures [5]. In 2011, El-Khayatt reported another program (NXcom), that can calculate both fast neutrons effective removal cross-sections and gamma rays attenuation coefficients [6]. In Poland, models based on the Monte Carlo N-Particle Transport Code – MCNP – are most frequently used to assess the shielding properties of composite materials [7]. The use of MCNP allows, among other things, the determination of the linear attenuation coefficient both for gamma and neutrons for an element of a specified thickness. In order to reduce the energy of a neutron, it is recommended to use materials whose chemical composition contains molecules with the lowest possible atomic mass, such as hydrogen. Average number of collisions required to reduce a neutron’s energy from 2 MeV to 0.025 eV by elastic scattering with hydrogen is 27. For the same energy reduction coal needs at least 119 collisions [8].

In cementitious composites, hydrogen occurs in the form of free water (water vapour, physico-chemically and physico-mechanically bound water) as well as water that is chemically bound (constitutive water), and it is also embedded in the chemical...
structure of some aggregates such as limonite (2FeO3·3H2O) or goethite (FeO(OH)) [9,10]. The content of both types of water in concrete can be determined by thermogravimetric testing. Free water is lost at temperatures of up to 105 °C [11]. The decomposition temperature of bound water depends on the cement phase: ettringite (80–130 °C) [12,13], gypsum (80–400 °C) [14,15], C-S-H (40–600 °C) [16,17], hydrogarnet (250–550 °C) [11,18], or calcium hydroxide (410–550 °C) [12,19]. A measurement uncertainty associated with the decomposition of calcium carbonate at temperatures ranging from 520 to 950 °C [16,20] appears when the content of constitutive water is determined using the gravimetric method. Calcium carbonate is present in the phase composition of the main cement component, i.e. limestone. Additionally, CaCO3 is formed through the long-term carbonation process [21].

Several works have been performed to obtain linear attenuation coefficients (LAC) theoretically and experimentally for different aggregates and concretes [22,23]. However, complex study on the shielding properties of concretes with different cement types, w/c ratio and aggregates is not so often observed. This is why the aim of the paper was to evaluate the influence of cement type, aggregate type and w/c ratio on bound water content and shielding properties against neutron radiation (expressed in neutron linear attenuation coefficients (NLAC) and the ionising current attenuation) of magnetite and granite concrete. The most relevant parameters for concrete shielding properties were determined by multiple regression analysis.

2. Experimental testing programme

The study is performed on concretes prepared with different cement type, aggregate type and w/c ratio. Cements and used aggregates are characterized in next section. Research methodology is presented in chapter 2.3.

2.1. Materials and specimens

Three types of cement (CEM II, CEM III and CEM IV) were used in the tested concrete mixes. Their compositions and properties are presented in Table 1. Each of the cements belonged to a different strength class (from 32.5 to 52.5). The types of cement were selected in order to determine the possible effect of the three main ingredients of cement (limestone, blast furnace slag and silica fly ash) on the bound water content and concrete shielding properties. The results of chemical composition measured by XRF and specific surface area (SSA) was delivered by the manufacturer. Compressive strength was measured according to EN 197–1.

In accordance with DIN 25143–1 and 25143–2, heavy concrete with shielding properties was obtained using magnetite with a grain size of 0/8 mm and 0/16 mm and with a density of approximately 4.8 kg/dm3 as coarse aggregate. Reference specimens were made using a granite aggregate with 4/8 mm and 8/16 mm fractions and a density of 2.64 kg/dm3. Three different w/c ratios from 0.40 to 0.50 were also selected in order to determine the relationship between the w/c ratio and the free and bound water content. The compositions of concrete mixes presented in Table 2 were designed according to the EN 12390–2 and EN 206 standards, and those compositions met the relevant requirements as to the amount of cement used, the w/c ratio and aggregate properties.

Two types of test specimens were made: 100 mm cubes and 50 cm × 50 cm × 5 cm slabs. The specimens were stored for 24 h at 24 ± 2 °C, covered with moist material and foil. After demoulding, the specimens were stored in a climatic chamber at a temperature of 20 ± 2 °C and at a relative humidity above 95% for a total of 28 days, in accordance with the guidelines stipulated in the standards. The bound water measurement was conducted on 3 cubic samples for every mix after 28 days. The ionizing radiation tests in REM 2.8 chamber were done on 1 slab sample for every mix after 90 days.

