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Research paper

The influence of water pretreated recycled aggregate on the required time of concrete care

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Abstract: Sustainable building projects has become increasingly important in recent years. To improve the circulation of materials in the construction sector, circular economy-inspired actions have been taken into account for CDW management The article investigates the possibility of using recycled aggregate as a reservoir of water for internal curing of concrete, in accordance with the principles of sustainable development and circular economy. The experiment consisted of four different curing scenarios and different proportions of recycled aggregate. The experiment measured the following properties: compressive strength, density, porosity, and SEM analysis of the interfacial transition zone between the aggregate and the cement paste. The analysis revealed that substituting ten percent of natural aggregate with recycled aggregate can shorten the external water curing time required for the concrete without affecting its final strength adversely. This solution also does not cause a significant increase in the porosity of concrete or a deterioration in the quality of the interfacial transition zone.

Keywords: closed-cycle economy, ecological concrete, internal curing, recycled aggregate

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1. Introduction

Sustainable building projects have become increasingly important in recent years. To improve the circulation of materials in the construction sector, circular economy-inspired actions have been taken into account for CDW management [1,2]. This issue includes both waste management and the preparation of environmentally friendly building materials, considered in life-cycle analysis (LCA) [3]. Construction and demolition waste (CDW) is the most significant waste stream across the EU, accounting for over 800 million tonnes per year [4]. It is estimated that an average of 35% of CDW is landfilled globally, therefore, effective CDW management is crucial in order to minimize detrimental impacts of CDW on the environment [5]. As such, the EU's Waste Framework Directive set the target for all European member states to achieve a minimum of 70% recycling or reuse rate of non-hazardous CDW by 2020 [4]. In many countries, concrete waste accounts for the largest share of CDW [7]. This waste is mostly used as landfill, neglected, and dumped [8], which does not exhaust the potential of this material. Research on recycled aggregate has been conducted for several decades around the world. The conclusions of the research mainly indicate the deterioration of the technical characteristics of concrete. The following effects of increasing the proportion of recycled aggregate (*RA*) in the aggregate mix in concrete were observed: a decrease in workability [9]; a decrease in density [10]; a decrease in permeability [11]; a decrease in mechanical strength [12, 13]; and a decrease in elastic modulus [14], an increase in bleeding [15]; an increase in drying shrinkage [16]; and an increase in creep deformation [17]. These changes in concrete properties can be attributed to the presence of adhered mortar in *RA* [18], which usually has a higher porosity than natural aggregate. To minimize the negative impact of using *RA*, many researchers suggest appropriate quality selection of *RA* and its proper preparation. Concrete prepared in this way may have good mechanical [19] and durability [20] properties. The strength of the mentioned effects of using *RA* is determined by the parameters of the recycled aggregate used. Consequently, many countries impose quality restrictions on the use of recycled aggregate.

One way to prepare *RA* is through methods that involve complete or partial removal of the adhered mortar. Another method involves soaking or rinsing the *RA*. This method allows for dusting off the *RA* and increasing its adhesion to the cement slurry. However, it is problematic to determine the effective content of water. Compressive strength seems to be notably affected by how *RA* water absorption is taken into account in mix proportioning and full compensation of water absorption of aggregates is not recommended [21]. This suggests that water absorbed by the aggregate partially will remain in the aggregate longer than cement setting occurs. It will only begin to be released in the later stages of hardening, contributing to the maintenance of the concrete. The concrete curing could be external or internal. Traditionally the external curing methods, such as water spraying and wet cloth covering, are used. However, the external curing water stays only on the surface of concrete. Therefore, interior curing is becoming increasingly popular [22]. Internal curing is achieved by introducing a material that stores water within itself [23]. In the process of cement hydration, a humidity difference between the internal curing material and cement generates a certain level of capillary pressure. The water in the internal curing material will be released due to the capillary pressure so that the internal humidity of concrete could be maintained to meet the demand for the continuous hydration of cement [22]. Several studies on using waste-based materials as internal curing water reservoirs in concrete have been conducted [24].

They have been used because of their potential suitability for this application, economic benefits, and environmental advantages [25]. Examples of waste-based materials as internal curing agents include ceramic-recycled aggregate [26] and coal bottom ash [27]. However, other granular by-products have been found to be debatable fits. For example, recycled concrete aggregate exhibited inadequate desorption properties, owing to the tight pore structure of the adhered old mortar [28]. However, some studies have insisted on the potential feasibility of RA [29], and others have attributed part of their performance to the internal curing effect [30]. Furthermore, the characteristics of the old concrete from which the recycled aggregates are obtained and the processes involved in their transformation result in recycled aggregates of different qualities [31–34]. In the presented research, an attempt was made to analyze the possibility of reducing the external curing time by using soaked recycled aggregate.

2. Experimental program

The purpose of the conducted research was to determine the impact of partial substitution of the coarse aggregate with the recycled aggregate on the possibility of reducing the required curing time of cement concrete. Concrete samples were prepared according to the experimental design. The prepared samples were subjected to the following tests: compressive strength after 28 days, microscopic observations of the transition zone structure. The study examined the possibility of reducing the external curing time without significant negative impact on the concrete properties.

2.1. Materials and concretes

Due to the fact that the designed concretes are supposed to be ecological, it was decided to use cement with low clinker content. The cement used was CEM V – A(S,V) 32.5 R, with a clinker content of 40% to 64%, blast furnace slag of 18% to 30%, silica ash of 18% to 30% and 32.5 MPa of compressive strength according to EN 197-1 [35]. CHRYSO Optima 294 was also used as a water reducing admixture. As virgin coarse aggregates, two size fractions were used, one with aggregate size 2–8 mm (marked 2-8N) and the other with 8–16 mm (marked 8-16N) with a fineness modulus of 5.56 and 5.63 respectively. Both of them are from natural gravel. Furthermore, recycled coarse aggregates obtained from the demolition of concrete structures were used, so they mainly consisted of aggregates with adhered mortar.

