The Effect of Curing Conditions on Selected Properties of Recycled Aggregate Concrete

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Abstract: The paper presents the influence of different curing conditions – wet, dry and protection against water evaporation on selected properties of concretes with different amount of recycled concrete aggregate previously subjected to atmospheric CO2 sequestration. Additionally, the eco-efficiency bi and ci indexes as well as eco-durability S-CO2 index were calculated. It was found that dry conditions deteriorate the properties of concrete, especially made of blast furnace slag cement, while protection against evaporation allows to achieve results comparable to wet conditions. Moreover, for series with the highest amount of coarse recycled aggregate and after longer period of curing, the difference between the effects of wet curing and protection against water evaporation disappears. The eco-efficiency and eco-durability indexes approach confirms the beneficial effect of blast-furnace slag cement used as a binder but on condition of proper way of curing.

Keywords: curing conditions, carbonated recycled concrete aggregate, eco-efficiency indexes, eco-efficient index

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1. Introduction

Sustainability has been becoming the main idea of modern technology in civil engineering. With its increasing profits in human activity, despite time limitation in designing, it is capable to achieve continuous development in modern society. Such perception of the concept of sustainable development requires the fulfilment of the 4R principle, i.e.: reduction of material and energy consumption, reuse of products, thus extending their life expectancy, processing of products by recovering some part of raw materials as well as recovery of materials from waste products.

The construction industry is burdening the environment by, among others, exploiting deposits of natural resources and simultaneously producing large amounts of waste. The annual production of concrete – as the most popular construction material – amounts to nearly 10 billion tons per year.

Undoubtedly, significant consumption concerns mineral natural and crushed aggregates resulting from crushing of rock raw materials. This leads, among others, to depletion of natural resources, violation of ecosystems, carbon dioxide emission; the latter also resulting from cement production (in 2017 with a 4% share in global anthropogenic CO_2 emission [1], which, apart from aggregate, is a key component of concrete and despite a smaller share in the quantity of concrete compared to the share of aggregate, exceeds the emission from the exploitation of natural aggregates, production of crushed aggregates and transport of aggregates.

According to [2], production of 1 m^3 of concrete with a strength of 32 MPa generates emission from 251 kg CO_2 for CEM III – blast-furnace slag (BFS) cement – to 322 kg CO_2 for CEM I – Portland cement – while the production of 1 t of pure clinker cement is connected with the emission of 820 kg CO_2, 1t of ground granulated blast-furnace slag – 143 kg CO_2, and 1t of aggregates between 35.7 kg (basalt) and 45.9 kg (granite).

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On the other hand, the construction industry generates large amounts of waste through the reconstruction and demolition of buildings, which means that it takes up space and generates high costs for waste disposal.

A rational way to mitigate the above mentioned factors detrimental to the environment is to use recycled concrete aggregate (RCA). It is perceived as a material of a poorer quality (e.g. large porosity, water absorption, content of irregularly sharper grains, lack of uniformness, higher water demand) in comparison with the quality of natural aggregates. Therefore, the use of RCA without quality control, modification of properties and properties of concrete made with RCA, is not technologically justified. Properties of RCA can be modified in different ways, among others by: heating and rubbing [3,4], ultrasonic cleaning [5], mechanical grinding, acid cleaning [6], and even by biodeposition [7,8]. An effective method to improve the quality of recycled aggregate is to carbonate it [9,10]. In such an approach, according to the authors of this study, the concept of sequestrational carbonation can be introduced, as at the same time the effect of absorbing CO_2 from the atmosphere is achieved, which also brings environmental benefits – carbonation closes the CO_2 cycle that began with the production of cement. According to [11] 1 m^3 of concrete can absorb even more than 100 kg of CO_2. [12] in life cycle assessment, taking into consideration the carbonation studies of the recycled aggregate, they stated that per one ton of concrete, from the moment of its crushing, there were 11 kg of absorbed CO_2, which corresponds to the absorption of approximately 25 kg CO_2 per 1 m^3 of concrete. This reduces CO_2 emission by 5.5% over the entire life cycle. Surface carbonation of a model mortar contributes to the improvement of the structure of the interfacial transition zone (ITZ), especially in the case of composites, where higher values of the w/c ratio (w/c both of parent and new mortars) were used [13].

According to [14], durability of recycled aggregate concrete can be impacted by coarse aggregate replacement proportion, concrete age, w/c ratio, and moisture content in RCA.

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Mostly, a lower w/c ratio leads to a more durable concrete. Porosity is related to the apparent density of aggregate [15] and is the cause of its water absorbability, which is in the range of 3-10% [16]. Water absorbability of recycled aggregates does not necessarily have to be a technological problem in the concrete manufacturing process if it is measured correctly. If it is underestimated, the water suction effect of water contained in cement paste by recycled grains may occur [16].

