Usage of Crushed Concrete Fines in Decorative Concrete

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Abstract. The article is devoted to the questions of usage of crushed concrete fines from concrete scrap for the production of high-quality decorative composite materials based on mixed binder. The main problem in the application of crushed concrete in the manufacture of decorative concrete products is extremely low decorative properties of crushed concrete fines itself, as well as concrete products based on them. However, crushed concrete fines could have a positive impact on the structure of the concrete matrix and could improve the environmental and economic characteristics of the concrete products. Dust fraction of crushed concrete fines contains non-hydrated cement grains, which can be opened in screening process due to the low strength of the contact zone between the hydrated and non-hydrated cement. In addition, the screening process could increase activity of the crushed concrete fines, so it can be used as a fine aggregate and filler for concrete mixes. Previous studies have shown that the effect of the usage of the crushed concrete fines is small and does not allow to obtain concrete products with high strength. However, it is possible to improve the efficiency of the crushed concrete fines as a filler due to the complex of measures prior to mixing. Such measures may include a preliminary mechanochemical activation of the binder (cement binder, iron oxide pigment, silica fume and crushed concrete fines), as well as the usage of polycarboxylate superplasticizers. The development of specific surface area of activated crushed concrete fines ensures strong adhesion between grains of binder and filler during the formation of cement stone matrix. The particle size distribution of the crushed concrete fines could achieve the densest structure of cement stone matrix and improve its resistance to environmental effects. The authors examined the mechanisms of structure of concrete products with crushed concrete fines as a filler. The results of studies of the properties of the crushed concrete fines were provided. It is shown that the admixture of the crushed concrete fines has little effect on the colour characteristics of the decorative concrete products. The preferred options to improve the surfaces of decorative concrete are also proposed.

1. Introduction

A considerable amount of concrete waste is generated as a result of the demolition and reconstruction of residential and industrial buildings. This type of waste is basically made from cement minerals and contains non-hydrated cement particles in its composition. Depending on the method of grinding, the concrete waste may have different properties which make it optimal for use in certain materials [1-2].

The usage of recycled crushed concrete aggregate produced by crushing of concrete waste may not only reduce the consumption of natural aggregate, but may reduce the amount of concrete waste that ends up in landfills as well. The screening process at the screening plants produces coarse recycled concrete aggregate (with particle size more than 5 mm) and fine recycled concrete aggregate (with...
particle size less than 5 mm). There were a lot of studies of coarse recycled concrete aggregate and fine recycled concrete aggregate, which shows that these aggregates could be used as a replacement for natural aggregates in structural concrete. Various researchers [3-4] have proved that the use of crushed concrete of a fraction of 5-40 mm in reinforced concrete and concrete products (up to 30% of the mass of a coarse aggregate without any special preparations) is possible; the technologies for the use of this aggregate had been developed. A little less research has been conducted on the application of fine recycled concrete aggregate in structural concrete and high performance concrete. The questions of usage of crushed concrete fines as filler for fine grain concrete, aerated and foam concrete products as well as technological solutions for the production of paving tiles on crushed concrete aggregates were worked out. All of these types of industry waste have been studied for possibility of their usage in decorative concrete previously [5].

However, the dust fraction of recycled concrete aggregate (which has particle size less than 0.063 mm) considered unwelcome in concrete technology. The main reasons of this are high specific surface which leads to high water consumption and influence on water/cement ratio and, therefore, the negative impact on strength of concrete. Hydration water accumulates in porous structure of dust fraction particles and increases the amount of capillary pores in solid concrete. The methods of lowering of influence of absorbed water are the constant interest of researchers [6].

To achieve dense concrete structure with a little number of capillary pores, negative effect of dust fraction could be compensated by usage of superplasticizer [7]. It could decrease the amount of water used to hydrate cement and, more important, the amount of water accumulated by porous structure of dust fraction. Thus, the usage of crushed concrete fines as fine aggregate in composition with polycarboxylate superplasticizers could allow to create concrete structures with strength and density compared with traditional concrete materials.

Besides low capillary porosity, decorative materials should also meet the specific requirements on the quality of the front surface of the windshield and to ensure the absence of snow accumulation on the surface of buildings. Traditional materials based on cement binder could not always meet these requirements, but their main disadvantage is the relatively low durability. This happens due to the presence of extensive network of capillary porosity, hairline cracks and other structural defects which are formed at the stage of manufacture and during the life cycle.

