Utilization of ceramic waste by using it as special concrete aggregate

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Abstract. In the article is presented the method of utilization of ceramic waste by using it as special concrete aggregate for special high temperature resistant concentrates. The research was performed on six empirically designed concrete mixtures of three on aluminous cement with simultaneous aerification with using air entraining admixture respectively at 0, 5 and 10%. In order to compare the results, three Portland cement concrete mixes were prepared which had exactly the same aerification of the mixture. All types of samples were made using recyclable aggregates of sanitary ceramics selected and crushed to 0-4 mm and 4-8 mm. This particular type of aggregate, as proved in previous authors’ workshowed very favorable features in terms of the influence for thermal loads. Selected samples were subjected to a thermal treatment according to the standard curve "temperature-time" for 120 minutes until the furnace chamber temperature reached approximately 1050°C. With interactive concrete mixture method design, assuming that the mixture substrates were limited to the commonly used cements and the appropriate amount of air entraining admixture, there were received tight concrete with high strength parameters, which also demonstrates resistance explosive concrete particles’ chipping off under conditions of high temperatures.

1. Introduction
The safe temperature at which ordinary concrete made of Portland cement can be used is 250°C. Concrete exposed to higher temperatures is classified as special concrete. Their composition is based on special refractory binders. In general, high temperature concrete is divided into two basic groups of refractory concrete [1]. It is generally assumed that refractory concrete can work above 1000 °C [2]. Refractory and refractory concrete are useful in various industries. In particular examples include the housing of industrial furnaces, chimneys, foundations in foundries and other industrial plants. A particular type of construction that requires the use of high temperature resistant concrete is tunnels for which fire safety is a very important requirement.

The basic effect on the resistance of concrete to high temperatures has a binder. The temperature limits for the use of Portland cement at elevated temperatures are due to the chemical reactions that take place during the chemical reaction [3]. More resistant to high temperatures than Portland cement is the so-called aluminous cements containing significant amounts of Al₂O₃ aluminium oxide in their composition. High temperature resistance increases along with the content of aluminium oxide in the cement. Hence, high aluminous cements with 80% content of Al₂O₃ can work even at temperatures above 1800°C [4].

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Some other strength characteristics during soaking have refractory concretes with low content of aluminous cement (LCC - Low Cement Castables) [4]. Due to the low content of slurry they are not so susceptible to chemical changes related to the release of water. The concrete up to a temperature of about 1000 °C is characterized by an increase of about 20% strength compared to traditional heat-resistant concrete, and this strength is rapidly decreasing. Cooled down LCC concrete along with the reinforcement of the resulting ceramic bindings often has higher strength than before the soaking [3].

2. Ceramics as recycled aggregate used for concrete

Ceramic waste can be divided into two basic groups according to the raw materials from which they are derived. The first group includes products made of fired red clay, such as brick, brick blocks or roof tiles [5]. The second group presents industrial waste made in plants which products are based on soft clay also known as white.

The use of red ceramics as an additive to concrete dates back to ancient times. In modern times, aggregate from the crumbling construction elements has been re-used for concrete production after World War II due to the large amount of material after the war damages. The use of ceramic bricks for concrete was governed by, inter alia, German regulations and building standards. Presently, attempts are made to use red ceramics as concrete aggregates. In research [6], the authors used concrete prepared on the basis of various waste of red ceramics. The aggregates included ceramic tiles and clay structural-wall tiles, which were the substitute for the thicker fractions of calcareous aggregate. There were prepared three blends containing corresponding 33% and 66% of ceramic aggregates and also the mixture which was made solely on the ceramic aggregate. For the purposes of comparison, there was made the control mixture without the use of a ceramic aggregate. The results of compressive strength and tensile tests of such prepared concrete indicate an unfavourable, almost linear relationship between the content of ceramic additive and the strengths. The smaller were strengths, the greater there was the amount of ceramic aggregate. Interesting tests of concrete with the addition of components derived from ceramic waste is shown in work [7]. They were run in two series. In the first series ceramic dust replaced part of cement, in the second series ceramic aggregate was replaced with part of the traditional aggregate. A number of physical and mechanical characteristics have been studied, including compression strength. Studies carried out in the first series showed that the introduction of 20% ceramic dust as a substitute for cement did not positively affect the strength properties of concrete. Compression strength tests showed a 10-20% decrease in strength compared to control samples. For the second series, the results show that replacement of the coarse fraction and sand fraction with red ceramic aggregate results in an increase in strength compared to control samples by approximately 10%. The overall conclusion is that the current research on the use of red ceramics is mainly focused on the environmental effect of recycling of waste materials.