As a consequence, the workability of the concrete mix deteriorates, and the hydration processes are disturbed. Therefore, two ways of adding water to concrete mix are proposed, resulting from the absorption of recycled aggregate [17]:

- compensation (use of additional water resulting from absorbability of recyclable aggregates),
- pre-soaking of RCA with water.

It is also essential to take into account the absorption time. It is unlikely to be full saturation, achieved usually after 24 hours or more, sometimes even up to 120 hours [16]. According to [18], the absorption time should be 10 minutes. However, other authors [19,20] point to a longer time (20-30 minutes). The choice of a not very long period is justified by a study of [21], who concluded that both the use of dry recycled aggregate as well as the use of aggregate in the state of full saturation, worsens frost resistance of concrete. [22] states that the use of aggregate soaked in water significantly reduces water absorbability and sorption of concrete in relation to composites, where superficially dried aggregate was used (without pre-soaking). The latter type of aggregate contributes to a higher porosity of the contact zone of the aggregate - paste (ITZ). The justification of this effect is the loosening of the contact zone structure, in which the development of C-S-H phase is blocked due to ettringite dominance.

Furthermore, the presence of water in aggregate grains is an additional source (apart from classical curing) of water during hydration processes. For this reason [23] recommend the Two-

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Stage Mixing Approach (TSMA), which is an effective way of ensuring the stability in the time of consistence of concrete mix, and achieving a higher compressive strength of concrete.

In the context of the mentioned RCA defects as well as RAC defects, it is particularly important to obtain the firm and tight microstructure of concrete, which is, among others, determined by the conditions of its curing. Improperly cured concrete achieves lower strength and durability. For this reason appropriate curing conditions of RAC seems to be more important than in the case of ordinary concrete, especially because of the different characteristics of their interfacial transition zones [24-26].

However, this does not mean that studies on the influence of curing conditions on the properties of concrete made of natural aggregates have been neglected. One of the most recent studies concerns the effect of curing conditions on properties of such concretes but produced from alkali-activated cements as binders which enable reduction of the carbon emission footprint in comparison with plain Portland cement. Special attention is focused on the influence of curing conditions on shrinkage, which to some extent determines the durability of concrete. [27,28].

The data in the literature concerning the influence of curing conditions on the properties of concrete with waste aggregates, including concrete recycled aggregate, are not numerous, and the results of researches conducted with different material assumptions as well as curing conditions may only contribute to the knowledge on this subject.

[29] have studied the effects of curing conditions in four ways: laboratory curing at 100% relative humidity and 20°C, outdoor natural curing (with a variable temperature and air RH from 25% to 88%), indoor storage (45%-65% relative humidity) and tap water storage. After using concrete recycled aggregate in 20%, 50% and 100% as a substitute for natural aggregate, the 56-day relative (relative to natural aggregate samples) compressive strength decreased slightly with an increase in the amount of recycled aggregate for all curing conditions, except for the case of curing of concrete samples stored in a chamber with RH equal to 100%. In the

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case of 100% RCA, only the external natural conditions of curing contributed to a significant decrease in strength (by 7%). In the case of modulus of elasticity, its reduction was more related to the increase in the amount of concrete recycled aggregate than to the curing method, although slightly better results were obtained for samples stored respectively: in tap water and climate chamber with RH = 100%.

Interesting insights are provided into the curing of recycled aggregate concrete in steam curing, which proved to have an adverse effect on the compressive strength of concrete. According to [30], steam treatment for 4 hours after concrete mixes were made, combined with the subsequent curing in chamber with high level of RH (>95%), resulted in a reduction of 90-day compressive strength of concrete. Although, 1-day compressive strength proved to be higher by approx. 20%, no difference was observed after 28 days. In turn, thanks to steam curing, the modulus of elasticity of recycled aggregate concrete slightly increased; such a trend was also observed in the case of splitting tensile strength.

Researches of [31] focused on the effects of steam temperature and its application time, conducted on a 28-day recycled aggregate concrete, indicated an upper temperature limit of low-pressure brewing at the level of 50°C and a steam curing application time of no more than 1 hour in order to avoid the reduction of compressive strength. The application within more than 2 hours significantly reduced the strength.

The strength and durability of concrete as key parameters determining its quality depend on the amount of cement, which should be optimised in terms of eco-efficiency. The proposal to optimise the cement content in accordance with the requirements of the designed concrete by taking into account two environmental impact factors when determining the composition of the concrete, is related to strength [32]. Index *bi* (binder intensity index), which expresses the mass of cement per 1 m^3 of concrete necessary to achieve the strength of 1 MPa ($kg/m^3/MPa$) as well as *ci* (carbon dioxide index) – being expressed as a mass of carbon dioxide emitted during the production process of such quantity of cement – will allow to achieve the strength of concrete of 1 MPa (kg/MPa).

