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Impact of Fine Fractions of Recycled Aggregate on Selected Properties of Cement Mortars

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1. Introduction

One of the most serious problems of the steadily developing economies is the high amount of waste from the construction sector, which in 2016 was equal to 36.4% of the total quantity of waste generated in UE countries (Eurostat 2016). Directive on Waste (Directive 2008/98/WE), points to the requirement of waste prevention but when this is not possible requires the creation of conditions necessary to implement the recycling policy focused on selective collection and then the recycling process itself. If it is not possible to recover the material for its reusing (when it is harmful to human health and life – e.g. reusing asbestos), then a safe disposal procedure or other methods of recovery (e.g. energy recovery) should be applied. Recycled aggregate, especially recycled concrete aggregate (RCA), is increasingly used in the production of concrete and mortar. Numerous authors point out the potential benefits and disadvantages of its usefulness (e.g. Poon et al. 2002, Eguchi 2007, Evangelista 2007, Etxeberria 2007).

The basic characteristics of RCA refers to the size of its fraction. Coarse recycled aggregate (fractions above 4 mm) is more willingly used in cement composites, and the main benefit of its use is the protection of raw material resources and even CO_2 absorption during carbonation process, which can be intensified after crushing of waste concrete (Zając & Gołębiowska 2012, Mądrawski et al. 2013, Grabiec et al. 2015). Unfortunately, a serious disadvantage of coarse aggregates is the fact that after crushing process irregular and elongated grains, polluted with dust from smaller fractions, are obtained. Such grains deteriorate the rheological properties of concrete mix. Also, the presence of old cement slurry results in increased porosity of aggregate, lower density, and increased water absorption.

Despite the fact that coarser fractions are more commonly used, some mortar properties can be improved by adding fine aggregates. Silva et al. (2009), present the effect of 5% and 10% participation (by volume) of brick dust addition with 0-0.15 mm grain size on the properties of cement mortar. It was found that the addition of brick dust improves not only the compressive strength but also the flexural strength of the cement mortar. The results obtained for mortars with brick dust were compared with the results for cement mortars in which limestone, red gravel and mica-slate as well as granulite were used (Angelim et al. 2003 cited by Silva et al. 2009). It was found that only ceramic dust contributes to the increase in compressive and flexural strength, whereas for mortars with the addition of gravel powder, shale dust and granite powder (in the amount of 10% by volume) the decrease in strength should be taken into account. Silva et al. (2009) indicated an almost linear function of water absorption coefficient decrease (during capillary absorption) with an increase in the amount of red brick powder. For samples with addition of 10% of brick powder the decrease of water vapour permeability and water permeability was also obtained. Of course, lower water vapour permeability in case of mortars is not always a positive feature (when it makes it difficult to remove moisture from a building barrier, e.g. plaster), but low values obtained in water penetration test is a most desirable property, especially for structures such as swimming pools, tanks.

Zhao et al. (2015) focused on the use of recycled concrete sand (RCS) with a grain size lower than 5 mm for mortar, which they divided into four fractions. The percentages of RCS were selected in such a way that the resulting recycled grading curve coincides with the grading curve of the natural sand. The volume of RCS replaced natural sand partially or completely. Three groups of series were prepared in order to: (I) verify the difference between the properties of mortar with pre-soaked aggregate (by adding water to the aggregate itself before mixing the other ingredients) and dry aggregate without soaking, with three different water and cement coefficients (0.5; 0.55 and 0.6), (II) determinate the effect of the RCS participation on the mechanical properties of mortar at a constant w/c = 0.5. (III) formulate the effect of each fraction of recycled sand on the mortar properties at two w/c levels (w/c = 0.5 and w/c = 0.6). In the third group all aggregate fractions were previously pre-soaked in water for 24 hours. Compressive strength for mortars with dry RCS was higher than for mortars with water-saturated RCS and this was valid for all investigated w/c coefficients. However, the thickness of the Interfacial Transition Zone of aggregate for pre-saturated RCS was higher than for aggregate in dry state. As the amount of RCS in the mortar increased, the compressive strength decreased and the relationship was quasi linear. The most unfavorable influence on mortar properties had the smallest fraction of aggregate (0-0.063 mm), which is a result of higher content of paste, connected with higher water absorption and lower mechanical parameters.