The fraction was 8–16 mm (marked 8-16R) with a fineness modulus of 6.95. Lastly, the fine aggregate was just a natural sand with a maximum aggregate size of 2 mm (marked 0-2N) and a fineness modulus of 4.70. Table 1 summarizes the basic properties of the aggregates used. Figure 1 exhibits the composition of the recycled coarse aggregates according to EN 933-11 [36]. On the basis of these results, they can be classified as recycled coarse aggregates from concrete demolition waste and named as RCA (recycled concrete aggregate) using the BS 8600:02 [37] classification, as type II according to the RILEM [38] and DIN 4223 [39] standards and as GBSB-II according to Belgian specifications [40].

Table 1. Basic properties of aggregates

Properties	0-2N	2-8N	8-16N	8-16R
Density (EN 1097-6), g/cm^3	2.54	2.64	2.68	2.53
Density in oven-dry conditions (EN 1097-6), g/cm^3	2.13	2.46	2.60	2.25
Water absorption (EN 1097-6), %	7.5	2.8	1.2	4.8
Los Angeles Abrasion (EN 1097-2), %	–	27.0	25.0	75.0
Fineness module (EN 933-1)	2.3	5.56	5.63	6.95
Fines percentage (EN 933-1)	1.0	0.1	0.1	0.9
Moisture content ((EN 933-1), %	0	0	0	4.8

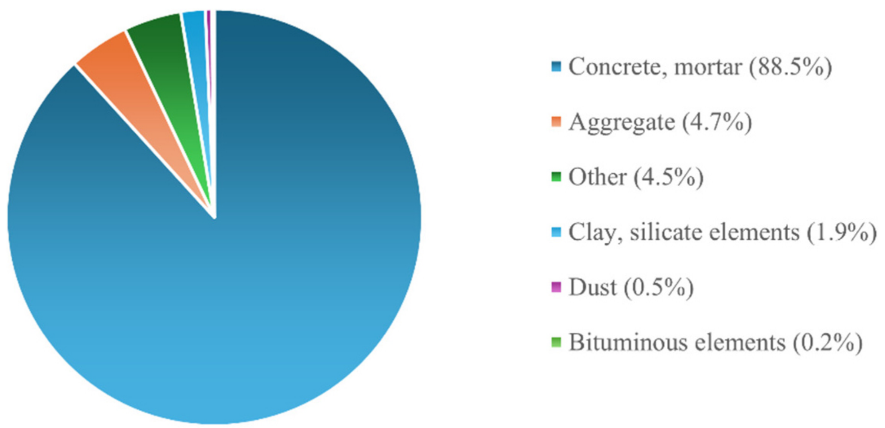

Fig. 1. Composition of recycled coarse aggregate according to EN 933-1 (percentage by weight)

Five different concrete compositions were adopted for the study, differing in the level of replacement of natural aggregate (marked 8-16N) with recycled aggregate (marked 8-16R) from 0% to 20%. The maximum level of replacement of natural aggregate by recycled aggregate was adopted in accordance with EN 206 [41]. A constant w/c ratio of 0.45 was assumed. A constant cement content of 310 kg was determined Table 2.

The dosage of the fluxing admixture was fixed at a constant level of 3.5% by weight of cement. The recycled aggregate was soaked in water for 24 hours before being added to the mix. After that time, the aggregate was surface dried and dosed. Considering the water contained in the aggregate as part of the effective water content is debatable and therefore two different water/cement ratios were calculated. The w/c ratio is the ratio of added recycled water to cement, and the wRA/c ratio is the ratio of the sum of recycled aggregate water and recycled water to cement.

Table 2. Concrete mix proportions in 1 m^3

In weight		**R/A–D**	**5/A–D**	**10/A–D**	**15/A–D**	**20/A–D**
Cement	kg	310	310	310	310	310
Water	kg	140	140	140	140	140
0-2N	kg	806	806	806	806	806
2-8N	kg	403	403	403	403	403
8-16N	kg	806	705	604	503	402
8-16R	kg	0	101	202	303	404
w/c		0.45	0.45	0.45	0.45	0.45
wRA/c		0.45	0.48	0.50	0.53	0.55
Admixture	%	3.5	3.5	3.5	3.5	3.5
In volume		R/A–D	5/A–D	10/A–D	15/A–D	20/A–D
Cement	l	100	100	100	100	100
Water	l	140	140	140	140	140
0-2N	l	304	304	304	304	304
2-8N	l	152	152	152	152	152

2.2. Curing scenarios

Four different curing scenarios were provided for each of the five prepared compositions. Scenario A assumed no moisture treatment, Scenario B assumed moisture treatment for 2 days, Scenario C assumed moisture treatment for 4 days – which is the EN 13670 [42] requirement for the cement used, and Scenario D assumed moisture treatment for the standard 28 days (Fig. 2).

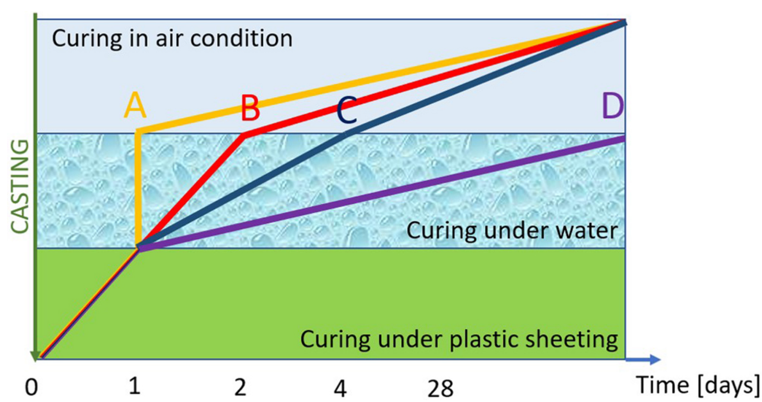

Fig. 2. Curing scenarios

2.3. Experimental tests

Firstly, the fresh concrete properties were obtained through the measurement of consistency and density according to standards EN 12350-2 [43] and EN 12350-6 [44] respectively. According to EN 12390-2 [45], for each concrete mix, a series consists of 3 specimens. Cubic 100 mm samples were compacted mechanically and then cured for 24 hours under plastic sheeting and then – after being removed from the mold – cured in water until the different time (A–D scenario) of testing at a temperature of (20 ± 2)°C.