In both cases, the lowest possible values should be obtained. The optimal solution is to produce concretes of higher strength, because if the compressive strength is higher than 50 MPa, the *bi* coefficient can reach 5 kg/m^3/MPa, while in low strength concretes (up to 20 MPa) *bi* increases even up to 13 kg/m^3/MPa. For the *ci* coefficient, the minimum value is assumed at the level of 1.5 kg/MPa (in case of using mineral additives in the production of cements), whereas in pure clinker cements it is not possible to achieve a value lower than 4.3 kg/MPa.

2. Materials and Methods

2.1. *Materials*

Two types of cement were used, Portland cement CEM I 42.5R and blast-furnace slag (BFS) cement CEM III/A 42.5N – LH/HSR/NA. Properties of binders are given in Table 1.

Table 1. Characteristics of cements used for RAC.

Characteristic	Cement type*	
	CEM I	**CEM III**
Compressive strength (MPa) after:		
2 days	29.6	14.4
28 days	56.8	52.7
Blaine specific surface (m^2/kg)	387	467
Ignition loss (%)	3.2	0.7
Insoluble parts (%)	0.9	0.3
SO_3 (%)	2.7	2.2
Cl^- (%)	0.07	0.07
Al_2O_3 (%)	5.2	7.65
Na_2O eq (%)	0.61	0,.7
MgO (%)	1.2	1.4
C_3S (%)	54.4	28.3
C_3A (%)	8.9	3.7

***** specifically: CEM I 42.5R and CEM III/A 42.5N - HSR/NA

The tap water (in accordance with EN-1008:2002. *Mixing water for concrete. Specification for sampling, testing and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concrete*) was applied for producing concrete mixes.

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The highly effective fluidifying admixture of a new generation – polycarboxylate ether superplasticiser was chosen for concrete mixes in order to improve workability. The properties of the admixture are as follows: pH – 6, specific density – 1.07 kg/dm^3, solid content – 30%, NaO_{eq}<0.8%.

Two types of aggregate – natural (sand and gravel) coming from the local sources and recycled concrete aggregate were applied. The latter was prepared about 6-year earlier before the beginning of the experiment by crushing three parent concretes with three different water to cement ratios. A laboratory jaw crusher was used for crushing. Next, the aggregate was separated on screens into fractions (4/6, 6/8, 8/12 and 12/16 mm) and placed in open boxes, located outside the building. The long storage period in variable thermal and moisture conditions contributed to the carbonation of the aggregate.

Recipes and compressive strength of parent concretes (PC) are given in Table 2. Recycled concrete aggregate (RCA) was the mix of these three parent concretes, and was applied for investigations as 0%, 50% and 100% replacement of natural coarse aggregate. The final sieve curves of natural and recycled concrete aggregate compositions used in the experiment are presented in Figure 1.

Table 2. Recipes and average compressive strength of parent concretes (PC).

Constituent	Unit	PC_1	PC_2	PC_3
CEM I 42,5 N-HSR/NA	kg/m^3	329	284	240
Water	kg/m^3	148	156	156
w/c ratio	–	0.45	0.55	0.65
Sand 0/2 mm	kg/m^3	646	645	649
Gravel 2/8 mm	kg/m^3	804	814	834
Gravel 8/16 mm	kg/m^3	536	543	556
60-d compressive strength*	MPa	61.8	45.2	36.8

* measured before crushing into aggregate

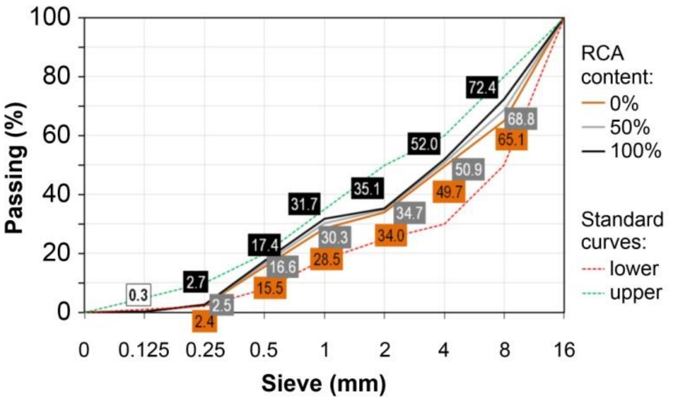

Figure 1. Final sieve curves of aggregate mixes.

