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BINDER EFFICIENCY AND CO_2 EMISSIVITY FOR CEMENT MORTARS CONTAINING RECYCLING AGGREGATES

Summary

The article presents the application of bi (binder intensity index) and ci (carbon index) coefficients as indicators determining the efficiency of using binders in cement composites in combination with their impact on the environment resulting from CO_2 emissions occurring during cement production.

Key words: binder intensity index, carbon index, cement mortar, recycling aggregate.

INTRODUCTION

The still increasing global production of cement proves a strong contribution of the construction industry to the development of the modern civilisation. Alas, it proves also its contribution to the increase in carbon dioxide emissions into air. According to the findings made by the Intergovernmental Panel on Climate Change (IPCC), the CO_2 emissions from cement production have been fluctuating since the beginning of the 20^{th} century around the level of 5% of total emissions caused by human activity. It is forecasted [Damineli et al. 2010] that the absolute mass of cement produced in 2050 can be 2.5 times higher than in the referential year 2005. The biggest share of cement used in the construction sector is provided by concrete and mortar production. The latest trend in production of

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new cement composites are reactive powder concretes (RPC), having a compressive strength increasingly approaching the strength of steel. However, as far as the reduction of CO_2 emissions is concerned, the compressive strength is not the only quality criterion of a composite. Its durability appears to be equally important. Usually, a high cement content is seen as a factor which helps to obtain a longer service life of concrete, which is moreover confirmed by exposure classes contained in EN-206. Therefore, increasing the cement content is a primary way of maintaining resistance against corrosion (along with other methods such as using special cements), despite the constant or seasonal impact of aggressive environmental conditions. Unfortunately, while the minimum cement content (for a particular exposure class) is substantially exceeded, such approach is contradictory to the third and increasingly important composite quality criterion which is the environmental friendliness, normally associated with the CO_2 emission, being a consequence of cement and concrete production processes.

PRESENTATION OF THE RESEARCH SUBJECT – THE *BI* AND *CI* COEFFICIENTS' CONCEPT

Damineli et al. [2010] recommend optimizing the cement content, according to performance requirements imposed on the particular concrete design, by taking account the two following environmental factors associated with CO_2 emissions:

- bi – binder intensity (efficiency) index expressing cement weight per 1 m^3 of concrete, which is necessary to obtain compressive strength of 1MPa ($kg/m^3/MPa$),
- ci – carbon index – expressed as the weight of CO_2 emitted during the production process of such cement quantity as to obtain concrete strength of 1 MPa (kg/MPa).

With a view to meeting the requirements resulting from applying the factors mentioned above, the optimal solution appears to be manufacturing concretes with high compressive strengths, as in case where the 50 MPa value is exceeded, the bi coefficient can be even 5 $kg/m^3/MPa$, while in concretes with a low compressive strength the bi coefficient achieves 13 $kg/m^3/MPa$ (for $f_{cm} \approx 20$ MPa). As for the ci coefficient, the minimum value shall be 1,5 kg/MPa (if using mineral aggregates), while in pure clinker cements (without aggregates) it is not possible to achieve a value lower than 4,3 kg/MPa. In laboratory conditions the following values can be obtained: bi = 4 $kg/m^3/MPa$ and ci = 2 kg/MPa. The bi and ci values are affected not only by the cement content and its individual CO_2 emissivity but also by the quality of concrete curing. While curing of the external layers of concrete is subject to a technological regime, the difficult of curing of the internal concrete increases with the thickness of the concrete element. The only solution in such cases is to complete classical curing with internal concrete curing. For instance, it can be performed by applying cellulose fibres, providing an internal water buffer in concrete's microstructure. The idea of modifying concrete properties by using cellulose fibres arose in 1986. Back then, in Australia, sewage pipes were constructed, being an alternative to asbestos-cement pipes [Fisher et al., 2001]. The forerunner of the technology involving using these pipes as substitution to asbestos fibres as well as to cement was James Hardie [Coutts, 2005].