According to EN 12390-3 [46], after removal of the specimen from curing, specimens were tested for strength as soon as practicable, within 1 hour. The test facility was (20 ± 5)°C. Before placing in the testing machine, the excess of moisture from the surface of the specimen was wiped. The cube specimens were positioned so that the load was applied perpendicularly to the direction of casting. The constant rate of loading was 0.5 MPa/s (N/(mm^2·s)). After the application of the initial load, which did not exceed approximately 30% of the failure load, the load increased continuously until no greater load could be sustained. The maximum load indicated in kN was recorded. Compressive strength was calculated as the quotient of recorded load and cross section area and expressed in the nearest 0.1 MPa.

Samples with varying levels of recycled aggregate substitution (0D, 5D, 10D, 15D and 20D) were subjected to detailed SEM-EDS studies to determine the structure of the paste-aggregate transition zone, with particular attention to microcracking. From the 100 mm concrete cubes, a slice was cut from the middle. Then a smaller piece was cut (20 × 20 × 5 mm) for SEM examinations. Figure 3 and Fig. 4 present an example of polished inner sections of samples with marked places where the smaller samples were cut for SEM examinations. Small samples were dried in an oven at a temperature of 40°C and put into epoxy resin under vacuum for better filling of the air voids. The final step of preparing the samples was polishing their surface. The samples were gold evaporated before examining them in the microscope.

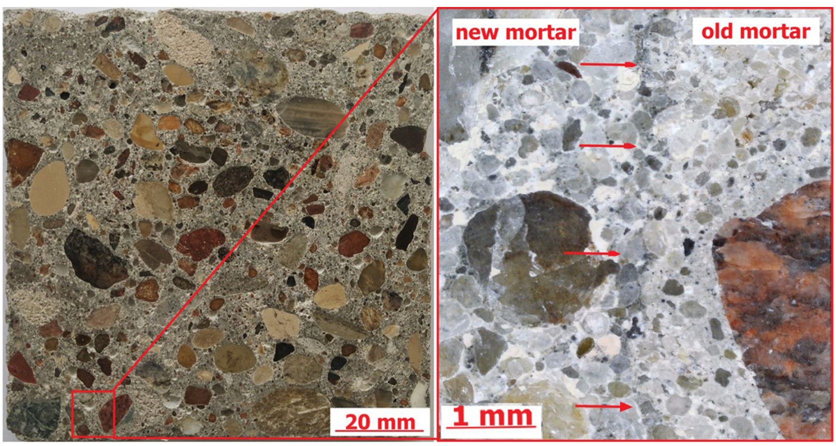

Fig. 3. Examples of inner sections of the 100 mm cube concrete samples and exanimated area by SEM technique (red arrows show the border zone); recycled aggregate with old mortar form sample 15D

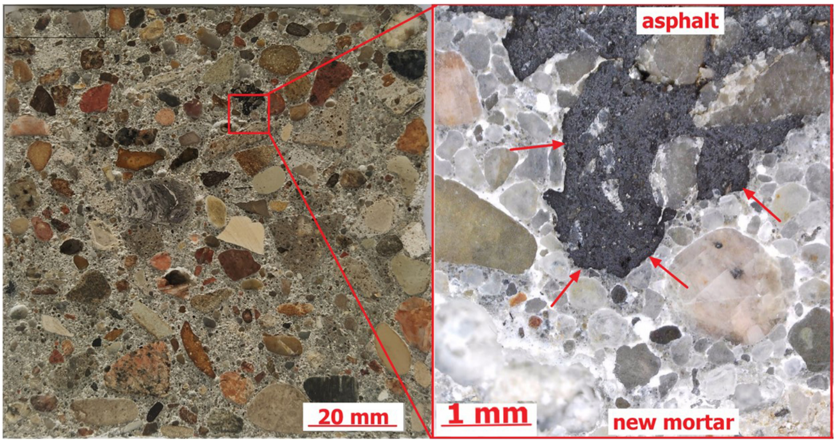

Fig. 4. Examples of inner sections of the 100 mm cube concrete samples and exanimated area by SEM technique (red arrows shows the border zone); asphalt particle from sample 20D

Microstructure observations were made using a scanning electron microscope (SEM) produced by Zeiss, model Sigma 500 VP (Carl Zeiss Microscopy GmbH, Köln, Germany). Secondary electron (SE) and backscattered electron (BSE) images were collected. Phase compositions and mapping were analysed using the EDS detector model Oxford Ultim Max 40.

3. Results and discussion

3.1. Concrete properties

This is related to the more complex and angular shape of the aggregate and may suggest that the water contained in the recycled aggregate was not released during mixing. The density of fresh concrete values between 2453–2465 kg/m^3 displayed a decrease as the replacement ratio of recycled coarse aggregate increased [22–32]. It was mainly due to the adhered mortar of the recycled coarse aggregates [47, 48]. As already reported by other authors [33, 47–49], it could be seen that, in general, when the replacement percentage increased, the mechanical strengths of recycled concretes were reduced. The reduction was a maximum of 30% of compressive strength (standard care – 28 days in water; 20% aggregate replacement rate).

As aforementioned, the main goal of this research is to determine the curing time-dependent behavior of recycled concretes in order to design curing with the same approximation degree as with conventional concretes. It is noteworthy that using twenty-eight days of care, the strength differences obtained for compositions with RA dosages in the range of 5–15% are within the standard deviations of the measurements. Under construction conditions, implementation of a 28-day cure would significantly delay the progress of the construction work and is therefore often limited to the time required by Standards. The required curing time, considering the type of cement used, is 4 days. Therefore, the results obtained with the maximum four-day care were subjected to statistical analysis Table 3.