2.2. *Methods*

2.2.1. Granulometric Analysis of Aggregate

Granulometric analysis conformed to the European standard EN-933-2:1999. *Test for geometrical properties of aggregate – part 2: determination of particle size.*

2.2.2. Water absorption of recycled concrete aggregate

Measurements referred to each fraction of RCA were realized according to the following procedure:

- preparing aggregate samples (for each fraction: 4/6, 6/8, 8/12 and 12/16 mm) and weighting them in mass balance,
- putting aggregate into small buckets,
- adding water to each bucket with aggregate sample,

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- waiting for 2 hours for pre-soaking aggregate samples in water,
- removing aggregate samples from the bucket (using sieve) and placing it on the towel for drying,
- waiting until the surface of aggregate will be still in wet state but without visible layer of water on the grains surface,
- rotating grains of aggregate in order to ease evaporation of surface layer of water,
- weighting aggregate in wet state.

Before measurements of water absorption RCA was superficially dried by keeping it at relative humidity of 50-60% for 2 weeks. Results of water absorption measurements of recycled concrete aggregate are presented in Table 3.

2.2.3. Concrete Recipes

Concrete recipes applied in the experiment are presented in Table 4.

Table 3. Water absorption of RCA.

Fraction (mm)	**Mass of aggregate (g)**		**Water absorption (%)**
	Dry state	**Wet state**	
4/6	400	411.3	2.8
6/8	600	614.2	2.4
8/12	800	823.6	3.0
12/16	1200	1228	2.3

Table 4. Recipes of RAC concrete series.

Constituent	**Unit**	**0% RCA**	**50% RCA**	**100% RCA**
Cement (CEM I or CEM III)	kg/m^3	386	386	386
Superplasticiser	% of CEM	0.2	0.2	0.2
w/c	–	0.45	0.45	0.45
Water	kg/m^3	175	175	175
W_{abs}*		0	11.5	23.0
W (total)		175	186.5	198
Sand 0/2 mm	kg/m^3	577	616	648
Natural 2/4 mm		0	137	278
Gravel 2/8 mm		636	316	0
Gravel 8/16 mm		636	316	0
RCA 4/6 mm	kg/m^3	0	93	184
RCA 6/8 mm		0	79	157
RCA 8/12 mm		0	139	278
RCA 12/16 mm		0	101	202

***** W_{abs} – additional water needed as the result of RCA absorbability

2.2.4. Manufacturing Concrete Mixes

The components of concretes were mixed using a paddle-type 0.05 m^3 mixer. Mixes were prepared using the two stage mixing approach proposed by [23]. The approach involves adding 50% of water (which amount was calculated according to the mass of total amount of aggregate) only with the aggregate leaving it for 30 minutes to saturation, while the remaining water is added in a traditional way. According to the authors, such method improves significantly the concrete quality. After a 30-minute break, cement was added and the composition was mixed for a 60-second period. Then the water remainder with total amount of superplasticiser was added and mixed for a 3-minute period.

2.2.5. Properties of Concrete Mixes

The slump of concrete mix was measured according to the method specified in the European standard EN 12350-2:2009. *Testing fresh concrete – Part 2. Slump flow*.

The air content in fresh concrete was tested according to the method specified in the European standard EN 12350-7:2009. *Testing fresh concrete – Part 7. Air content. Pressure methods*.

2.2.6. Properties of Hardened Concretes

The compressive strength tests were conducted on 100 mm cubic samples. After demoulding the samples were divided into three groups and subjected to three different conditions of hardening until the time of testing came: in curing chamber at RH > 95% and 20°C (WET conditions), in sheltered space at RH 50-60% and 20°C (DRY conditions), and protected against drying (preventing water evaporation) under foil at 20°C (PEV conditions). The number of samples for each examined series of concrete was five.

The obtained results were recalculated to the case of 150 mm cubic samples and these ones were analysed further. Testing of compressive strength was carried out according to the European standard EN 12350-3:2009. *Testing hardened concrete – Part 3. Compressive strength of test specimens*.

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Testing of sorption as a useful parameter for assessment of concrete durability is proposed, among others, by [33] and alternatively by the European standard EN 13057:2002. *Products and systems for the protection and repair of concrete structures. Test methods. Determination of resistance of capillary absorption*. Sorption were conducted on 100 mm diameter cylindrical samples. The number of samples for each examined series of concrete was four. Each sample was dried at 50°C for 5 days in the laboratory dryer. In the subsequent stage they were put onto a plastic mesh to allow for free water capillary sorption on the entire base surface without a direct contact with the container bottom. At the beginning, water level was equal to 1/5 of the sample height. Measurements were performed after: 1, 5, 10, 20, 40, 60 and 75 minutes in order to evaluate the rate of sorption. Calculations of saturated water sorption (S) were done according to the equation (Eq. 1) given below [33]:

$$S = \left(\frac{\Delta M_t}{t^{\frac{1}{2}}}\right) \cdot \left(\frac{d}{M_{sat} - M_o}\right)$$

where: S is sorptivity (mm/h$^{0.5}$); ΔM – change of mass with respect to dry mass (g); M_{sat} – saturated mass of concrete (g); M_o – dry mass of concrete (g); d – sample thickness (mm); t – period of absorption (h).