The degree of mortar fluidity – as a criterion for the quality evaluation of mortars containing fine RCA – was proposed by Kumar (2019). Three fixed values of the flow were proposed: 110±2.5 mm, 135±2.5 mm and 160±2.5 mm. It turned out that in order to obtain the same flow in the samples, the water content must be higher for the pre-soaked aggregate than in the control samples. Moreover, the setting time of the pre-soaked mortar was shorter than the setting time of the reference mortar. In addition, the values of the strength parameters of the RCA samples are worse for the higher participation of recycled aggregate. Moreover, more recycled fine aggregate leads to lower content of chemically bound water, higher porosity in the mortar, and consequently higher water absorption and sorption (compared to the control mortar).

The pressaturation technique was also used by Katzer & Domski (2013). This procedure proved to be useful and increased the workability and required consistency of mixtures with ceramic waste. The second benefit was an increase in compressive strength compared to ceramic waste itself.

In the studies presented by Corinaldesi & Moriconi (2009) three types of fine aggregate were used: brick, RCA and mixed aggregate. The highest values of compressive strength were recorded in series with natural aggregate (reference series). Significantly worse results (but close to each other) of compressive strength were obtained for mortar samples made of RCA, brick and mixed aggregate. In the case of flexural strength tests (after 28 days of hardening) the situation was slightly better - the highest values were found for mortars with RCA, then for mortars with natural sand. The lowest values of flexural strength were recorded for mortar with mixed aggregate and slightly higher values for mortar with brick sand.

Dobiszewska (2016) also obtained results confirming the positive influence of fine aggregate (in case of waste basalt powder) on the mortar and concrete strength. The highest increase in compressive strength was observed when 30% of natural sand was replaced (by mass) by waste aggregate. It reached even 40% after 28 days and 60% after 56 days. The remaining series of mortars, in which sand mass was replaced by basalt powder (10% and 20%), were also characterized by higher values of compressive strength than the control sample. The explanation for the increased strength is the fact that basalt powder has a smaller particle size than natural sand grains, so it tightens the structure of the cement matrix, reducing the total volume of pores in the mortar, pore diameter and porosity of the structure. The effect of filler on mortars was also confirmed by lower water absorption in each series with the addition of basalt powder compared to the results of the reference series.

The research conducted by Domski & Głodkowska (2017) have also confirmed that the properties of cement composites containing waste sand as a fine aggregate meet the requirements for building materials and can be used on a larger scale. This can solve problems related to the depletion of natural resources and reduction of material waste.

2. Material and methods

Two types of cement were used in the research: CEM I 42,5 N and CEM III/A 42,5 N LH/HSR/NA. The proportions of ingredients were as for standard mortars (EN 197), i.e. 450 g of cement, 225 g of water and 1350 g of aggregate (gradation presented in Fig. 1a), modifying only the proportions of natural and RCA within a given fraction (Table 1). 5-level Central Composite Design (CCD) for 3 independent factors was implemented, i.e. the volume participation of recycled grains in the total volume of aggregates in each of the three groups of fractions: 0/0.25 (designed as *f*), 0.25/1 (*m*) and 1/2 mm (*c*). Each factor was present in a given group at levels based on rotatability of CCD: 0% (level -α), 17 (level "-1"), 42 (central level), 67 (level "+1") and 84% (level +α), which corresponded to the share of natural aggregates: 100, 83, 58, 33 and 16% respectively. Three repetition of central series (no. 5, 10 and 17 – series with RCAs amount equal to 42% in each group of fraction) was applied (which is a basic rule of CCD). Fig. 1b presents an example of 2-dimensional CCD. Statistical analysis was performed using Statistica Software, licence no.: JPZ612B037802AR-P.

After mixing the all components, flow diameter (measured on the flow table after 30 compactions) was investigated. Then the mixes were placed and compacted in moulds (triple 4x4x16 mm). After 28 days compressive strength was measured (Fig. 2) using 6 samples per each series (with testing area of 40x40 mm), followed by a water absorption test (three 40x40x40 mm samples).