2.2. Basic mix and concrete properties

The granite-based concrete mixes exhibited densities in the range from 2,320 to 2,395 kg/m3. For heavy magnetite-based concrete, the density ranged from 3,510 to 3,600 kg/m3. In order to minimise the influence of other parameters on the linear attenuation coefficient, efforts were made to obtain mixes with similar properties in terms of their consistency class and compression strength within the given w/c ratio and cement type limits (Table 3). Mix consistency was controlled using low concentrations of the Sika ViscoFlow polycarboxylate superplasticiser. The cone slump was measured according to EN 12350–2 and consistency classes S3/S4 were obtained. Compressive strength values for both types of aggregate allow the concretes to be classified as strength class C35/45 and above.

2.3. Research methods

The research contains analysis of bound water content and neutron shielding properties of concrete samples. The bound water content is examined by thermogravimetric method. Neutron shielding properties of concrete are tested with MCNP test and ionising current measurement. To understand correlation between NLAC and cement type, aggregate type or w/c ratio in concrete the multiple regression analysis is prepared.

2.3.1. Bound water measurement

In line with the PN-B-0625 standard, the dry mass (m0) of the specimen was determined. A laboratory furnace was programmed to test the bound water (BW) content in accordance with RILEM recommendations [24]. It was assumed that the temperature would rise from room temperature to 1000 °C with a gradient of 1 °C/min, the set maximum temperature would be maintained for four hours and then the specimen would be gradually cooled down to 80 °C. Both concrete specimens and dry materials (cement, aggregate) were subject to firing. The constitutive water content was calculated using the formula [21,25]:

\[
BW = p * (m_0 - m_f) / C_s
\]

where,

- \(m_f\) - the mass of the specimen after firing at 1000 °C, g
CS - the cement content in the specimen tested, g
p - correction parameter for the percentage content of limestone and the concrete carbonation process.

The p parameter is calculated as [26,27]:

\[ p = 1 - \left( 0.44 \cdot g + 0.786 \cdot \frac{2 \cdot k \sqrt{t}}{d} \cdot f_{\text{CAO}} \cdot r_{\text{CAO}} \right) \]  \hspace{1cm} (2) 

where,
- \( g \) - percentage content of limestone in the cement composition;
- \( t \) - time of carbonation in years;
- \( k \) - the carbonation coefficient; \( d \) - the size of the cubic specimen (cm);
- \( f_{\text{CAO}} \) - the percentage content of CaO in cement;
- \( r_{\text{CAO}} \) - the extent to which CaO has been transformed into CaCO₃.

In the specimens tested, the degree of carbonation is negligible due to the curing time and conditions. The only correction is due to the limestone content of CEM II. For mixes based on this cement type, the Eq. (2) is rewritten as:

\[ p = 1 - 0.44g \]  \hspace{1cm} (3) 

### Table 2
Concrete mix designs.

| Concrete   | Cement type | Content, kg/m³ | Cement | Water | Aggregate \(^{1}\) | Coarse \(^{2}\) |
|------------|-------------|----------------|--------|-------|----------------|--------------|
| CII_G_0.40 | CEM II/A-M (5-LL) 52,5N | 380 | 152 | 578 | 1344 | 0.9 |
| CII_G_0.45 | | 171 | | | |
| CII_G_0.50 | | 190 | | | |
| CII_M_0.40 | | 152 | 480 | 2610 | 0.8 |
| CII_M_0.45 | | 171 | | | |
| CII_M_0.50 | | 190 | | | |
| CII_G_0.45 | CEM III/A 42,5N - LH/HSR/NA | 380 | 152 | 578 | 1344 | 1.6 |
| CII_G_0.50 | | 171 | | | |
| CII_M_0.40 | | 190 | | | |
| CII_M_0.45 | | 152 | 480 | 2610 | 1.2 |
| CII_M_0.50 | | 171 | | | |
| CIII_G_0.40 | | 190 | | | |
| CIII_G_0.45 | | 152 | 578 | 1344 | 1.3 |
| CIII_G_0.50 | | 171 | | | |
| CIII_M_0.40 | | 190 | | | |
| CIII_M_0.45 | | 152 | 480 | 2610 | 1.5 |
| CIII_M_0.50 | | 171 | | | |
| CIV_G_0.40 | CEM IV/B (V) 32,5 R - LH/NA | 380 | 152 | 578 | 1344 | 1.1 |
| CIV_G_0.45 | | 171 | | | |
| CIV_G_0.50 | | 190 | | | |
| CIV_M_0.40 | | 152 | 480 | 2610 | 0.6 |
| CIV_M_0.45 | | 171 | | | |
| CIV_M_0.50 | | 190 | | | |