The GAM analysis [50] was performed for the compressive strength testing results. The following equation was found Eq. (3.1):

$$f_c = 28.93 + 5.09 \cdot t - 0.66 \cdot RA - 0.65 \cdot t^2 - 0.07 \cdot t \cdot RA + 0.02 \cdot RA^2 \tag{3.1}$$

where:
f_c – compressive strength after 28 days in [MPa],
t – curing in water conditions [days],
RA – level of natural gravel substitution by recycled aggregate.

Table 3. Basic properties of the concretes

Concrete	**Curing scenario**	**Slump values [mm]**	**Density of fresh concrete [kg/m^3]**	**Density of hardened concrete [kg/m^3]**	**Compressive strength [MPa]**
R	A	190	2465	2300 ± 21	35.2 ± 0.3
	B			2296 ± 13	35.9 ± 3.7
	C			2314 ± 9	38.9 ± 3.0
	D			2351 ± 26	39.9 ± 0.2
5	A	160	2463	2253 ± 4	28.3 ± 1.7
	B			2237 ± 22	30.6 ± 2.5
	C			2267 ± 20	35.0 ± 2.5
	D			2325 ± 4	33.4 ± 1.1
10	A	120	2459	2245 ± 10	29.3 ± 0.3
	B			2270 ± 7	32.7 ± 1.0
	C			2278 ± 12	33.4 ± 0.5
	D			2319 ± 8	34.5 ± 0.5
15	A	100	2457	2210 ± 16	26.3 ± 1.3
	B			2237 ± 12	29.6 ± 0.9
	C			2237 ± 6	26.6 ± 4.0
	D			2284 ± 15	34.1 ± 1.9
20	A	70	2453	2229 ± 14	26.4 ± 0.9
	B			2244 ± 8	28.9 ± 1.1
	C			2247 ± 5	28.8 ± 2.0
	D			2305 ± 8	28.5 ± 3.0

For the obtained equation, the coefficient of determination was calculated $R^2 = 0.85$ and MAPE = 4.8%. The partial autocorrelation function and autocorrelation function of the residual number were verified [51]. It could be concluded that equation Eq. (3.1) is a regression equation and could be used to the further analysis.

The test results indicate that there is a possibility to reduce the curing time when using soaked recycled aggregate. The greater the proportion of recycled aggregate, the possibility of a greater reduction in its time. At 10–20% substitution of natural aggregate for recycled aggregate, a two-day treatment is sufficient to achieve the compressive strength achieved with a four-day treatment (Fig. 5). In the absence of recycled aggregate in the composition, the impact of time of care is significant. It accounts for approximately 30% of the difference in compressive strength achieved.

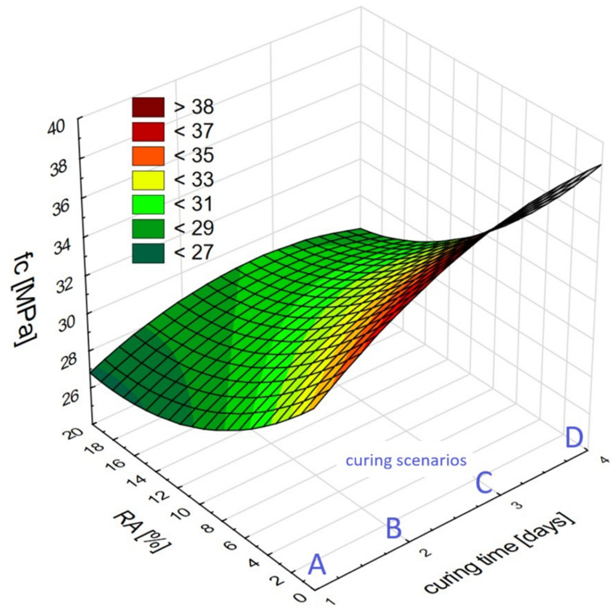

Fig. 5. 28 days compressive strength depending on curing time and level of natural gravel substitution by recycled aggregate

3.2. Microscopic analysis

Figure 6 presents an example of observed microstructure of concrete. Grout of newly formed cement matrix contained clicker relicts and some grains of fly ash and blast furnace slag. Concrete also contained a various types of grains of recycled aggregate.

SEM examinations were focused mainly on the transition zones between: natural aggregates and mortar (as a reference), recycled aggregates and new mortar, old mortar and recycled aggregate, old mortar and new mortar, asphalt particles and new mortar.

Transition zone between natural coarse aggregate and cement matrix was well formed with no cracks. C–S–H phase was properly formed what proves that curing process was sufficiently carried out. Natural aggregates recovered from concrete were also well bonded to the cement matrix in areas where the old mortar did not stick to their surface. In some areas the old mortar had a large cracks in the transition zones between the old aggregates what might be caused by the mechanical treatment during the mechanical recycling process.