At regular time intervals mass of absorbed water is determined using a balance. Measurements are terminated after 75 minutes and specimens are then vacuum-saturated and soaked in water in order to determine the effective porosity. Plotting the mass of water absorbed against the square root of time gives a linear relationship. The sorptivity of concrete is calculated from the slope of the straight line plot. According to [33] acceptable limit is <9 mm/h$^{0.5}$ (<6 mm/h$^{0.5}$ for laboratory conditions).

Saturation degree (sd_i) was determined using the results of the sorption test (based on the difference between the weight of saturated samples and samples dried at 50°C for 5 days) according to the formula (Eq. 2):

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$$sd_i = \left(\frac{M_{sat} - M_o}{M_o}\right) \cdot 100\%$$

where: M_{sat} is saturated mass of concrete (g) and M_o mass of concrete sample dried at 50°C (g).

2.2.7. Eco-efficiency and Eco-durability Indexes

The average emission value of CEM I cement taken to calculation of *bi* and *ci* [32] is 761 kg CO_2/ton while CEM III is 360 kg CO_2/ton (data from production in one of Polish cement plants). Furthermore, for CEM III series, the *ci* coefficient was also calculated in an alternative configuration, i.e. taking into consideration the emission associated with the production of ground granulated blast-furnace slag (143 kg CO_2/ton – according to [2]).

The authors of this paper have used a method proposed by [33] and described in chapter 2.2.6 as the basis for the determination of eco-durability (S-CO_2 index). It is used to determine one of the three so-called durability indices (i.e. sorption), next to oxygen permeability index (OPI) and chloride conductivity (CC). The calculation of the proposed $S\text{-}CO_2$ index should be performed in accordance with the formula (Eq. 3):

$$S\text{-}CO_2 = \frac{1}{E_{CO2} \cdot S}$$

where: E_{CO2} – CO_2 mass emitted to obtain 1 m^3 of concrete (t/m^3), S – sorptivity ($mm/h^{0.5}$). Higher index values indicate higher eco-durability.

2.2.8. ANOVA and Tukey's Test

Analysis of variance (ANOVA) was performed for density and compressive strength results. Additionally, differences were checked using post-hoc Tukey's test at 95% confidence level (alfa=0.05). Statistical calculations were performed using Statistica Software, licence no.: JPZ612B037802AR-P.

3. Results and Discussion

3.1. *Fresh Mix Properties*

Slump and air content measurements for concrete mixes made of CEM I and CEM III in relation to RCA participation is presented in Table 5. Slump of concrete mix CEM I and 100% of RCA content was the lowest and significant loss of workability compared to concrete mixes made of CEM III was observed while at 0% and 50% of RCA results of slump measurements are similar in both cases. And air content results show that more RCA content results in the higher air content. This is clearly linked to the presence of air pores in the structure of the recycled aggregate. However, the differences are not significant, which can be justified by the use of carbonated aggregate, which has a lower porosity than the material obtained immediately after crushing.

Table 5. Slump and air content of RAC mixes.

Cement type	**RCA content (%)**	**Slump (mm)**	**Air content (%)**
CEM I	0	135	3 .6
	50	150	4 .4
	100	58	3 .8
CEM III	0	165	2 .8
	50	130	4 .3
	100	120	4 .9

3.2. *Density*

Density of concretes made of CEM I and CEM III after 90 days of hardening in relation to RCA participation is presented in Figure 2. Density is slightly higher for RCA concrete series made of both CEM I and CEM III in the case of wet conditions of hardening comparing to dry conditions of curing. The trend refers to both 0% and 50% RCA. However, concretes including 100% RCA presented similar density in the case of both WET and PEV conditions.

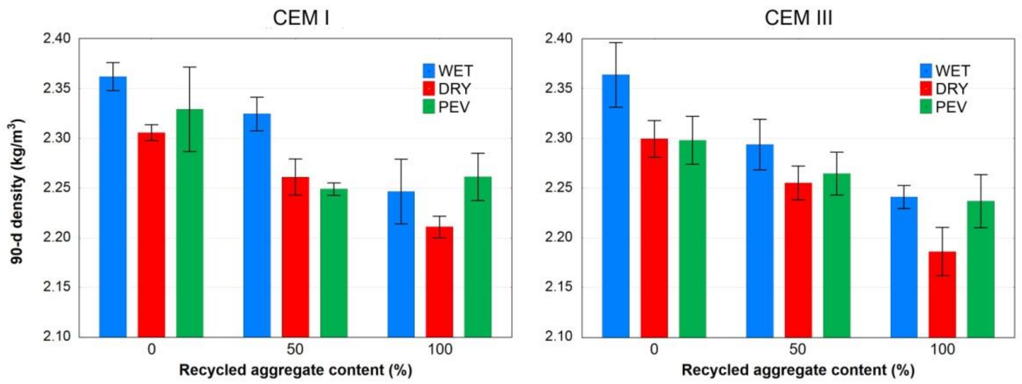

Figure 2. Average density of 90-day concrete.

