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Concrete resistant to spalling made with recycled aggregate from sanitary ceramic wastes – The effect of moisture and porosity on destructive processes occurring in fire conditions

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HIGHLIGHTS

- Concrete with recycled ceramic aggregate and high-alumina cement was evaluated.
- Polypropylene fibers and aeration is an effective protection against the spalling.
- Defects of the ITZ were investigated using SEM.
- Water vapor diffusion through the ceramic aggregate's structure was modeled.

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ABSTRACT

The paper describes a new model of the production of the concrete that is resistant to the conditions of a sudden temperature rise, which simulate a fire. Aluminum cement and aggregate obtained from the sanitary ceramic ware wastes were used for the production of the concrete. The composite was modified by the addition of the polypropylene fibers or by introducing additional porosity into the material. The purpose of the work was to produce a concrete, which would have optimal strength parameters despite the impact of a high temperature equal to 1000 °C. The paper presents the results of the research on the physical properties of the cementitious composites, as well as compressive strength before and after thermal loading. In addition, the microstructure of the heated concretes in various moisture states was investigated using a scanning electron microscope (SEM). On this basis, conclusions were drawn regarding the influence of destructive physical changes within the cement paste on the strength properties of the concretes; the beneficial characteristics of the ceramic aggregate in the aspect of the water vapor diffusion were pointed. In addition, the process of the cracks' propagation in the structure of the cement matrix due to thermal load, and the diffusion of water vapor by the structure of the ceramic aggregate has been schematically modeled in the paper.

1. Introduction

The issue of a load transfer by cement composites under high temperature conditions is an issue thoroughly analyzed by a number of research teams [1–8]. Scientific research takes two seemingly close directions. On the one hand, materials are searched, which can operate without failure in an environment with constantly increased temperature [9]; on the other hand, the behavior of materials is investigated for which the high temperature load is only an emergency situation as it is in the case of fire [10].

There are a number of composites meeting the first criterion. Fireproof and refractory concretes are used in a variety of applications, e.g., steel furnace enclosures, floors in steel foundries, elements of chimneys and heating furnaces. Due to the use of special components for their production, these composites can operate without failure at temperatures reaching up to 1500 °C, while for their proper functioning a slow pre-heating process lasting up to 160 h is necessary [11–13].

Despite the fact that in the case of fire issues the range of temperatures is lower, but their rapid increases (thermal shocks) make it still difficult to obtain concrete composites that would have the

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ability to operate without failure under this type of exceptional load. A particularly unfavorable phenomenon is the thermal spalling of concrete fragments [14]. According to literature sources [15] its most probable cause is the increasing pressure of water vapor contained in the free spaces of concrete. Under the influence of increasing temperature, the water volume is increasing and causes pressure on the pores' walls, which results in tensile stresses within the mentioned zone. If these stresses exceed the value of the concrete's tensile strength, an explosive detachment of its fragments occurs [16–18]. The described phenomenon applies in particular to the concretes of high classes with high tightness [19,20], in which water vapor does not have the possibility of free expansion. The main method currently used to reduce spalling is the use of polypropylene fibers [21–23], as an additive to concrete. At high temperatures, they melt [24], which results in the formation of free spaces in the composite's volume that enable lowering the water vapor pressure. Such treatments significantly reduce the strength of the concrete elements in the heating phase due to losses caused by the fibers' melting.

One of the innovative approaches in the production of the concretes, which are resistant to high temperatures is the use of ceramic wastes [12,13]. All products made of fired clays have the advantage of resistance to high temperatures. As research shows, not all types of ceramics are suitable for composing concretes with high strengths that could be used to construction. Studies described [25–35] prove that crushed red ceramics wastes generally reduce the strength parameters of concretes, and their use for the cementitious composites is dictated mainly by the ecological effect.

It is different in the case of concretes obtained using ceramic wastes from the white ceramics [36–41]. In this case, the crushed ceramic sanitary wastes allowed to improve the parameters of the concretes. The paper [41] describes a composite that contained in its entirety the aggregate of the white ceramic origin; as binder an aluminum cement was used. The concrete had very high strength parameters (compressive strength – 90.5 MPa, tensile strength – 9.54 MPa). Samples were subjected to slow heating process up to 1000 °C; the test proved that the concrete in these conditions and after cooling retains the invariance of the form as well as relatively high strength parameters (compressive strength – 58.3 MPa, tensile strength – 4.0 MPa).

