Analysis of the Impact of Filler in the Form of Shredded Ceramic Waste on Selected Properties of a High-Strength Concrete Composite

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Abstract. The paper presents the results of research of selected properties of high-strength concrete modified with a filler derived from the recycling of shredded ceramic flowerpots. The concrete features such as: air content in the concrete mix, consistency of the concrete mix, compressive strength and frost resistance were evaluated. Frost resistance tests were carried out by two methods: the first direct method for 150 cycles of freezing and thawing and the second by determining the structure characteristics of concrete porosity using automatic image analysis.

Damaged ceramic flowerpots were subjected to a mechanical treatment consisting on grinding them in a mill and then in a disintegrator. Powdered ceramic waste was added in amounts: 10, 20 and 30% of cement mass as a filler, simultaneously the same amount of mineral aggregate was reduced. In concretes made with the addition of shredded waste ceramics, mechanical features have been improved, which leaded to achieving higher average compressive strength compared to the reference concrete without this additive. Concretes with the addition of ceramics was also characterized with greater frost resistance. Frost resistance tests carried out with the help of automatic analysis of pore distribution in concrete proved to be an effective tool for assessing concrete resistance to cyclic freezing and thawing.

1. Introduction

Declining deposits of mineral aggregates and materials for the production of cements, as well as increasing amounts of post-production waste have led to the necessity of developing new concretes using unconventional aggregates and additives to reduce the consumption of mineral binders. There is an ongoing research into the possibility of managing waste in the form of CRT glass, cullet of various origins, white, red [1] and other ceramics, car tyres, brick and concrete rubble, etc. With growing landfills for post-production waste, the need arises for management of this waste.

It is estimated that during the production of ceramic tiles, their waste accounts for about 7%, and in some sectors of ceramic products, even up to 30% of the daily production [2,3]. These wastes are chemically and biologically resistant material, so there is a possibility of their reuse, among others, for the production of materials with a cement matrix. In the research conducted in this area, ceramic waste of various origins was most often introduced into concrete as a partial or total substitute for mineral aggregates.
In the paper [2] an attempt was made to replace coarse aggregate with waste from ceramic electrical insulators. It was found that the workability of concrete mix with waste aggregate was satisfactory and the mechanical parameters of concrete with their share were comparable to traditional concrete. Farinha et al. [4] used recycling aggregate from sanitary ceramics for mortars. They found that replacing 20% of natural mineral aggregate with white ceramic aggregate leads to obtaining mortars with much higher strength compared to mortars without them. The main goal of research in paper [5] was to evaluate the effects of using recycled concrete aggregate (RCA) of an average quality as a 50% replacement for natural coarse aggregate. Siddique et al. [6] used recycled fine aggregate from porcelain vessels for the production of concrete. They replaced 20, 40, 60, 80 and 100% of natural sand. They found that the most satisfactory results were obtained in concrete composites, in which 40 and 60% of sand was replaced by recycled aggregate. Concretes with recycled aggregate were characterized by a slightly higher pore content, but with the pozzolanic activity of pulverized precious ceramics, the researchers obtained concretes with higher compressive strength. Concretes with fine ceramic aggregate were also characterized by much better resistance to cyclic freezing and thawing. It is commonly known that resistance to cyclic freezing of concrete composites is affected not only by the degree of aeration, but also by the size and distribution of pores in the concrete [7,8]. Only with the correct pore distribution in hardened concrete can a frost-resistant concrete composite be achieved. Additives in the form of pulverized ceramic waste can therefore also have a positive effect on pore distribution and pore size. The positive effect of pulverized white ceramics (sanitary ceramics), ceramic tiles and ceramic roof tiles on the properties of concrete is discussed in the paper [9]. This waste in the form of pulverized material (dust) was dosed in quantities of 5 and 10% of cement mass. Concretes made with the addition of pulverized ceramics were characterized by greater frost resistance and compressive strength. The highest increase in compressive strength was obtained for concrete in which pulverized ceramic tiles were used in the amount of 10% of cement mass. The average compressive strength of this concrete was by 14.6% higher than that of the control concrete. Similar results were obtained in studies [10-12], in which natural aggregates were replaced by the addition of white ceramics. The findings of these studies lead to the conclusion that the replacement of natural aggregates with recycling aggregates made of white ceramics leads to obtaining concrete with much better mechanical properties. In the study by Zahra K. et al. [13] red ceramics and wastes in the form of ceramic tiles were used for concrete composites. This waste replaced gravel, with quantities of 25, 50, 75 and 100%. The mean compressive and bending strength of concrete with ceramic tile aggregate was 41% higher than that of control concrete. The use of red ceramic recycling aggregate increased the average concrete strength by 29%. However, both additives had a negative effect on water absorption. Water absorption increased by 54% for aggregate from ceramic tiles and by 91% for red ceramics. The addition of red ceramics was shown to be less favourable due to its increased porosity. In other studies [14,15] there was a decrease in the strength of concretes in which recycling aggregates from waste ceramics, especially red ceramics, were used. This can be evidence of the great diversity of this waste. Amr S. El-Dieb et al. [16] used ceramic powdered waste with SiO2 and AL2O3 content of over 85% as a partial replacement for cement. Cement was replaced with amounts of 10, 20, 30 and 40%. Concretes with powdered ceramic waste were characterized by a lower rate of increase in strength. Concretes with a partial replacement for cement in the form of powdered ceramic waste have achieved satisfactory compression strength values on 90th day. All concretes with a partial replacement of cement in the form of pulverized ceramics also showed significant resistance to penetration of chloride ions. Similarly, Serkan Subasi et al. [17] used pulverized ceramics with SiO2 and AL2O3 content of over 78% in self-compacting concrete. Pulverized ceramics of less than 0.125 mm in size were used as a partial replacement for cement. It was found that replacing 15% of cement with a ceramic filling material has a positively effect on the properties of the concrete mix and only slightly reduces the compressive strength of the concrete composite. Review of the published research carried out in various centres reveals that concrete has become a material to which ceramic waste can be successfully added, replacing mineral aggregates and cement.
2. Methodology and research results
The research program was aimed to determine the effect of pulverized ceramics from pots damaged in the production process on selected properties of concrete composites. The ceramic pots were crushed in a mill and then in a disintegrator into the form of ceramic dust. The obtained ceramic dust was characterized by the following contents of individual fractions: 5% of fraction 0.25÷0.5 mm; 36% of fraction 0.125÷0.25 mm; 29% of fraction 0.063÷0.125 mm and 30% of fraction 0÷0.063 mm. Ceramic dust was dosed into concrete in quantities: 10, 20 and 30% of cement mass, at the same time using the same amount of mineral aggregate (concrete series C10, C20 and C30). The concretes were made of Portland cement CEM I, mixture of natural aggregates, superplasticizer SikaCem Superplast (in the amount of 1.0% m.c.) and aeratino admixture SikaCem Plast (in the amount of 0.8% m.c.) in A1N series concrete. The compositions of the tested concrete mixes are presented in Table 1.