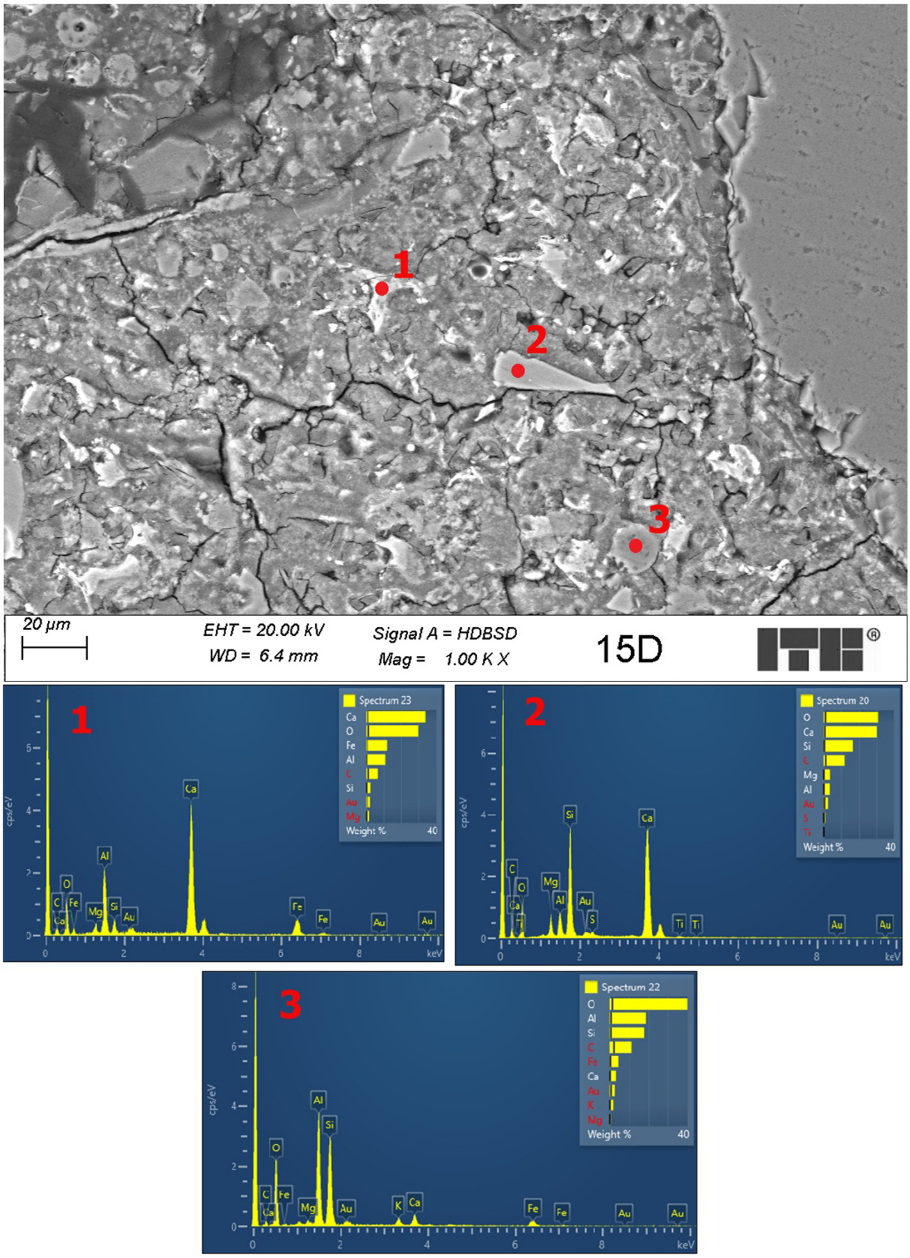

Fig. 6. Sample 15D with identified constituents of cement matrix (1 – clinker, 2 – blast furnace slag, 3 – siliceous fly ash)

Figure 7 presents BSE images and an EDX mapping of an area of transition zone between old and new mortar. The transition zone was well formed with only a few cracks on the border. A new mortar had more air voids than the old one in the area surrounding the grain of recycled aggregate. This might be caused by the higher porosity of the recycled mortar grain which effected in draining the water from border area. Also a cumulation of aggregate grains in the border area was noticed. Old mortar was completely carbonated and contained less clinker relicts than the new one. The fly ash grains were spotted also in the old mortar.

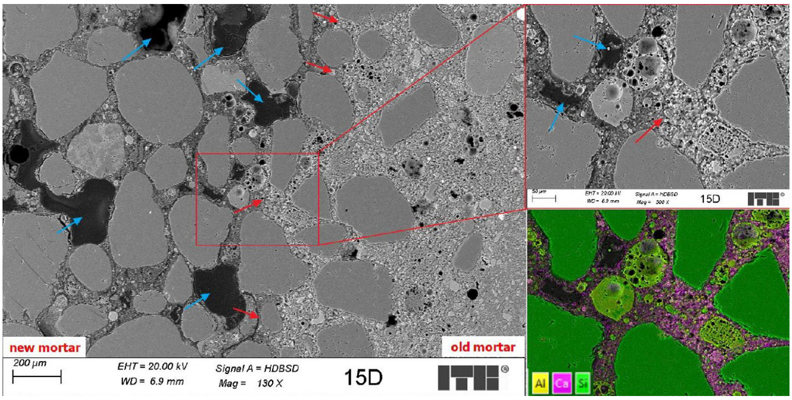

Fig. 7. Transition zone between new and old mortar in sample 15D (red arrows marks the border line, blue arrows marks the air voids)

Figure 8 presents BSE images and an EDX mapping of an area of transition zone between new mortar and an asphalt particle. The transition zone was well formed with no cracks or breakout tendency. C–S–H phase was properly formed with no excessive air voids or cracks. Asphalt particle contained dolomite aggregates and it was much less porous than the old mortar. Less number of air voids in the transition zone in new mortar might be caused by the lower porosity of asphalt grains.

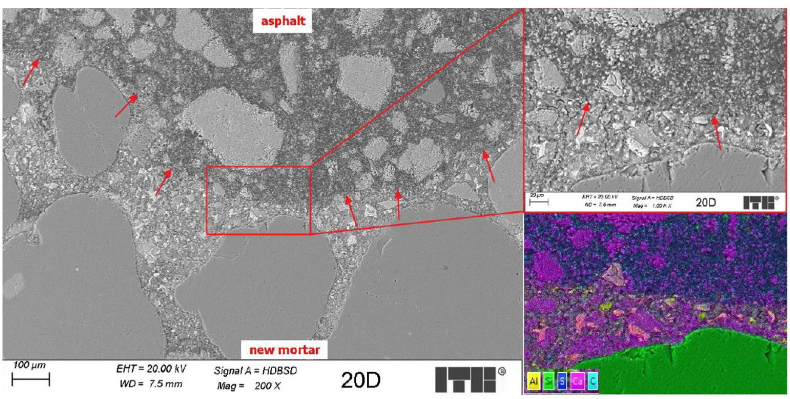

Fig. 8. Transition zone between new mortar and an asphalt grain in sample 20D (red arrows marks the border line)

4. Conclusions

The results of the analysis indicate that it is possible to shorten the time of required external moisture care of cement concrete using 10% substitution of natural aggregate with recycling aggregate. Such dosing allows you to shorten the external water care time, without significantly affecting the final strength of the concrete. Such a solution does not significantly increase the porosity of concrete and does not worsen the aggregate-leaven transition zone.