3.3. *Compressive strength*

Compressive strength results of concretes made of CEM I and CEM III after both 28 and 90 days in relation to RCA participation are presented in Figure 3. Compressive strength differences calculated on the base of 28 and 90 days results are shown in Figure 4. The results of Tukey's post-hoc test for 90-day strength are presented in Table 6. Wet conditions of hardening are better for concretes made of both CEM I and CEM III, but after 90 days more effective in the case of CEM I used as a binder. PEV is more effective way of curing for both cements in the case of 0% and 100% RCA while less effective is the influence on compressive strength of concrete with 50% RCA. Probably the amount of water delivered during pre-soaking for samples with 50% RCA may not be sufficient to prevent water consumption during hydration processes. After some time, the water no longer reaches the paste from the outside or from the recycled aggregate. In such a situation, the process of hydration of samples treated with PEV is similar to the process of hydration of samples treated under WET conditions – with water deficit, which contributes to lower strength. On the other hand, increasing the share of water from pre-soaking in the series from 100% RCA (from 11 to 22 kg/m^3) eliminates this unfavourable effect.

Table 6. Tukey's test results of 90-day compressive strength (f_c 90-d) of RAC series.

Cement type	**RCA (%)**	**Curing conditions**	**f_c 90-d (MPa)**	**Homogenous groups**							
				1	2	3	4	5	6	7	8
III	100	DRY	39.4	***							
III	0	DRY	41.8	***	***						
III	50	DRY	41.8	***	**						
III	50	PEV	42.3	***	***						
I	50	PEV	45.2		***	***					
I	0	DRY	46.1			***					
III	0	PEV	46.9			***	***				
I	100	DRY	47.5			***	***	***			
I	50	DRY	47.6			***	***	***			
I	0	PEV	48.5			***	***	***			
III	0	**WET**	50.0				***	***			
III	100	**WET**	50.0				***	***			
III	50	**WET**	50.2				***	***			
III	100	PEV	50.5					***	***		
I	0	**WET**	53.7						***	***	
I	100	PEV	55.7							***	***
I	50	**WET**	57.3								***
I	100	**WET**	57.6								***

alfa = 0.05, MS Error = 2.1118

Dry conditions of hardening turn out to be more hazardous for compressive strength of concretes made of CEM III than those made of CEM I. Statistically, wet conditions of hardening made compressive strength higher (strength of samples of all 6 series treated under WET conditions exceeded the value of 50 MPa), while dry conditions made compressive strength lower. 100% participation level of recycled concrete aggregate brought similar 90-day compressive strength of concrete cured with use of PEV way in comparison to the compressive strength of concrete cured in water and it referred to both cements applied as binders (both series of concretes treated with the PEV method and with 100% RCA constitute one homogeneous group with corresponding series of concretes of the WET group with 50% and 100% RCA). That effect is connected with internal curing process, because of bigger (than for 50% RCA) amount of water uptaken by RCA during pre-soaking procedure.

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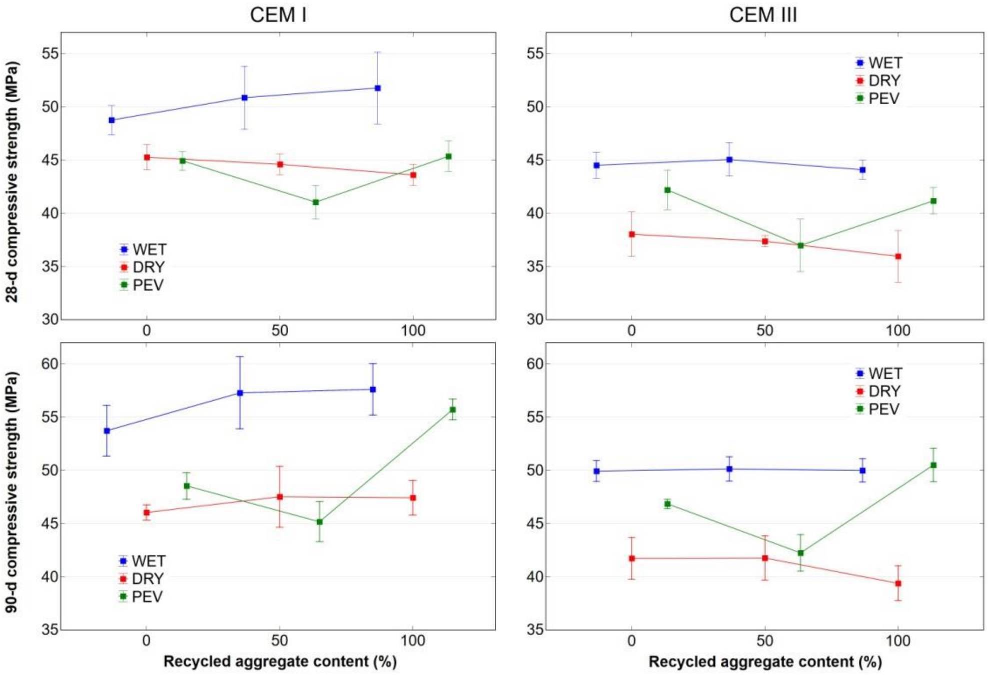

