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A fine fraction from the recycled concrete as an addition in the cement composites*

Key words: cement composites, recycling, fine fraction, calcination, thermal analysis

Introduction

Using technologies to recover building materials from waste is justified both economically – recycled materials are cheaper, and environmentally – obtaining natural resources and a capacity of landfills are limited (Sas and Sobańska, 2010). For this reason, the use of waste aggregate from reinforced concrete structures is becoming more and more popular. It is also supported by the guidelines in the Polish standard PN-EN 206:2014. The quality of the aggregate can be improved by removing from its surface cement mortar (fraction < 4 mm) which constitutes even 60–70% of the volume. This fine material is usually waste or it is used for stabilizing the sub-base. For several years researchers have been looking for opportunities to manage the recycled fine fraction in order to produce cement composites. In the research, for example, different amounts of recycled powder (< 63 μm) were used mainly to produce clinker, and long-term test results were promising (Gastaldi et al., 2015). Florea, Ning and Brouwers (2014) studied the influence of thermal activation of the recycled fine fraction at the temperatures of 500 and 800°C, and the possibility of replacing a part of the cement with it. It was found that up to 20% of the cement in mortar can be replaced with either a roasted or non-roasted recycled material without a significant decline in its strength. It was also noticed that the fine fraction roasted at 800°C possesses properties similar to fly ash. Kim and Choi (2012) examined the possibilities of using concrete powder obtained in the production of high quality aggregate as a binder. Shui, Xuan, Wan and Cao (2008) dealt with rehydrating the re-

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cycled mortar exposed to heating (up to 800°C). They found out that this process resulted from the contact with water, but the structure of hydration products was weaker in comparison to ordinary cement paste. Ahmari, Ren, Toufigh, and Zhang (2012) attempted to use the fine fraction from the recycled concrete to produce a new geopolymeric binder. Their findings indicate that with an appropriate amount of the recycled powder (up to 50%) and the fly ash, it is possible to produce the geopolymeric binder with the required compressive strength. Bordy, Younsi, Aggouna and Fiorio (2017) examined the possibilities of replacing the Portland cement by a recycled cement paste. The obtained results show that recycled particles not provide any additional filler effect and nucleation sites compared to the replaced cement, but just fills the granular gap left by the substituted cement.

The purpose of this research is to determine the possibility of using the fine material obtained by grinding fine fractions from concrete debris as an addition in the cement composites and setting directions for further research. For producing the recycled addition, ground laboratory samples from the cement paste (w/c = 0.45) were used to eliminate disturbances resulting from the presence of possible impurities in demolition rubble.

Research materials

CEM I 42.5 R Portland cement, CEN standard sand and superplasticizer (SP) were used for concrete specimens. Siliceous fly ash with 51.5% of silica was generated from burning coal.

Production technology and properties of the recycled fine material

The fine recycled material was generated by processing the cement paste obtained from cubic specimens of 10 × 10 × 10 cm (w/c = 0.45, cement CEM I 42.5 R). After 28 days of curing, the specimens were crushed in a jaw crusher and ground in a ball mill. Next, the material was sieved through a 0.125 mm screen and roasted at 700°C. For further testing only roasted recycled material was used. The properties of tested fine materials are shown in Table 1.

Roasting the recycled addition increased the specific surface area (measured with the Blaine apparatus), and thus, brought it a lot closer in size to the surface area of the fly ash and cement. The skeletal and bulk densities rose too. Figures 1 and 2 show changes in the non-roasted and roasted recycled addition, when heat is applied.