The situation is somewhat different for white ceramics, conducted research in most cases have confirmed the beneficial effect of using such aggregate on the strength parameters of concrete. In studies [8] the authors present the results of investigations of mechanical properties of concrete in which the coarser aggregate fractions (5-20 mm) were replaced with aggregate prepared from the sanitary cullet. The study program assumed preparing of five blends including a control mix made on gravel aggregate.

The research showed that with the amount increase of thick aggregate from sanitary ceramics, the strength parameters of concrete increased within the scope of 2-8%. Also, other studies [9-12] confirmed beneficial effect of the use of ceramic aggregates on the concrete strength parameters. The strength characteristics of such concrete are similar or even higher than the parameters of concrete on conventional aggregates.

3. Ingredients characteristics of the concrete mixtures and samples

Six concrete mixtures were prepared for the study which were divided into two groups with different binders. The first group was based on the "Górkal 70" aluminous cement. The second group was made on Portland cement 32.5R. The aggregate used to prepare the sample was analyzed with the EDS detector. The research shows that the following weight percentages of the individual compounds: silica SiO₂ - about 68%, aluminum oxide Al₂O₃ - 24%, potassium oxide K₂O - 3%, Nickel(II) oxide
NiO - 3%, sodium oxide Na₂O - over 1% trace amounts (less than 1%) of iron-III-oxide, molybdenum and magnesium oxide. All samples were made exclusively from sanitary ceramic waste aggregates, which were crushed into two fractions. Both series of samples were divided into three types of samples: base(without additional aeration) and samples containing a certain amount of air entraining admixture producing 5% and 10% aeration of the concrete mix. Composition of six empirically designed concrete mixtures used in the study:

- Mixture A0: aluminous cement „Górkal 70” (488kg), aggregate 0-4mm (997,14kg), aggregate 4-8mm (398,86kg), water (199 l).
- Mixture A5: A0 + air entraining admixture Mikroporan (0,025% concrete mass – napowietrzenie mieszanki 5%).
- Mixture A10: A0 + air entraining admixture Mikroporan (0,1% concrete mass– mixture aerification 10%).
- Mixture B0: Portland cement „Jedynka 32.5R” (488kg), aggregate0-4mm (997,14kg), aggregate 4-8mm (398,86kg), water (199 l).
- Mixture B5: B0 + air entraining admixture Mikroporan (0,1% concrete mass – mixture aerification 5%).
- Mixture B10: B0 + air entraining admixture Mikroporan (0,2% concrete mass– mixture aerification 10%).

All samples corresponding to blends A0, A5, A10, B0, B5, B10 were divided into three groups. The first group was not subjected to thermal treatment. The second group was subjected to thermal treatment in the furnace at temperature about 1050°C. Whereas the third group was immersed in tap water for 24 hours, and then the samples were allowed to dry for 2 hours. Then the samples were subjected to soaking as did the samples of the second group. This has provided 18 groups of samples, shown in Table 1.

Table 1. Methodology of determination samples used in the tests.

| Binder type          | Aluminous cement | Portland cement |
|----------------------|------------------|-----------------|
| Concrete aerification| 0% 5% 10%        | 0% 5% 10%       |
| Base samples         | A0 A5 A10        | B0 B5 B10       |
| Soaked samples       | A0T A5T A10T     | B0T B5T B10T    |
| Soaked and wet samples| A0TW A5TW A10TW | B0TW B5TW B10TW |

Compression strength testing was performed on beam samples halves [13] which initial dimension was (4 cm x 4 cm x 16 cm). In total, there were made 252 tests with 14 for every group.

4. Strength of concrete on ceramic aggregates in fire conditions

4.1. Thermal treatment of samples

The heat treatment of the samples was performed in chamber electric furnace type PK 1100/5. The furnace is equipped with a heating system that allows to determine increase in temperature during the test. The device has a measurement and registration system for real-time temperature monitoring of 16 thermocouples. The structure of the furnace is made of steel pipes and its plating is from stainless steel. The insulating layer is made up of fittings and ceramic fibre mat. The regulating thermocouple is introduced through the rear wall of the furnace and located near its ceiling. Figure 1 shows the furnace used during soaking process and the sample in casings during soaking.
Figure 1. Furnace type PK1100/5 for samples soaking (a) Samples placed in metal casings in the furnace chamber (b).