BUILDING MORTARS AND CONCRETES WITH RECYCLING AGGREGATES AS A REMEDY FOR ENVIRONMENTAL THREATS

Using recycling aggregates as an additional concrete component began after the World War II [Levy & Helene, 2002 after Aragão, 2007)]. Only in the last decades it was normalized by the European EN 933-11 standard: Tests on aggregate geometrical features – Part 11: Classification of the components of recycling coarse-grain aggregates. Naturally, there have been internal guidelines within certain countries before, such as the German DIN 4226-100 and British BS 8500-2 [after Gonçalves & de Brito, 2008]. Italian guidelines [Corinaldesi, 2011] indicate the possibility to substitute natural aggregates with recycling aggregates even to 30% (by volume), as long as the concrete strength grade is not higher than C30/37. Similar recommendations were presented in Germany [Grübl & Nealen, 1998]. In Holand, a 20% level of substitution [Ajdukiewicz, A., Kliszczewicz, 2009] has been admitted. Usually, to produce concretes, recycling aggregate with larger fraction is used, although there are also cases where smaller fractions are used – in Japan, endurance tests were conducted on prefabricated concrete elements, where recycled sand (which substituted 50-100% of natural sand) was used. After compressive strength tests carried out on concrete it was found that the compressive strength value fell within the scope of 30-40 MPa [after Zając & Gołębiowska, 2010]. EU Directive 2008/98/EC of 19 November 2008 on waste prescribes that until 2020, Member States must adjust their provisions and procedures so as to facilitate the recycling on a mass scale of at least 70% of construction and demolition waste. This requirement puts a mechanism in place to seek for new areas of application and quality improvement of residual construction materials, as aggregates not only for concrete but also for building mortars.

The problem of construction waste management is only one aspect of what is a much wider and complex issue – the reduction of the impact of wastes on the environment. Reducing greenhouse gas emissions, mainly CO_2, plays a crucial role in this respect. A possible way to balance the emissions at least partially is using the process of carbonation of aggregates obtained from concrete crushing. As a granular material, aggregate has a very large specific surface. By this method, a very high level of CO_2 absorption from the atmosphere can be obtained.

Its maximum upper limit can be determined basing on the model well-known from the source literature [Pade et al., 2007]:

$$Sekw_{CO_2} = 0{,}75 \cdot C \cdot CaO \cdot \frac{M_{CO_2}}{M_{CaO}} = 0{,}59 \cdot C \cdot CaO \quad \left(\frac{kg}{m^3}\right) \tag{1}$$

where:
C – cement content in m^3 of concrete (kg),
CaO – calcium oxide content in cement (-),
M_{CO_2} – carbon dioxide molar mass (44 kg/kmol),
M_{CaO} – calcium oxide molar mass (56 kg/kmol).

In the positive assessment presented above – entirely different than the first phase of the corrosion process in reinforced concrete, i.e. the neutralization of the bar jacket – the carbonation process of recycling aggregates can be defined as carbonation by sequestration. Its inclusion in the preparation process of recycling aggregates (by submitting aggregate obtained from concrete crushing to periodical carbonation) leads to an improvement of the CO_2 emission balance in the concrete's life cycle, which is demonstrated, among others, by Kikuchi and Kuroda [2011].

TEST MATERIALS AND METHODS

Within the tests, 8 batches of cement mortars were prepared. The materials used for the tests were the CEM I 42,5 R cement, recycling aggregate and cellulose fibres by Buckeye (fig. 1) which are (according to the information provided by the producer) characterised by: 2,1 mm average length, 18 μm diameter, 1,10 g/cm^{3}density, 116,7 mean shape coefficient (shape coefficient = length/diameter), 8,5 GPa Young module and tensile strength of approx. 750 MPa. A concentrated polymer superplasticizer with 1,075±0,02 kg/dm^3 density was used as super plasticizer.