The decorative effect of decorative concrete products could be created in various ways [8]. The most preferred method in technology of coloured waste-and-concrete-based products is the joint mechanochemical activation of crushed concrete fines together with a mixture of pigment and binder [9].

Thus, the creation of high-performance concrete-based decorative materials could be economically attractive. This could be achieved by development of high-performance concrete with high compressive strength (60-120 MPa and above), frost resistance (more than the F400), water-resistance (more than the W12), low abrasion (less than 0.4 g/cm²), and high bleaching resistance.

2. Experimental
To confirm the theoretical propositions, concrete mixes with mechanically activated admixture based on the screenings of crushed concrete had been developed. The composition of admixture includes polycarboxylate superplasticizer, silica fume, iron oxide pigment and crushed concrete fines dust fraction with an average grain size less than 0.063 mm. The design of concrete mixes was calculated according to high performance concrete design methods [10-15].

Before experiment, available admixtures for use with high-performance decorative concrete were analyzed. As superplasticizers, three types of polycarboxylate superplasticizers (Neoplast, Polyplast SP HPC and Glenium 51) as well as traditional naphthalene sulphonate plasticizer C-3 were chosen for experiment. Lanxess Bayferrox iron oxide pigment was chosen to obtain colour characteristics. Crushed concrete fines were obtained from crushed concrete, generated as a result of demolition of load carrying structures of buildings. Crushed concrete fines fraction 0-5 mm with an average density of 2.1 g/cm³, bulk density of 1.3 g/cm³, porosity of 7%, void content of 38%, crushing capacity grade 400; portland
cement M500 with a standard consistency of 27.5% and portland cement of the M400 with a standard consistency of 27%; sand with the fineness modulus 1.35 and the amount of the dust fraction (0-0,14 mm) of 5%; technical water – all these components were chosen as concrete components.

Concrete mixes were tested to evaluate their workability, freeze-thaw resistance and unit elongation during freezing and thawing, porosity and water absorption, compressive strength and water resistance. All of the properties were determined on the samples with dimensions of 10x10x10 cm according to EN and GOST codes and standards. The experiment was made on the equipment of Moscow State University of Civil Engineering.

Standard samples of designed concrete were tested according the GOST methodic to find out the strength, porosity and capillary suction process, as well as dilatometric studies of samples based on the mechanically activated coarse aggregates. The components were introduced in two stages: silica fume, crushed concrete fines dust fraction and pigment were added to the cement prior to mechanochemical activation, plasticizer was added to the mixing water. Mechanochemical activation was carried out using an activator with an annular working chamber. The main feature of this type of activation device is the collision type: the particles in the vortex are subjected to collide at a velocity ~80 m/s. Initial tests were carried out for concrete mixes based on non-activated coarse aggregate. Compositions of these mixes are shown in Table 1.

| Mix design | B30 | B35 | B40 | B45 | B50 | B60 | B70 |
|------------|-----|-----|-----|-----|-----|-----|-----|
| Binder/water ratio | 1.92 | 2.14 | 2.39 | 2.64 | 2.83 | 3.3 | 3.77 |
| Cement, kg/m³ | 383 | 428 | 478 | 529 | 565 | 660 | 754 |
| Volume concentration of cement in water-cement paste | 0.33 | 0.36 | 0.39 | 0.42 | 0.44 | 0.44 | 0.55 |
| Silica and crushed concrete fines dust fraction, kg/m³ | 112 | 102 | 94 | 77 | 73 | 32 | 0 |
| Cement after , kg/m³ | 271 | 326 | 384 | 452 | 492 | 628 | 754 |
| Absolute volume of aggregate | 664 | 651 | 636 | 621 | 609 | 584 | 557 |
| Coarse aggregate, kg/m³ | 868 | 851 | 832 | 812 | 796 | 763 | 728 |
| Fine aggregate, kg/m³ | 868 | 851 | 832 | 812 | 796 | 763 | 728 |
| Compressive strength, MPa | 38.6 | 44.9 | 51.4 | 58.8 | 64.3 | 77.1 | 90.0 |
| Porosity, % | 13.7 | 13.5 | 13.4 | 13.0 | 12.8 | 12.2 | 11.2 |