During soaking there was adopted the standard temperature-time distribution according to [13]. The "temperature-time" standard curve is described by formula:

\[ T = 20 + 345 \cdot \log (\theta t + 1) \]  

where:
- \( T \) - temperature [°C],
- \( t \) - time [min].

The formula (1) defining the temperature distribution in the fire environment adopted for the determination of fire resistance of construction elements by the experimental method. Sample heating was performed according to the assumed curve for 120 minutes until the furnace chamber temperature reached 1050°C. The beams were cooled in the furnace for 24 hours. Then the strength tests were performed. In order to eliminate the possibility of furnace chamber damage during preheating, samples were placed in metal casings during the process.

4.2. Compression strength tests

Compression strength testing of beam halves according to [14] was carried out in the Building Laboratory of the Faculty of Civil Engineering and Architecture of the University of Lublin using the Servo-hydraulic testing system for Concrete and Mortar Advantest 9 of company Controls, shown in Figure 2. The beam halves were placed in the middle of the plates with an accuracy of ± 5 mm in length so that the leading surfaces of the beams project about 10 mm beyond the plates. The system works with the strain gauge bridge with the ability to read deformations at 4 measuring points. Additional cylinders give possibility to test the tensile strength of concrete elements such as standard cylindrical or cube samples or finished products in the shape of paving stones. During the test, the samples were loaded with increasing force at a constant speed of 2400 N /min until the time when the destruction occurred.
5. Research results

The graphs below show the average values with the standard deviations of the compressive strength of the beam halves made exclusively on the basis of ceramic aggregates. Figure 3 shows the results for a series of samples containing Portland cement, while Figure 4 shows the results of samples relating to the series containing aluminous cement. The white color on the graphs shows the results of the base samples, the gray is for the samples that was only heated, and the black for samples, which were pre-moistened and then heated. The description of the samples is shown in Table 1.

5.1. Samples made of Portland cement

The whole series contained 126 samples as beam halves. Base samples identified as A0 were distinguished by average compressive strength of approximately 83.1 MPa, samples from group A5 - 62.2 MPa and group of samples P10 - 67.2 MPa. During soaking 14 samples were destroyed (6 from the sample group with 0% aerification and 8 from the sample group with 5% aerification) and the remaining samples in this group showed large changes in the material structure, which became more brittle.

The obtained values of bending strength after sample soaking and soaking with moisteningshowed drops of up to 80%. Obtained reduction in compressive strength was not practically dependent on the degree of aerification. This dependence is due to the properties of Portland cement which
demonstrates low resistance to high temperatures occurring in fire. It should however be emphasized that in case of samples which were not aerated and undergone heat treatment, the average compressive strength does not deviate from the concretes on conventional aggregates.

5.2. Samples made of aluminous cement

In this series also made 126 samples. After soaking, none of them were destroyed and no changes were observed in their structure. The average compressive strength of the base samples containing 0, 5, 10% the degree of aerification showed almost identical values, with differences of only 2%. In each case tested, there were not observed negative effect of moisturing on samples strength. The highest decrease in beam compressive strength was recorded for samples subjected to thermal treatment without B0T air entraining admixture. The smallest decrease in beam compressive strength of wet samples as well as those heated is found for samples with 10% aerification.

![Figure 4. Average strengths for compressing beam samples (aluminous cement).](image)

6. Conclusions

The obtained results confirmed the possibility of using waste ceramic as a full-value concrete aggregate. The use of aluminous cement guarantees the production of high compressive strength and resistance to both high temperatures and moisture concrete. Such concrete can be successfully used in building with high requirements for fire resistance. The utilization of white ceramics by using it as a concrete aggregate will allow it to be fully utilized. It also helps reducing the use of natural aggregates. This way of using waste materials is also part of the design of so-called green concrete. Such concrete must meet the requirements for strength, durability and also, e.g., heating capacity and its components should be obtained, produced and used in an environmentally friendly manner. It should be emphasized that aerating the mixture and thus increasing the number of air pores in the structure of the concrete allows the flow of the water vapour, reducing the possibility of occurrence of the spalling phenomenon, i.e., thermal, explosive flaking. This is particularly important both to protect the structure of the building before uncovering reinforcement of load bearing elements. It also improves safety during rescue operations for responding to the fire risks.

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