TABLE 1. Test results of the applied fine materials (own studies)

Properties	Material			
	recycled addition		cement 42.5R	fly ash
	0°C	700°C		
Blaine specific surface area (EN 196-6) [$cm^2 \cdot g^{-1}$]	3 275	3 550	3 820	3 700
Skeletal density (EN 1097-7) [$cm^3 \cdot g^{-1}$]	2.42	2.87	3.05	2.10
Bulk density (EN 1097-3) [$cm^3 \cdot g^{-1}$]	0.72	0.81	–	–

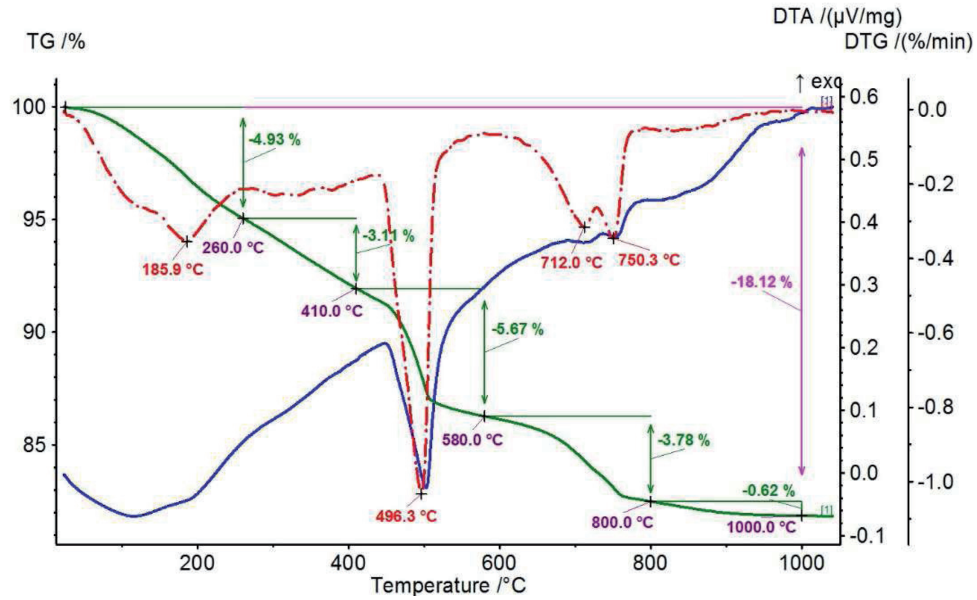

FIGURE 1. Changes in the non-roasted recycled powder heated to 1,100°C (own studies)

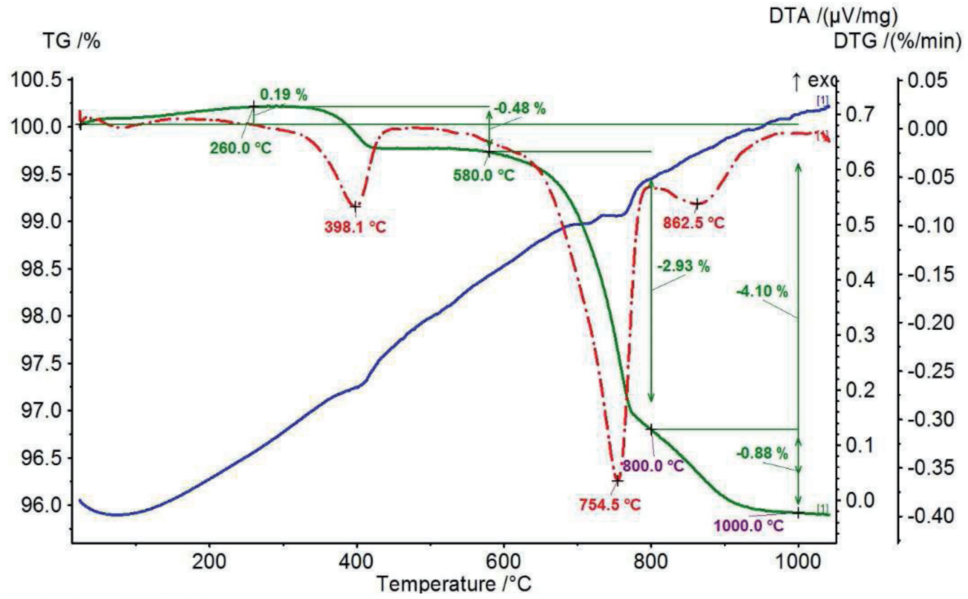

FIGURE 2. Changes in the recycled powder roasted at 700°C and heated to 1,100°C (own studies)