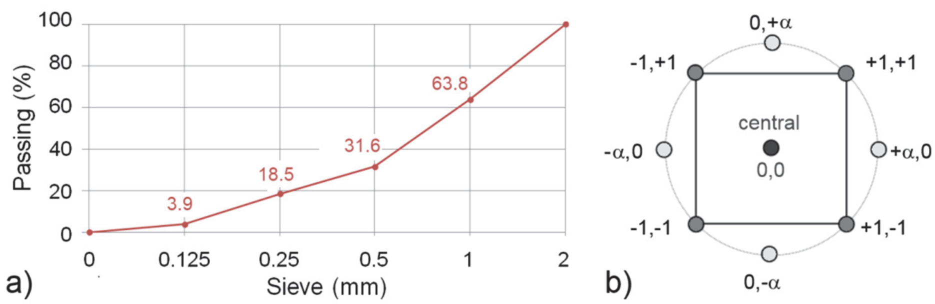

Fig. 1. Composition of natural aggregate (a) and the scheme of CCD approach (b)

Table 1. Mixture composition with weights of individual fractions

Series	RCA total	f – 0/0.25 mm			m – 0.25/1 mm			c – 1/2 mm		
		Nat	Rec		Nat	Rec		Nat	Rec	
	(%)	(g)	(g)	(%)	(g)	(g)	(%)	(g)	(g)	(%)
1	17.0	208.3	37.7	17	507.2	91.8	17	405.6	73.4	17
2	57.7	208.3	37.7	17	201.7	361.5	67	161.3	289.1	67
3	44.3	82.8	148.4	67	507.2	91.8	17	161.3	289.1	67
4	48.9	82.8	148.4	67	201.7	361.5	67	405.6	73.4	17
C-5*	42.0	145.5	93	42	354.4	226.6	42	283.4	181.2	42
6	35.1	208.3	37.7	17	507.2	91.8	17	161.3	289.1	67
7	39.6	208.3	37.7	17	201.7	361.5	67	405.6	73.4	17
8	26.3	82.8	148.4	67	507.2	91.8	17	405.6	73.4	17
9	67.0	82.8	148.4	67	201.7	361.5	67	161.3	289.1	67
C-10*	42.0	145.5	93	42	354.4	226.6	42	283.4	181.2	42
11	34.2	251	0	0	354.4	226.6	42	283.4	181.2	42
12	49.8	40.1	186.2	84	354.4	226.6	42	283.4	181.2	42
13	23.0	145.5	93	42	611	0	0	283.4	181.2	42
14	61.0	145.5	93	42	97.8	453.2	84	283.4	181.2	42
15	26.8	145.5	93	42	354.4	226.6	42	488.7	0	0
16	57.2	145.5	93	42	354.4	226.6	42	78.2	362.5	84
C-17*	42.0	145.5	93	42	354.4	226.6	42	283.4	181.2	42

* 3 identical series with amount of each RCA fraction equals to central (C) level of 42% (according to 5-level CCD for 3-factors at least three C series are needed)

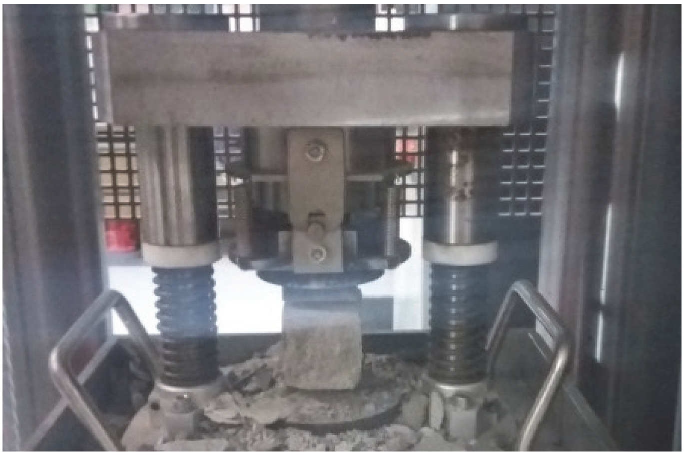

Fig. 2. Compressive strength test

3. Results

The results of flow diameter (which is a measure of the degree of consistency) and water absorption of mortars are presented in Table 2.