The density of the natural aggregate (sand) amounted to 2,65 kg/dm^3, while the density of the recycling aggregate was 2,3 kg/dm^3, which resulted from the estimated average parent concrete density. After its crushing, a division in fractions on screens with meshes of 1, 2, 4, 8 and 16 mm has been performed – 1/2 mm fraction has been used for the tests. Cellulose fibres were supplied to mixtures by mixing the natural and recycling aggregate with 100 g water, in which, previously, cellulose fibres had been soaked for 24 hours (in order to loosen the structure of 5x5 mm packets). When using cellulose fibres and recycling aggregate, the so-called redundant water had to be taken account off in the formula. Its level has been established by EN 1097–6: 2002 (Tests on mechanical and physical properties of aggregates – Determining grain density and absorbability) at

3,6% related to aggregate weight. In case of cellulose fibres, the water absorbability amounted to 1,2g/1g dry mass.

Photo 1. Packets of cellulose fibres [author's photo]

Tab. 1. Composition of cement mortar [authors' results]

Symbol	N-0	N-1	NN-0	R-0	R-0,5	R-1	R-1,5	RR-0,5
Cement [g]	450	450	510	450	450	450	450	510
Effective water [g]	225	225	202	225	225	225	225	202
w/c [-]	0,5	0,5	0,4	0,5	0,5	0,5	0,5	0,4
Sand 0/1 [g]	905	905	905	905	905	905	905	905
Sand 1/2 mm [g]	445	445	445	-	-	-	-	-
Recycling 1/2 mm [g]	-	-	-	445	445	445	445	445
Water 2 [g]	-	-	-	16	16	16	16	16
Cellulose fibres [% cement weight] [g]	-	1,0% 4,50	-	-	0,5% 2,25	1,0% 4,50	1,5% 6,75	0,5% 5,10
Water 3 [g]	-	5,40	-	-	2,70	5,40	8,10	6,12
SP [% cement weight]	0,3	0,6	0,3	0,6	1,1	1,6	2	0,7
Water (total) [g]	225	230	202	241	244	246	249	224

For each batch of cement mortar, the properties of a fresh and hardened cement mortar were defined. This included examining the consistence by the spilling table method (according to EN 1015-3: Methods of test for mortar for masonry. Determination of consistence of fresh mortar) with modification (10-

times striking) and examining the compressive strength (after 28 days, according to EN 196-1: Test methods for cement. Part 1: Determining strength), carried out on 6 specimens (obtained from splitting 3 sticks of 40x40x160 mm). They provided a base for the calculation of bi and ci coefficients, which were conducted with CO_2 emissivity from cement production (CEM I 42,5 R) assumed at the level of 740 kg CO_2/t (figures obtained several years ago from one of Polish cement producers). The same cement emissivity has been adopted when calculating negative emission (for recycling aggregate) – assuming three hypothetical sequestration carbonation levels (10%, 20% and 30%), a simulation of bi and ci values has been conducted, taking into account carbonation by sequestration. In the tests, aggregate from concretes produced in a laboratory with cement content of 209–408 kg/m^3 and w/c ratio between 0,45 and 0,70 has been used. Therefore, for calculating bi and ci values, it has been assumed, that the average proportion of cement in the original concrete was 300 kg/m^3. As a basis of calculation of CO_2 absorbed by recycling aggregate during carbonation by sequestration, a value necessary to calculate the ci coefficient, a previously presented model had been applied (1).

TEST RESULTS

The results of consistence tests on mortars are presented in fig. 1. Compressive strength results for specimens are displayed in fig. 2. They were used for the calculation of the coefficients bi and ci, which are presented in fig. 3 and table 2, respectively (cement amount, used in particular mortar batches, has been calculated for 1 m^3).

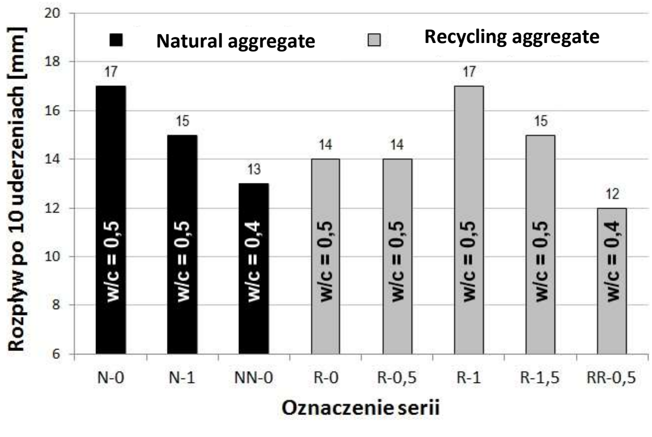

Fig. 1. The results of spreading tests after 10 strokes [authors' results]