\(^{1}\) Natural sand, 0–2 mm; \(^{2}\) crushed granite rocks 2–4 mm and 4–8 mm or magnetite 0–4 mm and 0–8 mm; \(^{3}\) superplasticizer.

### Table 3
Properties of fresh concrete mixes.

| Concrete   | Slump, mm | Density, kg/m³ | Compressive strength at the age of 28 days, MPa |
|------------|-----------|----------------|-----------------------------------------------|
| CII_G_0.40 | 160       | 2379           | 74.23                                         |
| CII_G_0.45 | 170       | 2395           | 67.89                                         |
| CII_G_0.50 | 170       | 2360           | 60.20                                         |
| CII_M_0.40 | 170       | 3600           | 71.48                                         |
| CII_M_0.45 | 165       | 3548           | 67.69                                         |
| CII_M_0.50 | 155       | 3555           | 53.44                                         |
| CII_G_0.40 | 135       | 2385           | 65.81                                         |
| CII_G_0.45 | 140       | 2362           | 55.48                                         |
| CII_G_0.50 | 130       | 2350           | 50.93                                         |
| CII_M_0.40 | 125       | 3582           | 66.04                                         |
| CII_M_0.45 | 135       | 3514           | 54.58                                         |
| CII_M_0.50 | 130       | 3536           | 46.00                                         |
| CIV_G_0.40 | 135       | 2345           | 57.72                                         |
| CIV_G_0.45 | 155       | 2337           | 51.84                                         |
| CIV_G_0.50 | 135       | 2322           | 45.15                                         |
| CIV_M_0.40 | 165       | 3569           | 59.43                                         |
| CIV_M_0.45 | 165       | 3548           | 54.91                                         |
| CIV_M_0.50 | 155       | 3517           | 46.49                                         |

2.3.2. MCNP simulation

Simulations of neutron transport through the shielding composite were performed for slabs using the MCNP code. The random number generator (RNG) determined the probabilities of various interactions between a neutron and the material tested. The simplified algorithm of used MC neutron transport simulation based [4] on is presented in Fig. 1.

A statistical analysis of 1x10⁷ molecule path histories was carried out with a relative error of less than 10⁻⁴ [28]. The simulation results obtained together with the bound water content determined for individual types of concrete made it possible to determine the neutron linear attenuation coefficient (NLAC) defined as:

\[ \mu = \frac{x}{l} \ln \left( \frac{l_0}{l} \right) \]  \hspace{1cm} (4) 

where,
- \( x \) - slab thickness in cm;
- \( l_0, l \) - the number of neutrons registered by the detector with and without the shielding material inserted between the radiation source and the detector.

2.3.3. Ionising current measurement

Additionally, real-life tests were conducted at the National Centre for Nuclear Research in Świerk (Poland). A specially prepared test stand (Fig. 2) was used, with an REM 2.8 recombination ionisation chamber that is sensitive to both neutron and gamma radiation. The ionising current measurement was done using a Pu-Be source in accordance to the individually implemented program [29] at a predestined prepared stand allowing to place 50 cm x 50 cm x 5 cm concrete slabs perpendicularly to the positioning mechanism of the ionic radiation source at a height of 100 cm ± 3% above the floor surface. The relatively large surface area of the sample created an isotropic radiation as the measurement consisted mainly of the beam passing through the barrier and not the reflected radiation from the walls and devices in the room [30]. This made it possible to determine the value of the ionising current for the concrete slabs tested in relation to unit current flow in an empty chamber.