TABLE 2. Percentage of individual components of the recycled fine material (own studies)

Roasting temperature [°C]	Components of the recycled addition [% of mass]					
	bound water			$\overline{C}$	$Ca(OH)_2$	$CaCO_3$
	H_I	H_{CH}	Σ			
0	8.04	5.67	13.71	4.40	23.30	9.99
700	0.00	0.48	0.48	1.81	1.97	4.11

On the basis of Figures 1 and 2, individual components of the recycled addition were calculated in accordance with the procedure developed by Krzywobłocka-Laurów (1998). The results are shown in Table 2.

The recycled non-roasted material had a high content of $Ca(OH)_2$ (approx. 23% of its mass). Generally the total decomposition of calcium hydroxide occurs in the temperature range of 480–580°C. Therefore, the material roasted at 700°C was almost completely devoid of $Ca(OH)_2$. In contrast, the total decomposition of calcium carbonate is expected in the temperature range of 580–1,000°C, which explains a high content of $CaCO_3$ in the non-roasted binder (approx. 10% of its mass) and its visible decline in the binder roasted at 700°C (4.11%). The calcination of the calcium carbonate is a progressive process, so its complete decomposition is likely to occur at higher temperatures (up to 1,000°C).

Preparation of a research plan

Two factors, x_1 and x_2, changing at five levels (–1.414; –1; 0; 1; 1.414) were selected to determine the most favorable amount of the recycled fine material as an addition. The experiment was based on a two-factor rotatable plan with star points. The variables were:

- x_1 – the recycled addition ranging from 0 to 40% of the cement mass;
- x_2 – the superplasticizer ranging from 0 to 1% of the cement mass.

The basic plan of the experiment included 10 research series. In two additional series, conducted for comparisons, the recycled addition was replaced by the fly ash. The tests were conducted by means of 40 × 40 × 160 mm mortar specimens.

Table 3 presents the experiment plan containing coded values of variables (X_1, X_2) and the composition of the cement composite for three 40 × 40 × 160 mm specimens. The basis was the composition of the standard cement mortar in accordance with the Polish standard PN-EN 196-1:2006-07. When calculating the composition of the mortar with additions (recycled and FA), the concept of the coefficient k was applied, which allows taking into account the presence of these additions in the mortar composition by replacing the w to s ratio with w/(c + k × addition) ratio. The value of coefficient k in the experiment was assumed equal to 0.40, as for fly ash (PN-EN 206:2014, Jura & Ulewicz, 2017).

TABLE 3. The components of the cement composite for three specimens (own studies)

Series	Coded variables		CEM I 42.5 R [g]	Re-cycled addition [g]	SP [g]	w/c	w/s	Water [g]	Sand CEN [g]
	X_1	X_2							
1	–1	–1	439.2	27	0.68	0.51	0.50	224.33	1 335.0
2	–1	1	439.2	27	3.83	0.51	0.50	221.18	1 335.0
3	1	–1	388.8	153	0.68	0.58	0.50	224.33	1 265.2
4	1	1	388.8	153	3.83	0.58	0.50	221.18	1 265.2
5	–1.414	0	450.0	0	2.25	0.50	0.50	222.75	1 350.0
6	1.414	0	378.0	180	2.25	0.60	0.50	222.75	1 250.3
7	0	–1.414	414	90	0	0.54	0.50	225.00	1 300.1
8	0	1.414	414	90	4.5	0.54	0.50	220.50	1 300.1
9	0	0	414	90	2.25	0.54	0.50	222.75	1 300.1
10	0	0	414	90	2.25	0.54	0.50	222.75	1 300.1
Series with fly ash									
6FA	1.414	0	378.0	180	2.25	0.60	0.50	222.75	1 225.6
9FA	0	0	414	90	2.25	0.54	0.50	222.75	1 287.8

w/c = (water + SP / cement; w/s = (water + SP) / (cement + k · recycled addition), k = 0.40.