Microstructural SEM examinations of concrete containing recycled aggregates showed different types of transition zones between new mortar and grains form recycled concrete depending form the type of the grain. Grains of clean recycled natural aggregates recycled from concrete were bonded to the cement matrix as well as a new natural aggregates. Grains containing an old mortar were quite well bonded to the new mortar but the transition zone in new mortar had many air voids what might be caused by the higher porosity of the recycled mortar grain which effected in draining the water from border area. Asphalt particles present in the recycled concrete aggregate was well bonded to the new mortar. The transition zone was well developed with no cracks or excessive air voids. Less number of air voids in the transition zone in new mortar might be caused by lower porosity of asphalt grains.

The porosity of recycled aggregate grains seems to have a key role in forming the air voids in new mortar in transition zone. The mechanism of such observations might be explained by the decreasing of water content in the transition zone by the recycled grains with high porosity such as an old mortar what effects in locally decreasing the consistency of mortar. That might leads to difficulties in proper compacting the mortar in transition zone. Grains with relatively low porosity such as asphalt grains do not lead to local increase of the porosity of new mortar.

To sum up, it is worth considering the use of soaked recycled aggregate as internal care, especially when using low-clinker cements, because their required care time is much longer. The combination of low clinker cement and recycled aggregate is a solution compatible with the circular economy. Although the solution seems promising, the impact of the modification on the durability of concrete, both chemical and physical, should be considered.

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References

[1] B. Langier, J. Katzer, M. Major, J. Halbiniak, and I. Major, "Strength and durability characteristics of concretes with crushed side window glass as partial aggregate substitution", *Archives of Civil Engineering*, vol. 69, no. 2, pp. 5–21, 2023, doi: 10.24425/ace.2023.145249.

[2] C. Zhang, M. Hu, F. Di Maio, B. Sprecher, X. Yang, and A. Tukker, "An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe", *Science of The Total Environment*, vol. 803, 2022, doi: 10.1016/j.scitotenv.2021.149892.

[3] M. Fąfara, Ł. Łukaszewski, E. Owczarek, and I. Źrebiec, "Life Cycle Assessment (LCA) and environmental comparison the selected construction methods of residential buildings in traditional and straw cubes technology – a case study", *Archives of Civil Engineering*, vol. 68, no. 3, pp. 241–255, 2022, doi: 10.24425/ace.2022.141883.

[4] Deloitte, "Resource efficient use of mixed wastes: improving management of construction and demolition waste – final report". European Commission, DG ENV, 2017.

[5] K. Kabirifar, M. Mojtahedi, C. Wang, and V.Y. Tam, "Construction and demolition waste management contributing factors coupled with reduce, reuse, and recycle strategies for effective waste management: A review", *Journal of Cleaner Production*, vol. 263, 2020, doi: 10.1016/j.jclepro.2020.121265.

[6] European Commission, "Construction and demolition waste", 2019. [Online]. Available: http://ec.europa.eu/environment/waste/construction_demolition.htm. [Accessed 10. Dec. 2023].

[7] J. Kim, "Construction and demolition waste management in Korea: recycled aggregate and its application", *Clean Technologies and Environmental Policy*, vol. 23, pp. 2223–2234, 2021, doi: 10.1007/s10098-021-02177-x.

[8] J. Kim, "Influence of quality of recycled aggregates on the mechanical properties of recycled aggregate concretes: An overview", *Construction and Building Materials*, vol. 328, 2022, doi: 10.1016/j.conbuildmat.2022.127071.

[9] A.M. Grabiec, D. Zawal, and W.A. Rasaq, "The effect of curing conditions on selected properties of recycled aggregate concrete", *Applied Sciences,* vol. 10, no. 13, 2020, doi: 10.3390/app10134441.

[10] H. Al Ajmani, F. Suleiman, I. Abuzayed, and A. Tamimi, "Evaluation of concrete strength made with recycled aggregate", *Buildings*, vol. 9, no. 3, 2019, doi: 10.3390/buildings9030056.

[11] G.L. Vieira, J.Z. Schiavon, P.M. Borges, S.R. da Silva, and J.J. de Oliveira Andrade, "Influence of recycled aggregate replacement and fly ash content in performance of pervious concrete mixtures", *Journal of Cleaner Production*, vol. 271, 2020, doi: 10.1016/j.jclepro.2020.122665.

[12] J. Kim, D. Lee, A. Sičáková, and N. Kim, "Utilization of different forms of demolished clay brick and granite wastes for better performance in cement composites", *Buildings*, vol. 13, no. 1, 2023, doi: 10.3390/buildings13010165.

[13] M. Etxeberria, E. Vázquez, A. Marí, M. Barra, "Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete", *Cement and Concrete Research*, vol. 37, no. 5, pp. 735–742, 2007, doi: 10.1016/j.cemconres.2007.02.002.

[14] C.S. Poon, S.C. Kou, L. Lam, "Influence of recycled aggregate on slump and bleeding of fresh Concrete", *Materials and Structures,* vol. 40, pp. 981–988, 2007, doi: 10.1617/s11527-006-9192-y.

[15] H. Zhang, Y. Wang, D.E. Lehman, Y. Geng, and K. Kuder, "Time-dependent drying shrinkage model for concrete with coarse and fine recycled aggregate", *Cement and Concrete Composites*, vol. 105, 2020, doi: 10.1016/j.cemconcomp.2019.103426.

[16] R.V. Silva, J. de Brito, and R.K. Dhir, "Comparative analysis of existing prediction models on the creep behaviour of recycled aggregate concrete", *Engineering Structures*, vol. 100, pp. 31–42, 2015, doi: 10.1016/J.ENGSTRUCT.2015.06.004.

[17] Y. Fan, J. Xiao, and V.W.Y. Tam, "Effect of old attached mortar on the creep of recycled aggregate concrete", *Structural Concrete*, vol. 15, no. 2, pp. 169–178, 2014, doi: 10.1002/suco.201300055.