Figure 3. Compressive strength of concrete after 28 and 90 days.

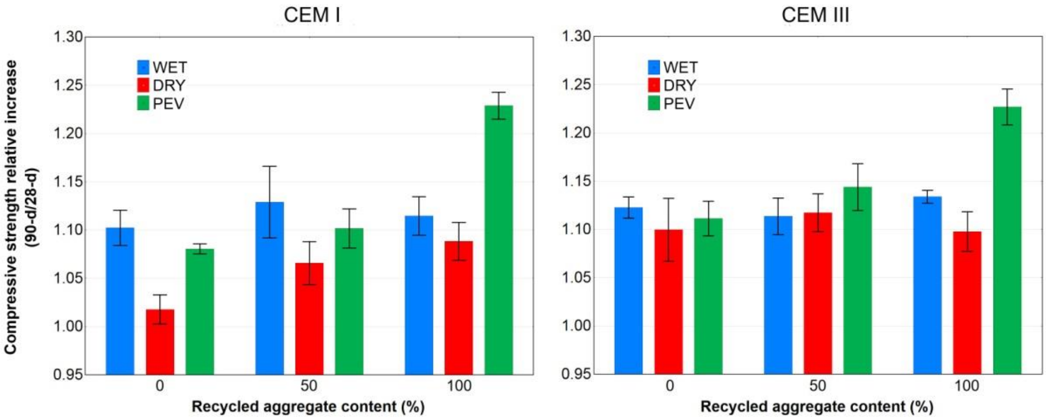

Figure 4. Compressive strength increase between 28 and 90 days.

3.4. *Sorption*

Sorption results of concretes made of CEM I and CEM III in relation to RCA participation is presented in Figure 5. Wet conditions of hardening and PEV way of curing were more suitable for concretes made of both CEM I and CEM III. In the case of CEM I as a binder, all conditions of hardening were more similar in comparison with CEM III. For CEM III used as a binder, dry curing conditions were more hazardous comparing to CEM I but on the other hand wet curing condition are slightly better for CEM III. Lower sorption for concrete made of blast-furnace slag cement follows the denser microstructure due to using just this binder, but only under the condition of proper curing (WET or PEV). DRY way of curing should be definitively excluded.

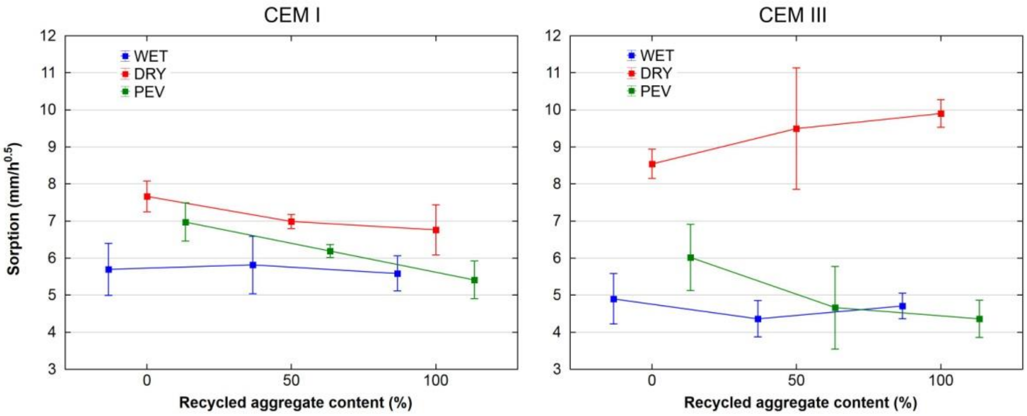

Figure 5. Sorption of concrete.

3.5. *Saturation degree*

Saturation degree of concretes made of CEM I and CEM III in relation to RCA participation is presented in Figure 6. Wet curing condition were more suitable for concrete made of both CEM I and CEM III. Moreover, CEM III are more susceptible to dry curing conditions than CEM I.