Research results and discussion

Table 4 presents average results of compressive strength tests after 7 and 28 days of curing, flexural strength after 7 and 28 days of curing, the absorbability and density of the cement composites.

On the basis of the statistical analysis of the results, equations describing the dependence of individual properties of the cement composites on the studied factors in the assumed ranges of their variability were developed. The statistical analysis included regression analysis, on the basis of which only statistically significant coefficients of the equation were taken into account and the variance analysis, which allowed to determine whether the considered factors affected the change in the value of a given composite feature. Figure 3 presents changes in physico-mechanical properties of the cement composites in relation to the amount of the recycled addition (X_1) and the superplasticizer (X_2). The diagrams were made on the basis of the coded values of the variables (Table 3). Figure 4 compares the properties of the composites with the recycled fine material and with the addition of the fly ash.

The findings show that in general, the recycled fine material in the form of the addition affected significantly the physico-mechanical properties of the cement composites. When the recycled addition constituted up to 20% of the cement mass, the results were comparable to the control series (series 5), but early compressive strength (after 7 days of curing) rose by approx. 10%. However, a par-

TABLE 4. Average test results of the properties of the cement composites (own studies)

Series	True variables		Compressive strength		Flexural strength		Absorbability [% of mass]	Density [kg·dm^{-3}]
	x_1 [%]	x_2 [%]	after 7 days [MPa]	after 28 days [MPa]	after 7 days [MPa]	after 28 days [MPa]		
1	6	0.15	32.87	42.07	6.84	8.81	9.1	2.13
2	6	0.85	38.17	45.51	7.17	8.68	8.9	2.17
3	34	0.15	7.01	11.27	2.58	3.45	16.2	1.84
4	34	0.85	6.92	8.87	2.33	3.34	14.7	1.80
5	0	0.50	33.55	42.63	7.01	8.81	9.2	2.03
6	40	0.50	5.45	5.98	2.10	2.63	19.0	1.68
7	20	0	35.85	45.72	7.05	7.25	9.7	2.14
8	20	1.0	41.46	50.98	7.11	8.10	9.8	2.13
9	20	0.50	37.80	39.90	6.80	7.40	9.6	2.07
10	20	0.50	37.72	39.62	6.94	7.19	9.5	2.06
6FA	40	0.50	32.87	42.07	6.84	8.81	10.2	2.03
9FA	20	0.50	38.17	45.51	7.17	8.68	9.9	2.06

ticularly unfavorable influence of the recycled fine material was observed when it exceeded 34% of the cement mass. All series achieved the lowest results of the flexural and compressive strength of the cement composites and the least favorable absorbability and density. While preparing the specimens in these series, it was noticed that the composite blends were clearly drier than the others. The impact of the superplasticizer was usually statistically insignificant, especially in the flexural strength. It affected the other analyzed features in a slightly positive way (an improvement of several percent), which may have been caused by its small amount (0–1% c.m.).

The results of series 6 prepared with the maximum content of the recycled addition clearly indicate a significant deterioration of all tested mortar properties but the results of series 9 with the addition of the recycled material (20% c.m.) are similar to the results of series 9FA with the addition of the fly ash (20% c.m.). Therefore, it can be assumed that the roasted recycled fine material and the fly ash have similar binding properties. Long-term studies are required to determine the pozzolanic activity index of the recycled addition. Therefore, the use of the recycled addition in the amount of more than 20% of the cement mass is not recommended for cementitious composites.

Conclusions

Roasting the recycled fine material at 700°C improved the following parameters: the specific surface area (increase by approx. 8%), the pycnometric density (increase by approx. 16%) and the bulk density (increase by approx. 14%) in comparison to the non-roasted material.