Table 2. Results of average flow and water absorption of mortars

Series	RCA total (%)	Participation of *f-m-c* (%)*	Flow diameter (mm)		Water absorption (%)	
			CEM I	CEM III	CEM I	CEM III
1	17.0	17-17-17	235	235	**9.4± 0.1**	**9.2**±0.7
2	57.7	17-67-67	175	150	10.5±0.1	12.6±0.6
3	44.3	67-17-67	175	175	10.1± 0.1	12.5±0.4
4	48.9	67-67-17	135	170	10.9±0.3	11.6±0.7
5-C	42.0	42-42-42	210	210	10.2±0.1	12.6±0.3
6	35.1	17-17-67	255	200	9.9±0.2	10.6±0.2
7	39.6	17-67-17	230	180	10.0±0.1	11.4±0.2
8	26.3	67-17-17	245	205	9.7±0.1	10.8±0.3
9	67.0	67-67-67	**110***	**130***	**11.3± 0.1**	**13.3**±0.9
10-C	42.0	42-42-42	200	200	9.5± 0.2	12.3±0.2
11	34.2	0-42-42	**270***	**240***	9.5±0.1	11.3±0.8
12	49.8	84-42-42	190	150	10.9± 0.1	10.9±0.5
13	23.0	42-0-42	260	215	**9.4**±0.1	9.8±1.0
14	61.0	42-84-42	140	**130***	10.7± 0.1	11.6±0.6
15	26.8	42-42-0	255	215	9.7±0.1	12.4±0.1
16	57.2	42-42-84	165	180	10.5±0.3	12.3±0.6
17-C	42.0	42-42-42	220	170	10.2±0.2	12.0±0.6

* Participation of RCA in each of aggregate group (not in the total amount of RCA)
** The lowest and highest values obtained for a given cement were marked

3-factor square regression model (taking into account all three independent factors, i.e. content of *f*, *m* and *c* fraction groups) was estimated for compressive strength of mortars. Statistical analysis showed the lack of relevance of some parameters of the model. Ultimately, the regression equations took the following forms (for CEM I and CEM III respectively):

- $compr\_str = 53{,}232 + 4{,}452\ f - 3{,}670\ f^2 - 1{,}663\ m - 2{,}558\ c - 3{,}175\ c^2 - 7{,}002\ fm - 3{,}323\ fc - 4{,}391\ mc$,
- $compr\_str = 51{,}918 - 1{,}803\ f - 1{,}971\ m - 4{,}021\ c - 6{,}780\ c^2 - 3{,}532\ fc$.

Values of R^2 are not high (0.667 and 0.637 respectively), however, they are similar for both cements. It should be pointed out that the value of R^2 should be interpreted each time in the context of the research area (a characteristic feature of RCA is the randomness of properties within each grain).

Figures 3-5 show the visual presentation of the compressive strength tests, but each figure shows the response area for 2 of 3 fraction group pairs: f (0/0.25 mm), m (0.25/1 mm) and c (1/2 mm). Each time the level of RCA amount for the third group is constant and is equal 42% (value of central level in 5-level CCD). The flow results as the function of total RCA content are presented in Fig. 6.

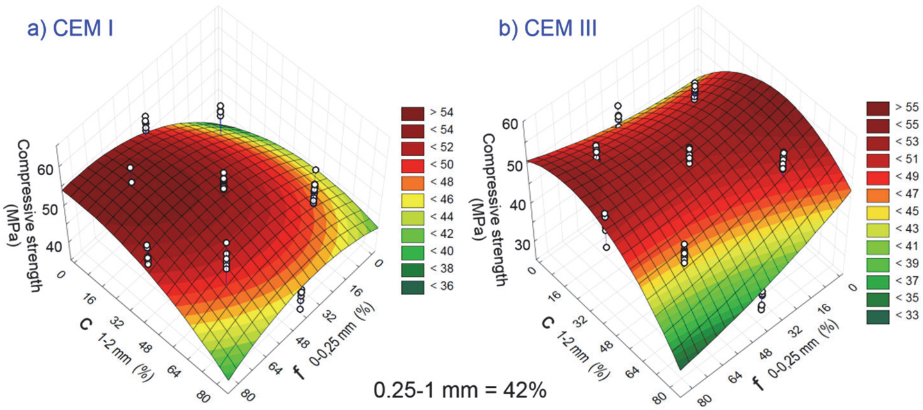

Fig. 3. Compressive strength results (relation of f and c RCA fractions; quantity of m is equal to 42%)

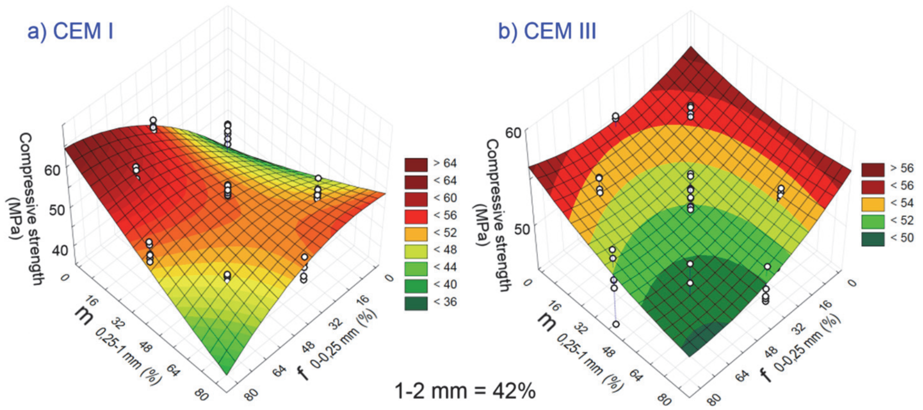

Fig. 4. Compressive strength results (relation of *f* and *m* RCA fractions; quantity of *c* is equal to 42%).