[18] A. Jayasuriya, M.P. Adams, and M.J. Bandelt, "Understanding variability in recycled aggregate concrete mechanical properties through numerical simulation and statistical evaluation", *Construction and Building Materials*, vol. 178, pp. 301–312, 2018, doi: 10.1016/j.conbuildmat.2018.05.158.

[19] J. Kim, A. Grabiec, A. Ubysz, S. Yang, and N. Kim. „Influence of Mix Design on Physical, Mechanical and Durability Properties of Multi-Recycled Aggregate Concrete", *Materials*, vol. 16, no. 7, 2023, doi: 10.3390/ma16072744.

[20] C. Thomas, J. Setien, J.A. Polanco, P. Alaejos, and M. Sanchez de Juan, "Durability of recycled aggregate concrete", *Construction and Building Materials,* vol. 40, pp. 1054–1065, 2013, doi: 10.1016/j.conbuildmat.2012.11.106.

[21] J. Kim and Ł. Sadowski, "Properties of recycled aggregate concrete designed with equivalent mortar volume method", in *Woodhead Publishing Series in Civil and Structural Engineering*. Elsevier, 2022, pp. 365–381, doi: 10.1016/B978-0-12-824105-9.00018-4.

[22] X. Fengming, L. Xiaoshan, Z. Annan, and L. Qing-feng, "Effects of recycled ceramic aggregates on internal curing of high performance concrete", *Construction and Building Materials*, vol. 322, 2022, doi: 10.1016/j.conbuildmat.2022.126484.

[23] M. Suzuki, M. Seddik Meddah, and R. Sato, "Use of porous ceramic waste aggregates for internal curing of high-performance concrete", *Cement and Concrete Research*, vol. 39, no. 5, pp. 373–381, 2009, doi: 10.1016/j.cemconres.2009.01.007.

[24] S.H. Alsayed and M A. Amjad, "Effect of curing conditions on strength, porosity, absorptivity, ans shrinkage of concrete in hot and dry climate", *Cement and Concrete Research*, vol. 24, no. 7, pp. 1390–1398, 1994, doi: 10.1016/0008-8846(94)90124-4.

[25] K. Audenaert and G. De Schutter, "Towards a fundamental evaluation of water retention tests forcuring compounds", *Materials and Structures*, vol. 35, pp. 408–414, 2002, doi: 10.1007/BF02483144.

[26] O.M. Jensen and P.F. Hansen, "Water-entrained cement-based materials: I. Principles and theoretical background", *Cement and Concrete Research,* vol. 31, no. 4, pp. 647–654, 2001, doi: 10.1016/S0008-8846(01)00463-X.

[27] R. Rodríguez-Álvaro, S. Seara-Paz, B. González-Fonteboa, and M. Etxeberria, "Study of different granular by-products as internal curing water reservoirs in concrete", *Journal of Building Engineering*, vol. 45, 2022, doi: 10.1016/j.jobe.2021.103623.

[28] D.M. Al Saffar, A.J.K. Al Saad, and B.A. Tayeh, "Effect of internal curing on behaviour of high performance concrete: an overview", *Case Studies in Construction Materials*, vol. 10, 2019, doi: 10.1016/j.cscm.2019.e00229.

[29] M. Suzuki, M. Seddik Meddah, and R. Sato, "Use of porous ceramic waste aggregates for internal curing of high-performance concrete", *Cement and Concrete Research*, vol. 39, no. 5, pp. 373–381, 2009, doi: 10.1016/j.cemconres.2009.01.007.

[30] H.K. Kim, K.A. Ha, and H.K. Lee, "Internal-curing efficiency of cold-bonded coal bottom ash aggregate for high-strength mortar", *Construction and Building Materials*, vol. 126, pp. 1–8, 2016, doi: 10.1016/j.conbuildmat.2016.08.125.

[31] K. Kovler and O.M. Jensen, *Internal Curing of Concrete – State of the Art Report of RILEM TC 196-ICC*. RILEM, 2007.

[32] M.S. Afifi and M.N. Abou-Zeid, "Internal curing of high performance concrete using lightweight and recycled aggregates", The American University in Cairo, 2016.

[33] S. Seara-Paz, B. Gonzalez-Fonteboa, F. Martínez-Abella, and I. Gonzalez-Taboada, "Time-dependent behaviour of structural concrete made with recycled coarse aggregates. Creep and shrinkage", *Construction and Building Materials*, vol. 122, pp. 95–109, 2016, doi: 10.1016/j.conbuildmat.2016.06.050.

[34] I. Gonzalez-Taboada, B. Gonzalez-Fonteboa, F. Martínez-Abella, and D. Carro-Lopez, "Study of recycled concrete aggregate quality and its relationship with recycled concrete compressive strength using database analysis", *Materiales de Construccion*, vol. 66, no. 323, 2016, doi: 10.3989/mc.2016.06415.

[35] EN 197-1 :2011 The Standard for Cement – Composition, specifications and conformity criteria for common cements. Brussels, Belgium: CEN, 2011.

[36] EN 933-11 :2009 Tests for geometrical properties of aggregates – Part 11: Classification test for the constituents of coarse recycled aggregate. Brussels, Belgium: CEN, 2009.

[37] BSI – BS 8500-2 Concrete – Complementary British Standard to BS EN 206 Part 2: Specification for constituent materials and concrete. 2015.

[38] 273-RAC : Structural behaviour and innovation of recycled aggregate concrete. International Union of Laboratories and Experts in Construction Materials, Systems and Structures, 2018.

[39] DIN 4226-100:2002 Aggregates For Mortar And Concrete – Part 100: Recycled Aggregates. 2002.

[40] NBN B 15-001:2018 Concrete – Specification, performance, production and conformity – National supplement to NBN EN 206:2013+A1:2016. 2018.

[41] EN 206+A2:2021-08 Concrete – Specification, performance, production and conformity. Brussels, Belgium: CEN, 2021.

[42] EN 13670: 2009 Execution of concrete structures. Brussels, Belgium: CEN, 2009.