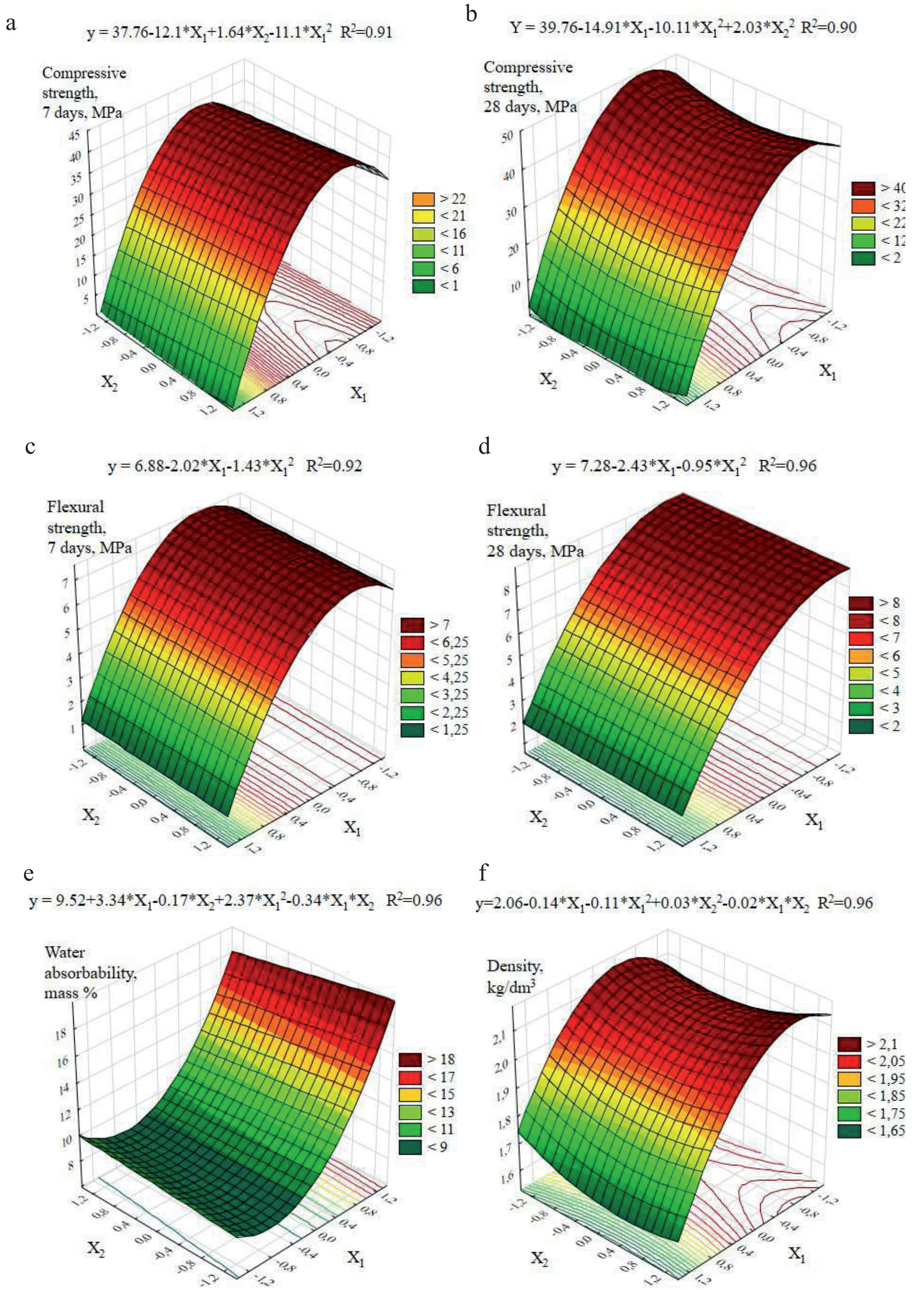

FIGURE 3. Changes in the properties of the cement composites in relation to X_1 and X_2 (own studies)