Table 1. Concrete mix composition in kg/m³.

| Number of components [kg/m³] | Concrete series tested |
|-------------------------------|------------------------|
|                              | Control A1 | A1N | C10 | C20 | C30 |
| Portland cement 42.5R        | 355        | 355 | 355 | 355 | 355 |
| Aggregates mixture           | 1920       | 1920 | 1884.5 | 1849 | 1813.5 |
| Water                        | 149        | 149 | 149 | 149 | 149 |
| Ceramic filler               | -          | -   | 35.5 | 35.5 | 35.5 |
| Superplasticizer             | 3.55       | 3.55 | 3.55 | 3.55 | 3.55 |
| Aeration admixture           | -          | 2.84 | -   | -   | -   |

For all concrete mixes, the following determinations were conducted: air content test in accordance with PN-EN 12350-7:2011 [18] and consistency test by concrete slump test in accordance with PN-EN 12350-2:2011 standard [19]. For hardened concrete, the following tests were conducted: compressive strength according to PN-EN 12390-3:2011 [20] standard, water penetration under pressure according to PN-EN 12390-8:2011 [21], and frost resistance for 150 freeze and thaw cycles according to PN-88/B-06250 [22]. The results of the tests are presented in Table 2.

Table 2. Results of tests of concrete composites.

| Series tested                              | Control A1 | A1N | C10 | C20 | C30 |
|--------------------------------------------|-------------|-----|-----|-----|-----|
| Air content [%]                            | 2.4         | 5.9 | 5.5 | 5.6 | 5.4 |
| Concrete slump test [mm]                   | 45          | 70  | 40  | 30  | 15  |
| Mean compressive strength $f_{cm}$ [MPa]   | 62.2        | 53.4 | 59.7 | 63.4 | 67.5 |
| Depth of penetration of water under pressure [mm] | 48          | 60  | 53  | 42  | 42  |
| Decrease in weight after 150 cycles of freezing and thawing [%] | 0           | 0   | 0   | 0   | 0   |
| Decrease in compression strength after 150 cycles of freezing and thawing [%] | 9.7         | 4.2 | 5.3 | 3.9 | 4.5 |

Graphic representation of the results is shown in Figures 1-5.
Figure 1. Effect of ceramic additive on air content in a concrete mix.