The research, in which attention was paid to the specific microscopic structure of the ceramic aggregate was presented in [42]. The authors, using methods of microscopic measurements, developed a model of the aggregate's structure made of the sanitary ceramics. As indicated by the analyzes, the aggregate have high strength parameters and is a porous aggregate with an open pore structure. This advantage as well as reinforcement of the interfacial transition zone (ITZ) was used to design the concrete resistant to the spalling presented in this study.

As in previous studies [41–43], the authors use in the research a binder in the form of the high-alumina cement. The main component of the cement are calcium aluminates, which account for over 70% of its composition (occur in the largest quantities: CA – $CaO{\cdot}Al_2O_3$ and $C_{12}A_7$ – $12CaO{\cdot}7Al_2O_3$). The amount of calcium silicates is up to several percent. The main hydrate in the crystalline form is the hydrated calcium aluminate (C_4AH_{13}) and the amorphous aluminum hydroxide ($Al_2(OH)_3$). In this case $Ca(OH)_2$ is not formed, as it is in the case with Portland cement. This affects the corrosion and high temperature resistance of the high-alumina cement. The significant feature is also the amount of water, which should be added to the cement binding (increased by approx. 30% compared to Portland cements), which in the previous years led to complications in its use [44].

This composition causes that the concrete with the high-alumina cement has the highest initial strength (up to 60 MPa after 24 h – approx. 85% of the final strength achieved after 14 days), a high calorific value (heat of hydration), the highest resistance to sulfate, ammonium, magnesium, acidic, and alkaline environments, and the highest fire resistance among the cements [45]. In spite of numerous difficulties in its application, many years of experience have led to many rules related to its safe use. Currently, they can be used in places where chemical resistance is expected. Concrete with the high-alumina cement is suitable for concreting at low temperatures down to −10 °C, and for the production of refractory products.

The main purpose of this work was to design a new cement composite that would be resistant to the phenomenon of spalling, and at the same time would maintain high strength parameters during and after heating at temperatures simulating the fire. Conclusions have been drawn regarding the influence of destructive physical changes within the cement paste on the strength properties of concretes; the beneficial characteristics of the ceramic aggregate for this purpose were pointed. A model of water vapor diffusion from cement paste into the aggregate was developed. Similar research with the use of the unconventional waste ceramic aggregate has not been recorded in the literature.

2. Experimental programme

The experimental programme involved testing the fresh concrete mix and the hardened composite: consistency of the concrete mix, compressive strength, apparent density, water absorption, water resistance, and compressive strength after heating process. The research was carried out in three stages. In the first, the samples based on aluminum cement and the gravel, basalt and ceramic aggregate were subjected to a rapid heating, which simulated the fire conditions. In the second stage, samples based only on the ceramic wastes were prepared; the composition and the structure of the composite were differentiated. Concretes containing the polypropylene fibers, aeration admixture, and porous concrete were tested. The last stage of the research consisted in the temperature loading of the composites mentioned, which were at different stage of moisture. The concretes' microstructure was also analyzed using a scanning electron microscope (SEM).

2.1. Materials used

The raw material for the production of the ceramic aggregate was the post-production wastes of sanitary ceramics. Ceramic products with cracks, enamel damage, and deformation of shapes were transported to a landfill where they were subjected to automatic fragmentation during transport (Fig. 1a). Wastes of 5–15 cm size were crushed in a laboratory jaw crusher, the work of which allowed the selection of 0–4 mm and 4–8 mm grain sizes (Fig. 1b).

The ceramic aggregate obtained was subjected to basic physical and mechanical tests, according to standards [46–50]. The results of these studies are described in detail in [41]. The tests carried out proved that the aggregate is suitable for composing the concrete resistant to high temperatures. The basic physical and mechanical features of the aggregates used in the research have been summarized in Table 1, and their particle size distribution curves are shown in Fig. 2.

The cement used for the production of the concrete mixtures was the "Górkal 70" high-alumina cement (content of aluminum oxide – 69–71%). This cement is recommended for use in concretes and mortars, which are exposed during operation to high temperatures. The declaration of its performance indicates the possibility of composing cementitious composites, which can operate at 1560 °C.