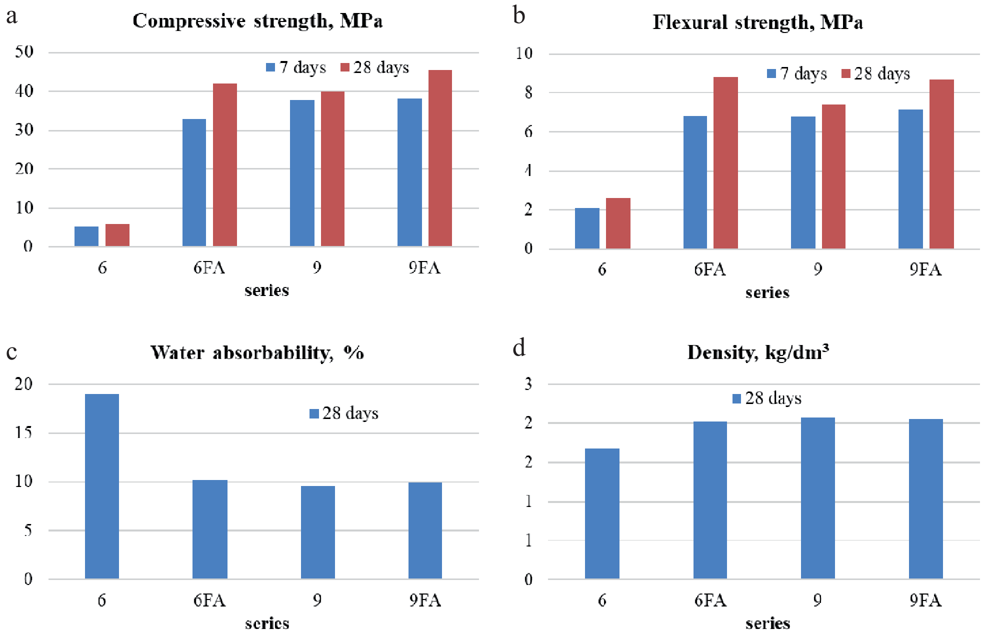

FIGURE 4. Comparison of the properties of the composites with the recycled fine material and with the fly ash (own studies)

During the thermal treatment of the cement paste, dehydroxylation of $Ca(OH)_2$ occurred, which probably resulted in the partial recovery of cement's binding properties, activated when it was re-exposed to water. The statistical analysis led to a conclusion that the recycled addition (constituting 0–40% of the cement mass) had a significant impact on the properties of the cement composites. However, both roasting and a specified amount of the recycled material (20% of the cement mass) allow to achieve satisfactory parameters of the cement composite. Subsequent research should focus, for example, on using a higher amount of the superplasticizer (> 1% c.m.) in order to improve the consistency of the cement composite. In addition, the results obtained for the series with 20% of the recycled material and with 20% of the fly ash were comparable. It can be assumed that the roasted recycled fine material and the fly ash have similar hydraulic properties. It would still be necessary to determine the influence of the rise in the specific surface area of the recycled addition (by grinding it to 0.063 mm) on the properties of the composites. The use of roasted fine recycled material after grinding will eliminate the need for waste disposal and will reduce the need to use natural resources (clinker or mineral additions). In addition, the production of cement is accompanied by energy consumption and high CO_2 emissions, which, in the case of production of the recycled material is significantly reduced due to the much lower roasting temperature. The use of recycled raw materials is in line with the principles of sustainable development and the circular economy and will contribute to achieving the required level of waste recycling of 70% in 2020.

The obtained findings are promising and set the basis for searching other new possibilities of using this material in construction, where its hydraulic properties can be applied. Currently, the research into using the recycled fine material as a cement substitute (Pawluczuk, 2017) and as an ingredient for autoclaved products is also being carried out.

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Summary

A fine fraction from the recycled concrete as an addition in the cement composites. The aim of the research was to determine the possibility of using the fine fraction from the recycled concrete to produce the cement composites. The research was based on a rotal plan with two variables: x_1 (the amount of the recycled addition, 0–40% c.m.) and x_2 (the amount of the superplasticizer, 0–1% c.m.). The recycled material was ground to 0.125 mm and roasted at 700°C. The statistical analysis of the findings led to the conclusion that the recycled fine fraction can be added to the cement composites (up to 20% of the cement mass) without a significant decline in their parameters' values.

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