2.3.4. Multiple regression analysis

In this study multiple regression analysis was used to determine the influence of cement type, aggregate type and w/c ratio.
on NLAC. The cement type and aggregate type were analysed as discrete variables and w/c ratio as continuous variable. The parameters importance on NLAC was analysed by coefficient of multiple regression (R), coefficient of determination (R^2) and probability parameter (p - value).

3. Results and discussion

3.1. Bound water content

The average bound water (BW) content in all the granite-based concretes is 11.50%, with a coefficient of variation of less than 18.5%. As Fig. 3 shows, for granite-based specimens on portland-composite cement with the addition of limestone (CEM II) or on pozzolanic cement with the addition of silica fly ash (CEM IV), no clear effect of an increase in the w/c ratio on the bound water content was observed. It is in contrary to previous researches in which authors concluded that bound water content is strongly influenced by the water content of the cement paste and it decreases with water/cement ratio [31,32]. However in this situation the different levels of bound water for CEM IV can be caused by alkali-activation of fly ashes and production of geopolymer hydrates [33].

The highest bound water content was recorded for CEM II and CEM IV, with w/c equal to 0.50 (13.90%) and 0.45 (14.63%), respectively. In the case of granite-based concrete on slag cement (CEM III), the content of bound water decreased by more than 31% together with the increase in the w/c ratio. This can be related to the slower hydration of slag cements as it was observed by Kolani.

**Fig. 1.** Simplified algorithm of used MC neutron transport simulation.

**Fig. 2.** Scheme of the experimental stand for ionising current measurement.
et al. [34]. The incorporation of slag particles in cement usually cause the dilution effect that decreases the hydration of cement particles [35]. Other researchers noticed also that cement with slag addition showed significantly higher pore volume than ordinary Portland cement at 28 days [36]. The more porous structure would allow free water to easily gather in the concrete pores and with the decreased level of cement hydration in CEM III samples it could justify the high content of free water (close to 30%) for CEM III granite based samples with w/c = 0.50, when for the other granite-based concretes, this value was close to 24%.

In magnetite-based shielding concretes, the CEM II specimens had a lower BW content than the CEM III and CEM IV specimens (see Fig. 3). It can be connected with the decrease of formation temperature in binder by ferrite phase from magnetite and insufficient cement hydration [37]. The best result achieved for CIV_M_0.50 (25.70%) is more than 13 times higher than the lowest value achieved for the CII_M_0.50 concrete (1.93%). The increased bound water values observed in the CEM IV concrete, are probably caused by combined effects of an enhanced cement hydration and to a contribution from the reaction of a pozzolana (fly ash available in CEM IV) [38,39]. The increase in w/c ratio guarantees sufficient amount of water for pozzolanic reaction in concrete allowing the reaction to occur until full depleting of calcium hydroxide reserves from cement hydration [40].

The average bound water content in magnetite concretes was 4.52% for CEM II, 8.86% for CEM III and 19.16% for CEM IV. However, the coefficient of variation was below 20% for CEM III only. In other cases, there was an average variation of results (below 40%). Unlike for the granite-based specimens, the impact of the w/c ratio on the bound water content was noticeable in CEM II and CEM IV. In the first case, a decrease in BW by 67% was observed with the increase in the ratio, while in the second case, an increase of almost 146% was recorded in the parameter tested.

Ordinary granite-based concretes exhibit less variation in their bound water content across all types of cement than heavy magnetite-based concretes. The values obtained for the granite-based specimens may be higher due to their lower resistance to temperature than that of magnetite-based specimens [41,42]. Other studies have indicated bound water contents of 13–17% after one month for both Portland and blast furnace cements [2,43]. The high BW level for concretes based on both aggregates and the CEM IV cement can be caused as described above by cement characteristic (fly ash as supplementary cement material) which allows the higher content of the hydration products in hardened concrete.

### 3.2. Linear attenuation coefficient and ionising current flow

The results of the MCNP neutron linear attenuation coefficient (NLAC) simulation for the specimens tested are presented in Fig. 4. The calculated NLAC value is primarily influenced by the density of the material tested, its chemical composition, the specimen dimensions and the assumed radiation source [4,7]. Given the constant dimensions of the specimens tested, the same radiation source and similar densities of the concretes tested for each aggregate type, the changes in NLAC values may only result from changes in chemical composition, including bound water content.