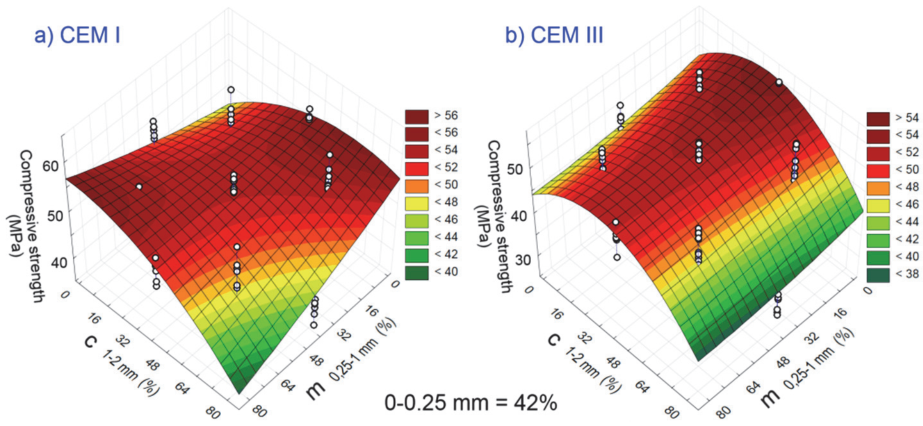

Fig. 5. Compressive strength results (relation of *m* and *c* RCA fractions; quantity of *f* is equal to 42%)

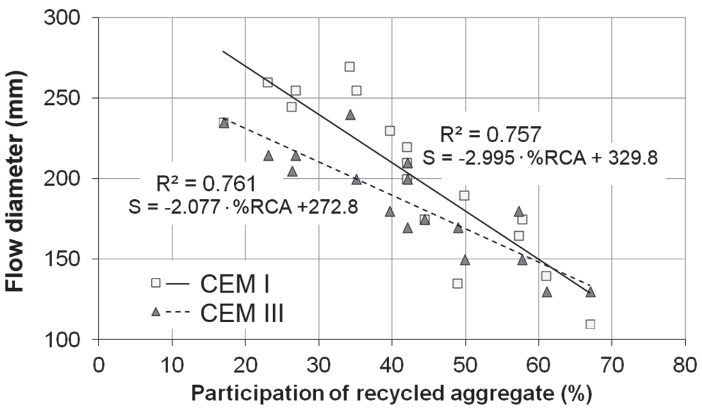

Fig. 6. Relation of flow results of mortars as the function of total mass content of RCA

4. Discussion

The results of the flow diameter (Table 2) show that the flowability is strongly influenced by the total amount of recycled aggregate. A significant linear correlation can be observed (Fig. 4) both for mortars with CEM I cement (R^2 = 0.757) and with CEM III (R^2 = 0.761). With the increase in the total amount of recycled aggregate, the flow of the mix decreases (worse workability is achieved). This is logical because recycled aggregate is more water-absorbable than natural aggregate.

Analysing the results of the water absorption tests (Table 2), it can be observed that the maximum values were obtained for the series with the highest participation of recycled aggregate (67%). It amounted to respectively: 13.3% for CEM III cement and 11.3% for CEM I. The effect on mortar absorbability, which Dobiszewska (2016) achieved in her studies for basalt powder, is not confirmed. The lowest water absorption values were obtained for mortars with the total amount of recycled aggregates equal to 17% – it reached 9.4% and 9.2%, for CEM I and CEM III respectively.