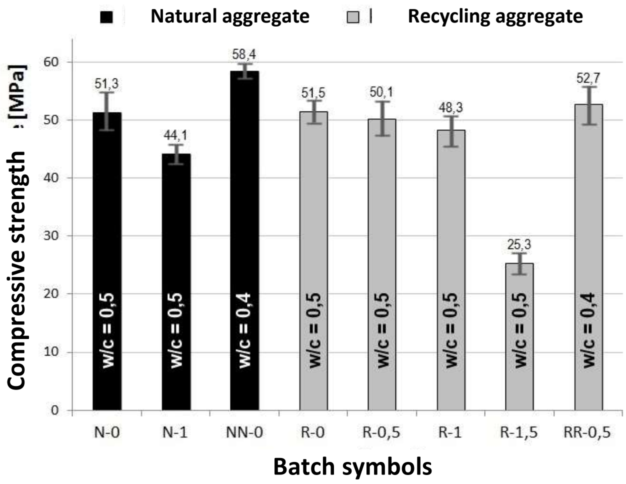

Fig. 2. Results from compressive strength tests (bars represent standard deviation) [authors' results]

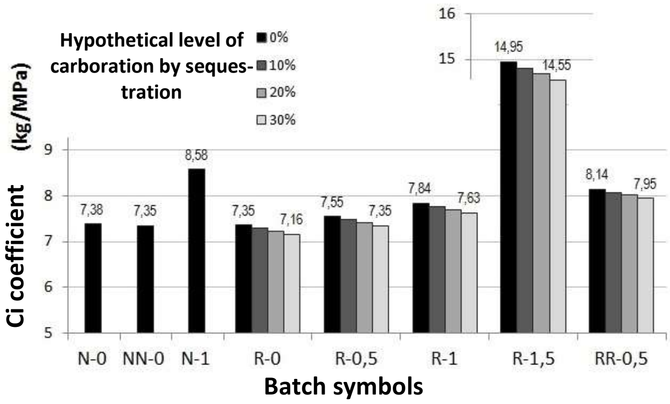

Fig. 3. Values of coefficients ci (in kg CO_2/MPa [authors' results]

Tab. 2. Values of bi coefficients (in kg/m3/MPa) [authors' results]

Symbol	*N-0*	*N-1*	*NN-0*	*R-0*	*R-0,5*	*R-1*	*R-1,5*	*RR-0,5*
Cement [kg/m^3]	511	511	580	511	511	511	511	580
bi [kg/m^3/MPa]	10,0	11,6	9,9	9,9	10,2	10,6	20,2	11,0

DISCUSSION OF RESULTS

The strength test results show that 1% is an acceptable level of cellulose fibres, where no noticeable degradation of a selected parameter is registered. This tendency occurred also in other batches (not displayed in fig. 3) with cellulose fibres content at 1,5% and 2%, where strength fell to a level below 50% of the value of reference samples (without fibres). A possible explantation of this effect may be a high content of fibres in the mortar, which could have prevented the densification process of specimen, which, in turn, may result in a higher aeration.

It is to be expected that the situation should improve in a concrete, as the fibres content has been dosed in respect of cement weight, which is relatively lower in concrete than in mortars.