Initial tests have shown (Table 2), that the concrete mixes suits the requirements of compressive strength and workability, but they does not meet the requirements for high-performance concrete freeze-thaw resistance (it was less than 400 cycles).

| Mix design | Compressive strength R, MPa | Porosity, % | Coefficient of water absorption, | Unit elongation εlim 10⁻⁵ cm |
|------------|-----------------------------|-------------|---------------------------------|-----------------------------|
| B40 | 51.4 | 13.4 | 9.92 | 10.2 |
| B45 | 58.8 | 13.2 | 9.0 | 10.5 |
| B50 | 64.3 | 12.8 | 8.41 | 10.4 |
| B60 | 77.1 | 12.2 | 7.84 | 9.6 |

To improve the properties of developed high-performance concrete, a method of pretreatment of coarse aggregate by complex admixture was used. This admixture consists of silica fume and polycarboxylate superplasticizer and added to the concrete mix in two steps. At first, part of the mixing water containing silica fume and polycarboxylate superplasticizer is premixed with the coarse aggregate in the mixer and then added to the remaining water and cement.
Concrete samples based on non-activated and activated coarse aggregate after 28 days of normal storage were tested to find out the structure of concrete and properties of their matrix-aggregate contact zones. The samples were split apart and the concrete from concrete-aggregate contact zones was collected. After that, collected material was disintegrated to powder and examined by differential thermal analysis and X-ray diffraction analysis. The degree of hydration of cement was determined based on the degree of hydration of C3S. Concrete samples based on activated coarse aggregate were also tested to find out their compressive strength, workability, and coefficient of absorption. The properties of high performance decorative concrete based on non-activated coarse aggregate are shown in Table 3.

| Mix design | Compressive strength R, MPa | Porosity, % | Coefficient of water absorption | Unit elongation \( \varepsilon_{\text{lim}} \times 10^{-5} \) cm |
|------------|-----------------------------|-------------|-------------------------------|-----------------------------|
| B40        | 66.8                        | 13.4        | 8.4                           | 8.1                         |
| B45        | 70.5                        | 13.2        | 7.56                          | 8.5                         |
| B50        | 77.8                        | 12.8        | 6.75                          | 8.3                         |
| B60        | 91.7                        | 12.2        | 6.42                          | 8.0                         |

The influence of atmospheric factors on coloristic characteristics of decorative concrete were examined in salt-spray chamber.

3. Results and discussions

Studies have shown that the compressive strength of concrete, obtained by a two-stage activation, increased by 19-23%; water absorption value decreased by 16-20%; and unit elongation of concrete samples during freezing and thawing decreased by 17-20%. All samples had W12 water resistance degree. It was also found that porosity of all samples was not more than 14%.

The results of X-ray diffraction analysis showed a higher amount of calcium carbonate in the concrete in the non-activated coarse aggregate. That could be connected with a loose structure of the contact zone. Analysing the results of the experiment it can be concluded that the complex admixture, distributed on the surface of the filler, is interacting with calcium hydroxide and alter the type, volume and number of the pores and helps filling the contact zone by cement hydration products.

X-ray diffraction analysis showed that the degree of hydration of the concrete samples on activated coarse aggregate filler was 84%, whereas the hydration degree of concrete on non-activated coarse aggregate was only 73%.

The thermograms for each of the samples shows that DTA curve has three main endothermic peaks: at 110-250° C, 490-510° C and 760-780° C. The first peak at \( T=110-250° \) C is the deepest, it shows dehydration of ettringite at \( T=140° \) C, the removal of adsorbed water and partial recrystallization of gypsum crystals. These processes are accompanied by a weight loss of 7% for the samples of concrete based on activated coarse aggregate and 4% for samples of concrete based on non-activated aggregate. This indicates that the degree of hydration of these samples is higher.

Second peak at \( T=490-510° \) C is connected with the presence of \( \text{Ca(OH)}_2 \), which has less significant weight loss in both samples (0.5% and 0.75% respectively) due to dehydration process. Third peak at \( T=760-780° \) C shows dehydration of hydrated calcium silicate. At \( T=820-850° \) C concrete samples with activated coarse aggregate shows exothermic effect of tobermorite presence.