3.6. *Eco-efficiency and eco-durability indexes*

The values of *bi* as well as *ci* and $S\text{-}CO_2$ are presented in Table 7. The highest, i.e. the least favourable, *bi* values were obtained mainly for concrete treated under DRY conditions, and the lowest under WET conditions (in both cases regardless of the RCA) and with 100% RCA under PEV conditions. Higher *bi* values were obtained for CEM III, which results from lower strength of the series with this cement. The *bi* index value should be treated as a supplementary information, which indicates both the quality of cement and the conditions of concrete curing. From the point of view of CO_2 emission during the cement production process, the more significant eco-efficiency coefficient is *ci*. The calculations show that *ci* index values are more favourable for CEM III due to the use of granulated blast furnace slag (BFS cement), which constitutes approximately 50% of the composition, and the best results were obtained for series treated under WET conditions. Only slightly higher were the values of the jest *ci* coefficient, when the emission associated with the production of ground granulated blast-furnace slag was taken into consideration. When considering the $S\text{-}CO_2$ index, the use of CEM III cement, regardless of whether the CO_2 emission associated with the production of ground granulated blast-furnace slag is taken into account or not, is more advantageous.

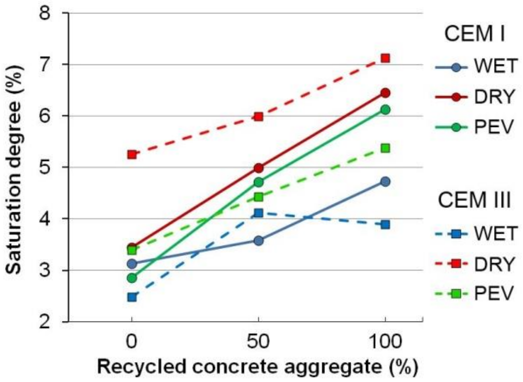

Figure 6. Saturation degree of concrete.

Table 7. Indexes of eco-efficiency *bi* ($kg/m^3/MPa$), *ci* (kg/MPa), and eco-durability $S\text{-}CO_2$ ($1/(t_{CO2}/m^3 \cdot mm/h^{0.5})$).

Cement type	RCA content (%)	Curing conditions								
		WET			DRY			PEV		
		b_i	c_i	$S\text{-}CO_2$	b_i	c_i	$S\text{-}CO_2$	b_i	c_i	$S\text{-}CO_2$
CEM I	0	7.2	5.5	0.231	8.4	6.4	0.172	8.0	6.0	0.189
	50	6.7	5.1	0.226	8.1	6.4	0.188	8.5	6.5	0.212
	100	6.7	5.1	0.201	8.1	6.2	0.204	6.9	5.3	0.249
CEM III*	0	7.7	2.8	0.567	9.3	3.3	0.325	8.2	3.0	0.462
	50	7.7	2.8	0.636	9.3	3.3	0.293	9.1	3.3	0.596
	100	7.7	2.8	0.590	9.8	3.5	0.280	7.6	2.8	0.637
CEM III**	0		3.0	0.526		3.6	0.302		3.2	0.428
	50		3.0	0.590		3.6	0.270		3.5	0.553
	100		3.0	0.547		3.8	0.260		3.0	0.591

* - taking into account only emission of CO_2 resulting only from cement production
** - taking into account emission of CO_2 resulting from the production of cement and ground granulated blast furnace slag

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4. Conclusions

Based on the obtained results the following conclusions have been formulated:

1. Concrete mix made of CEM I turned out to be more sensitive to slump loss at the maximal content of RCA in comparison to concrete mix with blast furnace slag cement as a binder. However, the worst influence of RCA presence on air content in concrete mix occurred when blast-furnace slag cement was used.
2. Conditions of hardening influenced sorption of concrete being definitely better for wet curing and protection against drying (water evaporation) and in both cases for CEM III than CEM I as a binder.
3. Dry conditions of hardening were perceived as more hazardous for compressive strength in the case of concretes made of both cement CEM I and CEM III.
4. The protection against drying (water evaporation) can be sufficient for concrete with high amount of RCA than for ordinary concrete taking into account compressive strength and in comparison to wet conditions of curing.
5. Statistical analysis showed the influence of RCA participation on compressive strength was less meaningful than dry curing conditions, which in obvious way are improper.
6. Binder intensity index *bi* occurred to be slightly higher for CEM III than CEM I. However carbon dioxide emission index *ci* was better in the case of blast furnace slag cement used as a binder.
7. In terms of durability, the authors of this paper propose eco-durability index S-CO_2, especially for composites with recycled aggregate. In the conducted researches, more favourable values of this index were obtained for concrete with blast-furnace slag cement, but on condition of proper curing.

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