For granite-based concretes with CEM II and CEM III cementitious matrices, the average value of the neutron linear attenuation coefficient (NLAC) is 0.333 1/cm, with a coefficient of variation of less than 1% (Table 4). Despite the bound water content ranging from 7.9% to 14.6% and the change in the w/c ratio, none of these parameters appear to affect the LAC value for granite specimens. This observation is in contradiction to the Belyakov research were the water addition enhanced the hydrogen content in shielding concrete and allowed to increase the shielding properties [44,45]. Only for CEMIV_G was the average NLAC level 7.8% higher than for other granite-based concretes (with an average value of 0.358 1/cm). This may be due to the fact that the composition of CEM IV is based on silica fly ash, or may be related to the high BW content for CIV_G_0.45 and for CIV_G_0.50 (Fig. 3). Ibrahim Türkmen et al. noticed that silica compounds added in Portland cement increased the neutron attenuation coefficient and were better photon attenuators [46]. However in another research Akkurt et al. analysed the influence of lime/silica ratios on concrete shielding properties and he has not observed obvious relation between the calculated mass attenuation coefficients values and this ratio. He concluded that since the calculated mass removal cross-sections of lime and silica are similar the lime/silica ratio it can be modified.
without decreasing of the neutron attenuation ability of concrete [47]. Owing to the fact that magnetite-based specimens are categorized as heavy concrete, they exhibit NLAC values at least 10% higher than the highest value obtained for CIV_G_0.50 (0.362 1/cm). The NLAC value of CEMII_M concrete is, on average, lower than that of CEMIII_M by more than 6%, and lower than that of CEMIV_M by almost 30%. Similarly as for CEMIV_G, the high BW

**Table 4**
The average NLAC values for concretes with different cement type (NLACc) and with different aggregate type (NLACA).

| Aggregate type | Cement type | NLACc, 1/cm | SD, 1/cm | CV, % | NLACA, 1/cm | SD, 1/cm | CV, % |
|----------------|-------------|-------------|----------|-------|-------------|----------|-------|
| Granite        | C II        | 0.333       | 0.002    | 0.65  | 0.341       | 0.012    | 3.58  |
|                | C III       | 0.332       | 0.004    | 1.30  |             |          |       |
|                | C IV        | 0.358       | 0.002    | 0.74  |             |          |       |
| Magnetite      | C II        | 0.403       | 0.003    | 0.68  | 0.450       | 0.050    | 11.26 |
|                | C III       | 0.428       | 0.003    | 0.69  |             |          |       |
|                | C IV        | 0.521       | 0.028    | 5.31  |             |          |       |

**Fig. 4.** The values of linear attenuation coefficient for examined concrete slabs.

**Fig. 5.** The ionic flow attenuation unit value for concrete slabs in REM 2.8 chamber.
content for CEM IV_0.45 and CEM IV_0.50 (Fig. 3) may affect the NLAC value. For the remaining specimens, the NLAC value across a single cement type differs only slightly, despite the change in the w/c ratio. The average value for CEMIII_M is 0.403 l/cm, and for CEMIV_M 0.428 l/cm, where the coefficient of variation for both cements is close to 1% (see Tab 4.).

In real-life tests of slab specimens in the REM 2.8 chamber, presented in Fig. 5, the best values of ionising current flow attenuation were obtained for the granite-based concrete made with CII_G_0.40 (0.298), and for magnetite-based concrete – CII_M_0.45 (0.351) and CIV_M_0.40 (0.350) specimens. These results partially correspond to the NLAC values obtained for CEM IV specimens, where, in CIV_M_0.40 for example, NLAC reached one of the highest values. For specimens with the highest bound water content (see Fig. 3), the ionisation current attenuation depended on the type of cement used. While the best result was achieved for the CIV_G_0.45 specimen, the CEM IV CII_G_0.50 and CIV_M_0.50 specimens exhibited some of the worst results out of any of the specimens based on a single aggregate (0.266 and 0.329, respectively). This confirms the previous observations on the importance of the chemical composition of concrete and the lack of impact of the w/c ratio on the shielding properties of concrete. It should be noted, however, that the REM 2.8 chamber registers gamma and neutron radiation simultaneously, while exclusively neutron radiation is analysed in the Monte Carlo simulation. The correlation between ionic flow attenuation unit value and linear attenuation coefficient of concrete samples is presented in Fig. 6. It is possible to observe a correlation between two result groups connected with the type of aggregate.