The particles of the investigated dust fractions are slightly different in size from the traditional filler and have a rather high specific surface area. The particle size of part of non-activated crushed concrete fines is comparable to the size of the cement particles and silica fume (figure 1) and could replace them in the creation of concrete structures. Mechanochemical activation makes it possible to average these dimensions and to obtain high homogeneity of the mechanochemically activated admixtures based on
crushed concrete dust fractions. The effect of mechanochemical activation allows to slightly reduce average size of particle depending of time of activation. The development of specific surface area of activated crushed concrete fines ensures strong adhesion between grains of binder and filler during the formation of cement stone matrix. The particle size distribution of the crushed concrete fines could achieve the densest structure of cement stone matrix and improve its resistance to environmental effects.

![Particle distribution of non-activated crushed concrete fines dust fraction](image)

Figure 1. Particle distribution of non-activated crushed concrete fines dust fraction

The main task of creating decorative concrete is the creation of high-quality surface that has highly decorative properties, persistent over time. The last property ensures high resistances to destructive surface environmental factors – freeze-thaw resistance, colour fade resistance, resistance to acids and alkalis and water-resistance. The most significant factor in these properties is the content of the concrete pores, especially capillary pores. The appearance of chipping, bleaching and discoloration at water saturation dramatically reduce the attractiveness of the product. To overcome the aforementioned defects of the front surface, it is necessary to increase the density of the concrete, and thereby increase its compressive strength [16]. One of the effective ways to solve this problem is the impregnation of high-performance decorative concrete by low viscosity concrete formulations which can be cured in the concrete pores. Such compounds are widely distributed, but they can affect the colour characteristics and general attractiveness.

The examined concrete mixes have a higher density and a smaller number of capillary pores. The high specific surface area of mechanically activated components allows them to more efficiently participate in cross-linked reactions. The particles of pigment are also crushed and more evenly distributed over the volume of the mixture. Unreacted cement grains after activation process partially lose their concrete coating and can hydrate as well. Used iron oxide pigments washed out of the dense concrete matrix less intensively. Dense surface of concrete shows little color loss after salt fog exposure in salt-spray chamber. Freeze-thaw tests showed high freeze-thaw resistance of decorative concrete, both at surface and body of concrete elements. However, surface scaling of high-performance decorative concrete appears before reaching the freeze-thaw resistance characteristic (which correlate with previous studies [17]).
The denser structure of the contact zone between the filler and the matrix enhances the strength of concrete products and thus expands their appliance range. For example, it becomes possible to obtain facial elements of ventilated façade systems based on concrete, which had a thickness of 5 mm and do not require reinforcement. Another application of the developed concrete could be small architectural forms – elements of the urban environment decoration, landscape architecture and landscape park art. Small architectural forms based on the developed concrete can maintain decorative properties without the usage of protective coatings. However, the finished products can be processed with water-repellent compositions of different types, provided that preliminary assessment of their impact on colour characteristics will be made. The densest concrete structure must be created on the surface of the element, because the quality and smoothness of the surface has a decisive influence on the resistance to weathering and abrasion and is less prone to sticking snow. Another option of surface decoration of decorative concrete is glassed surface of concrete elements, but this type of decoration requires decorative aggregate or different coloristic schemes of concrete matrix.

The main disadvantage of crushed concrete fines in decorative concrete technology is their nonhomogenity and presence of foreign inclusions depending on screening process. To compensate this, crushed concrete fines should be classified using density separation techniques before their usage in concrete mixes. Nevertheless, application of crushed concrete fines obtained from screening of pure concrete products requires no preparation process.

Developed concrete designs and products based on crushed concrete comply with the requirements of the Russian Federation and European standards and can be further improved without decreasing of their strength characteristics. At the same time, production line of concrete-based high performance materials does not require the development of a fundamentally new technology. This technique is simple and based on existing economically feasible vibration technology, traditionally used for the production of decorative concrete with a set of conventional equipment. Developed materials also could be used directly at worksites in warm periods.

4. Conclusions
The usage of crushed concrete fines, as well as silica fume and polycarboxylate superplasticizers could make high performance decorative concrete more economically attractive. As results of the study, high performance decorative concrete materials based on mechanochemically activated crushed concrete fines and coarse aggregate with compressive strength of not less than 60 MPa, porosity in the range of 15%, frost resistance not less than 400 cycles, water resistance not more than W12 and sufficient color stability, were designed. In further work it seems appropriate to conduct a more detailed study of the influence of various concrete plasticizers and various types of pigments on color characteristics of concrete-based materials.

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