The lowest bi coefficient was obtained for individual batches with natural NN-0 aggregate and with R-0 recycling aggregate. They are, however, similar to the analogue batch with the w/c ratio = 0,5 (N-0). The result shows that using recycling aggregates (1/2 mm fractions) does not necessarily impair the composite quality. The aggregate constitutes a water buffer which can be used in the hydration process. In this way, the negative effect of the existing recycling aggregate can be neutralized. Adding cellulose fibres did not contribute to this effect (the coefficient is slightly higher, but this similar), which can be associated with the small size of samples (4x4x16 cm), and therefore a better accessibility of water from outside. It appears possible that a more beneficiary effect would occur in concrete tests, such as supporting the reduction of the early shrinkage, which is moreover demonstrated by the tests of Ferrara et al. [2015 after Fu et al., 2017]. Analogue dependencies were observed in case of the ci coefficient (fig. 4). However, if the hypothetical impact of the sequestration carbonation of recycling aggregates is considered in calculations, the coefficient value for batches with waste aggregate can be even more advantageous than in batches with natural aggregates (batch R-0). It can be observed that even with a lower composite strength (resulting from the use of recycling aggregate) a similar effect in the changes of the CO_2 balance can be obtained. However, another aspect needs to be noted, which is the effect of composite microstructure improvement, propagated in the subject literature, resulting from using recycling aggregate submitted to carbonation (in comparison to aggregates used directly after concrete crushing). This effect contributes to an additional increase in composite strength [Li et al., 2018].

CONCLUSIONS

The results of the conducted tests and simulations can be concluded in the following statements:

1. It is possible to produce cement mortars where recycling aggregate of 1/2 mm fraction is added, that will not significantly impair the cement composite quality, if used.
2. The use of cellulose fibres requires further tests, as the impact of fibres, for instance and in particular, on the consistence of fresh mortars may not be advantageous if their content in a composite is high.

3. Soon, the concept of bi and ci coefficients suggested in the article [Damineli et al. 2010], may become an important requirement, according to which the environmental impact of cement mortars will be necessary. The assumptions of the concept are very simple and can be easily applied in practice.

LITERATURE

1. AJDUKIEWICZ A., KLISZCZEWICZ A.: Recykling betonu konstrukcyjnego. Inżynier budownictwa, 2, s. 65-69, 2009
2. ARAGÃO H.G.: Analise estrutural de lajes pré-moldadas produzidas com concreto reciclado de construção e demolição (Doctoral dissertation. Mestrado em Engenharia Civil. Universidade Federal de Alagoas), 2007
3. CORINALDESI V.: Structural concrete prepared with coarse recycled concrete aggregate from investigation to design. Advances in Civil Engineering, S. 1-6, 2011
4. COUTTS R.S.P.: A review of Australian research into natural fibre cement composites, Cement and Concrete Composites, 27, s. 518–526, 2005
5. DAMINELI B.L., KEMEID F.M., AGUIAR P.S., JOHN V.M.: Measuring the eco-efficiency of cement use. Cement and Concrete Composites, 32(8), s. 555-562, 2010
6. FISHER A.K., BULLEN F., BEAL D.: The durability of cellulose fibre reinforced concrete pipes in sewage applications, Cement and Concrete Research, 31, s. 543-553, 2001
7. FU T., MOON R. J., ZAVATTIERI P., YOUNGBLOOD J., & WEISS W. J.: Cellulose nanomaterials as additives for cementitious materials. In: cellulose-reinforced nanofibre composites (pp. 455-482), 2017
8. GONÇALVES P., BRITO J.D.: Utilização de agregados reciclados em betão. Análise comentada da regulamentação existente. Revista Engenharia Civil, Universidade do Minho, (32), 73-86, 2008
9. GRÜBL P., NEALEN A.: Construction of an office building using concrete made from recycled demolition material. Proceedings of Conference on Use of Recycle Concrete aggregate, 11, s. 89-90, 1998
10. KIKUCHI T., KURODA Y.: Carbon dioxide uptake in demolished and crushed concrete. Journal of Advanced Concrete Technology. 9(1), 115 – 124, 2011.
11. LI L., XIAO J., XUAN, D., & POON, C. S.: Effect of carbonation of modeled recycled coarse aggregate on the mechanical properties of modeled recycled aggregate concrete. Cement and Concrete Composites, 89, 169-180, 2018
12. PADE C., GUIMARAES M., KJELLSEN K., NILSSON A.: The CO_2 uptake of concrete in the perspective of life cycle inventory. International Symposium

on Sustainability in the Cement and Concrete Industry, Lillehammer, Norway, 2007

13. ZAJĄC B., GOŁĘBIOWSKA I.: Nowoczesne metody recyklingu betonu, Inżynieria i Aparatura Chemiczna. 49, 5, 136-137, 2010