Figure 2. Influence of the ceramic additive on the consistency of the concrete mix.

Figure 3. Influence of ceramic additive on compressive strength.

Figure 4. Influence of ceramic additive on the water penetration depth.

Figure 5. Influence of ceramic additive on the decrease in strength after 150 cycles of freezing and thawing.

For all concrete series, the characteristics of air pore distribution in hardened concrete were also determined according to the PN-EN 480-11:2008 standard [23]. The porosity structure examination was conducted using an image analysis device and the Lucia Concrete computer program. This set allowed for determination of total air content in concrete A, pore distribution index $L$ and $A_{300}$ micropore content. An example view of air pore distribution on the specimen section is shown in Figure 6. The results obtained are presented in Table 3.
Table 3. Results of air pore distribution tests in concrete.

| Series tested          | Control A1 | A1N | C10 | C20 | C30 |
|------------------------|------------|-----|-----|-----|-----|
| Total air content in concrete A [%] | 2.6 | 5.8 | 5.9 | 6.1 | 5.8 |
| Pore distribution index porów $L$ [mm] | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Micropore content A$_{300}$ [%] | 1.18 | 1.74 | 2.25 | 2.35 | 2.10 |

Figure 6. Example view of air pore distribution in hardened concrete.

The addition of ceramic dust had a positive effect on all the studied features of concrete composites. The average compressive strength of concrete without the addition of ceramic dust (A1 series) was 62.2 MPa. The addition of 20 and 30% of ceramic dust resulted in an increase in mean strength by 1.9 and 8.5% compared to the control concrete.

Pulverized ceramics reduced water penetration depth. The concrete of the control series obtained a value of 48 mm in this test, while the concrete with 10 and 20% of ceramic dust yielded water penetration depth of 42 mm.

Very good results of tests of concrete with the use of ceramic dust were obtained in the determination of frost resistance. In control concrete without an aeration admixture (A1 series), a decline in mean compressive strength by 9.7% was found after 150 cycles. The same concrete with aerated admixture (A1N series) yielded a compression strength decrease of 4.2%. Concretes with the addition of waste ceramic dust had values of strength declines after 150 cycles similar to concrete with aeration admixture. Concrete with the addition of ceramic dust in the amount of 20% of cement mass (series C20) led to the lowest decrease in strength of 3.9%.

The examination of characteristics of pore distribution in hardened concrete confirmed the correct aeration of concrete with dust. The important point in proper aeration of the concrete mix is the correct air pore spacing in hardened concrete defined by: pore distribution index $L$, i.e. the largest distance from any place in the cement matrix to the nearest pore and the appropriate content of micropores with a diameter below 300 µm, so called class 18 ($A_{180}$). Concretes with the index $L$ of $\leq 0.18$ mm and $A_{300} > 1.8\%$ are considered to be highly resistant to cyclic freezing and defrosting.

Concretes of C10, C20 and C30 series with the addition of ceramic dust had a higher content of micropores in class 18 than aerated concrete without the use of pulverized material (A1N series).

3. Conclusions

The tests conducted in the study lead to the following conclusions:
- the pulverized additive obtained from damaged ceramic pots used in the study can be a valuable component of concrete composites that modifies their structure and has a positive effect on physical and mechanical properties;
- concretes containing 10 and 20% by weight of cement with ceramic dust yielded higher compressive strength compared to concrete without this additive;
- addition of ceramic dust reduces water penetration depth in concrete composites;
- the addition of ceramic flour leads to the aeration of the concrete mixture, similarly to the aeration admixture, and makes it possible to obtain concrete with a high content of micropores of class 18 (with a diameter of less than 300 µm), which guarantees that frost-resistant concretes are obtained;
- the introduction of pulverized ceramic dust in the concrete in the amount of 20% of cement mass is the most optimal amount. Concrete of the C20 series had the mean compressive strength by 1.9% higher than control concrete and the highest micropore content in class 18, amounting to $A_{390} = 2.25\%$. This value is by 29% higher compared to aerated concrete (A1N series).

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