The results of the compressive strength tests presented in Fig. 3a (for mortars made of CEM I cement and containing a constant 42% participation of *m* RCA fraction in the mixture) showed that the highest values were obtained with a high amount of the smallest *f* RCA fraction and a minimum amount of 1/2 mm grains. With an increase in the proportion of the latter and a decrease in the weight of fine aggregate, the strength also decreased. This can be explained by four different effects. Firstly: when the amount of *f* is higher, there is (locally) a higher water uptake from the paste than in the case of *c* fraction (due to large specific surface area of *f* and resulted water content). The reduction of the mortar's w/c ratio results in reinforcement in terms of strength parameters. Secondly: fine recycled aggregate also has a certain amount of unreacted cement from the old matrix. When it comes into contact with water again, additional hydration may occur (in addition to the hydration of cement added as a component of the mortar), which also can improve strength. Thirdly, in the case of a large amount of fine grains and a small amount of *c* fraction, the role of stress transfer to the compression of natural aggregate (1/2 mm) increases. Fourthly: there is an effect of sealing the cement matrix and reducing the total volume of mortar pores, porosity and pore dimensions in the structure, in accordance with Dobiszewska (2016).

In the case of interaction of the *f* (0/0.25 mm) and *m* (0.25/1 mm) fractions of RCA, the higher participation of both fractions in the mortar resulted in a deterioration of compressive strength, regardless of the cement used (Figures 4a, 4b). The same happened in the case of *c* fraction and *m* fraction (Figures 5a, 5b). The higher the amount of these fractions in the composition, the lower the strength values, while using CEM I the highest strength was recorded with a low participation of RCA in the 1/2 mm fraction (up to 17%) and at the same time a very high participation in the *m* fraction (about 67-84%) and the reverse ratio of these fractions (Fig. 5a). In the case of CEM III, the dominant influence on the compressive strength was exerted by the RCA of the 1/2 mm fraction, while the strength did not depend so much on the amount of the RCA 0.25/1 mm fraction (Fig. 5b).

It can be stated that the studies of the impact of fine (up to 2 mm) RCA confirmed the studies of Kumar (2019) and Zhao et al. (2015), because the strength values are lower when the higher is the participation of RCA in the mortar. However, the effect of each grain fraction group is different and within certain limits of the volumetric participation use of fine RCA does not necessarily mean that the mortar's properties must be significantly affected.

5. Summary

Presented results confirmed the significant influence of fine RCA on the compressive strength and flow of cement mortars. However, its influence was not shown in the water absorption test (differences were not noticed). It depended mainly on the amount of RCA and not on the grain size, which was found in the occurrence of correlation between the total amount fine aggregate and the mortar flowability. Other conclusions can be drawn in case of compressive strength results – it is not possible to determine the positive effect of fine RCA on strength, as Dobiszewska (2016) and Salvini et al. (2009) stated. It is also not only a negative influence, as Corinaldesi and Moriconi (2009) claim. It seems that a very important factor is the selection of appropriate proportions of the fine RCA fractions in order to achieve the desired effects of i mortar strength. It can also be suggested that the right approach is not to use more than 30% RCA, which is often reported in the relevant literature sources.

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Abstract

The paper presents the influence of fine recycled concrete aggregate (RCA) on selected physical and mechanical parameters of cement mortar. RCA was divided into three groups: fine (0/0.25 mm), medium (0.25/1 mm) and the thickest fraction 1/2 mm. The investigations confirmed a significant correlation between the total amount of RCA and the obtained flow for the mixtures and compressive strength. Results showed that the fine RCA should be separated into subgroups as not only total RCA amount but quantity of RCA in each subfraction can have varying influence on mortar properties.

Keywords:
fine fractions, recycled concrete aggregate, cement mortar

Wpływ drobnych frakcji kruszywa z recyklingu na wybrane właściwości zapraw cementowych

Streszczenie

W artykule przedstawiono wpływ drobnego kruszywa recyklingowego (ang. RCA) na wybrane parametry fizyczne i mechaniczne zapraw cementowych. Kruszywo podzielono na trzy podgrupy frakcyjne: drobne (*f*: 0/0,25 mm), średnie (*m*: 0.25/1 mm) oraz najgrubszą frakcję *c*: 1/2 mm. Badania potwierdziły istotne powiązanie pomiędzy sumaryczną ilością RCA a uzyskiwanym rozpływem mieszanek i wytrzymałością na ściskanie. Uzyskane rezultaty wskazały również na to, iż w obrębie RCA warto wydzielić podgrupy frakcji, gdyż nie tylko sumaryczna ilość, ale również udział RCA w danej podgrupie może mieć znaczący wpływ na właściwości zapraw.

Słowa kluczowe:
drobne frakcje, kruszywo recyklingowe z betonu, zaprawa cementowa