In the multiple regression analysis, the three most important parameters explaining the LAC dependent variable were accounted for: aggregate type, w/c ratio and cement type (Table 5). The statistical significance of aggregate type results from the differences in density between magnetite and granite aggregates – the higher density value improves the shielding properties of cementitious composites. The obtained results make it possible to confirm the influence of cement type II and IV on the LAC value with a high regression correlation coefficient (R greater than 0.87) and p – value equal 0.04 and 0.001 respectively. At the same time, the w/c ratio is irrelevant.

4. Conclusions

The studies carried out concerning the assessment of bound water content and its impact on the linear ionising radiation attenuation coefficient in ordinary and heavy concretes have made it possible to formulate the following conclusions:

1. Granite-based concretes exhibit a smaller variation in bound water results than magnetite-based concretes. The bound water content in granite-based concretes are at the level of 11.5% after one month of storage in a climatic chamber and there is no clear relation with cement type. For magnetite-based concretes the

![Image](image-url)

**Fig. 6.** Correlation between ionic flow attenuation unit value and linear attenuation coefficient of concrete samples.

**Table 5**

| N = 18 | dependent variable: LAC |
|--------|-------------------------|
|        | R = 0.87  R² = 0.76     |
| p < 0.001 BSE: 0.037 |
|        | β   | SD β | B   | SD B | p   |
|        | aggregate | 0.817 | 0.130 | 0.110 | 0.018 | 0.000 |
|        | w/c     | 0.083 | 0.130 | 0.137 | 0.214 | 0.534 |
|        | CEM II  | -0.296 | 0.130 | -0.042 | 0.018 | 0.040 |
|        | constant term | 0.294 | 0.097 | 0.009 |

| N = 18 | dependent variable: LAC |
|--------|-------------------------|
|        | R = 0.84  R² = 0.70     |
| p < 0.001 BSE: 0.042 |
|        | β   | SD β | B   | SD B | p   |
|        | aggregate | 0.817 | 0.146 | 0.110 | 0.020 | 0.000 |
|        | w/c     | 0.083 | 0.146 | 0.137 | 0.240 | 0.578 |
|        | CEM III | -0.164 | 0.146 | -0.023 | 0.021 | 0.280 |
|        | constant term | 0.287 | 0.109 | 0.020 |

| N = 18 | dependent variable: LAC |
|--------|-------------------------|
|        | R = 0.94  R² = 0.89     |
| p less than 0.000 BSE: 0.026 |
|        | β   | SD β | B   | SD B | p   |
|        | aggregate | 0.817 | 0.090 | 0.110 | 0.012 | 0.000 |
|        | w/c     | 0.083 | 0.090 | 0.137 | 0.148 | 0.372 |
|        | CEM IV  | 0.461 | 0.090 | 0.066 | 0.013 | 0.001 |
|        | constant term | 0.258 | 0.067 | 0.002 |
bound water content is highly dependent from the cement type varying on average from 4.5% for CEM II to over 19.1% for CEM IV.

2. The impact of the w/c ratio on bound water content is not unequivocal. The increase of w/c does not make an increase in cement hydration rate.

3. There is no influence of w/c and no clear relation between neutron shielding efficiency and bound water content – more influencing are cement and aggregate type and their atomic composition rather than hydrogen from bound water.

4. When comparing the data obtained from the Monte Carlo simulation with the actual ionising radiation penetration results obtained for the mixes tested in the REM 2.8 chamber, a lack of correlation can be observed between the w/c ratio and the values of the linear attenuation coefficient (NAC) or ionising current flow. The best values of both parameters were obtained for specimens made using CEM II/A-M (S-L) 52.5 N and CEM IV/B (V) 32.5 R – L/H/NA. Although the LAC results partly overlap with ionising current flow attenuation, there is no clear conversion method available. Work is currently underway to determine the relationship between LAC and ionising current for comparison purposes.

CRediT authorship contribution statement

Piotr Prochon: Resources, Formal analysis, Investigation, Writing - original draft. Tomasz Piotrowski: Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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