[43] EN 12350-2: 2019 Testing Fresh Concrete – Part 2: Slump Test. Brussels, Belgium: CEN, 2019.

[44] EN 12350-6: 2019 Testing Fresh Concrete – Part 2: Density. Brussels, Belgium: CEN, 2019.

[45] EN 12390-2: 2019 Testing Hardened Concrete – Part 2: Making and Curing Specimens for Strength Tests. Brussels, Belgium: CEN, 2019.

[46] EN 12390-3: 2020 Testing Hardened Concrete – Part 3: Compressive Strength of Test Specimens. Brussels, Belgium: CEN, 2020.

[47] M. Etxeberria, E. Vázquez, A. Marí, and M. Barra, "Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete", *Cement and Concrete Research*, vol. 37, no. 5, 2007, doi: 10.1016/j.cemconres.2007.02.002.

[48] S. Seara-Paz, B. González-Fonteboa, J. Eiras-López, et al., "Bond behaviour between steel reinforcement and recycled concrete", *Materials and Structures* , vol. 47, pp. 323–334, 2014, doi: 10.1617/s11527-013-0063-z.

[49] K. Sagoe-Crentsil, T. Brown, and A.H. Taylor, "Performance of concrete made with commercially produced coarse recycled concrete aggregate", *Cement and Concrete Research*, vol. 31, pp. 707–712, 2001, doi: 10.1016/S0008-8846(00)00476-2.

[50] T. Hastie and R. Tibshirani, *Generalised Additive Models. Monographs on Statistic & Applied Probability*. United States of America: Chapman & Hall/CRC, 1990.

[51] N. Kumar Rai, D. Saravanan, L. Kumar, P. Shukla, and R. Nath Shaw, "Chapter ten – RMSE and MAPE analysis for short-term solar irradiance, solar energy, and load forecasting using a Recurrent Artificial Neural Network", *Applications of AI and IOT in Renewable Energy*. Academic Press, 2022, pp. 181–192, doi: 10.1016/B978-0-323-91699-8.00010-3.

Wpływ wstępnie nasączanego kruszywa z recyklingu na wymagany czas pielęgnacji betonu

Słowa kluczowe: ekologiczny beton, gospodarka obiegu zamkniętego, kruszywo z recyklingu, pielęgnacja wewnętrzna

Streszczenie:

Zrównoważone budownictwo stają się coraz ważniejsze w ostatnich latach. Aby poprawić obieg materiałów w sektorze budowlanym, podjęto działania inspirowane gospodarką o obiegu zamkniętym uwzględniane w zarządzaniu odpadami klasyfikowanymi jako budowlane i rozbiórkowe. W artykule zbadano możliwość wykorzystania kruszywa z recyklingu jako nośnika wody, pełniącej funkcję pielęgnacji wewnętrznej. Eksperyment składał się z czterech różnych scenariuszy pielęgnacji i różnych proporcji kruszywa z recyklingu. Zmierzono następujące właściwości: wytrzymałość na ściskanie, gęstość, porowatość oraz wykonano analizę SEM międzyfazowej strefy przejściowej między kruszywem a stwardniałym zaczynem. Analiza wyników wskazuje na możliwość skrócenia czasu wymaganego zewnętrznego nawilżania betonu cementowego przy dziesięcioprocentowym zastosowaniu zastąpienia kruszywa naturalnego kruszywem z recyklingu. Takie dozowanie pozwala na skrócenie czasu zewnętrznej pielęgnacji wodnej, nie wpływając znacząco na ostateczną wytrzymałość betonu. Takie rozwiązanie nie zwiększa znacząco porowatości betonu i nie pogarsza strefy przejścia między kruszywem a spoiwem. Badania mikrostrukturalne SEM betonu zawierającego kruszywo z recyklingu wykazały różne rodzaje stref przejścia między nowym zaprawą a ziarnami pochodzącymi z recyklingu betonu w zależności od rodzaju ziarna. Ziarna czystego kruszywa naturalnego pochodzącego z recyklingu betonu były dobrze związane z matrycą cementową, podobnie jak nowe kruszywo naturalne. Ziarna zawierające starą zaprawę były również dość dobrze związane z nową zaprawą, ale strefa przejścia w nowej zaprawie miała wiele pustek powietrznych, co mogło być spowodowane większą porowatością ziarna starej zaprawy, która powodowała odprowadzanie wody z obszaru granicznego. Cząstki asfaltu obecne w kruszywie z recyklingu betonu były dobrze związane z nową zaprawą. Strefa przejścia była dobrze rozwinięta, bez pęknięć ani nadmiernych pustek powietrznych. Mniejsza liczba pustek powietrznych w strefie przejścia w nowej zaprawie mogła być spowodowana niższą porowatością ziaren asfaltu. Porowatość ziaren kruszywa z recyklingu wydaje się mieć kluczowe znaczenie dla tworzenia pustek powietrznych w nowej zaprawie w strefie przejścia. Mechanizm takich obserwacji może być wyjaśniony przez zmniejszenie zawartości wody w strefie przejścia przez ziarna recyklingowe o wysokiej porowatości, takie jak stara zaprawa, co wpływa na lokalne zmniejszenie spójności zaprawy. To może prowadzić do trudności w prawidłowym zagęszczaniu zaprawy w strefie przejścia. Ziarna o stosunkowo niskiej porowatości, takie jak ziarna

asfaltu, nie prowadzą do lokalnego wzrostu porowatości nowej zaprawy. Podsumowując, warto rozważyć wykorzystanie namoczonego kruszywa z recyklingu jako pielęgnacji wewnętrznej, zwłaszcza przy użyciu cementów niskoklinkierowych, ponieważ ich wymagany czas pielęgnacji jest znacznie dłuższy. Połączenie cementu niskoklinkierowego i kruszywa z recyklingu jest rozwiązaniem zgodnym z gospodarką obiegu zamkniętego. Choć rozwiązanie to wydaje się obiecujące, należy uwzględnić wpływ modyfikacji na trwałość betonu zarówno chemiczną, jak i fizyczną.

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