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Modification of Refractory Concretes with Aeration Agents as a Method of Protection against the Phenomenon of Spalling

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Abstract: The aim of the work is to carry out tests analyzing the effectiveness of introducing pores to concrete on eliminating explosive spalling of concrete in fire conditions. A fireproof concrete is designed, which contains aluminum cement and aggregate obtained from waste sanitary ware. A Microporan aerating agent is used to modify the concrete features. The tests are carried out on cubic samples with nominal dimensions 10 × 10 × 10 cm and cylindrical dimensions 10 × 20 cm. Three batches of test samples are prepared, with different levels of aeration of the concrete mixture, i.e., without an aeration agent, with 0.5% and a 1% amount of aeration admixture weighted relative to the amount of cement used. Samples of all batches are divided into two series and conditioned in two types of environments with different humidity levels: dry and humid. The article presents the results of strength tests of concrete samples that are subjected to high temperatures similar to the temperatures occurring in the fire environment. The process of heating the samples proceeds according to the standard curve showing the temperature rise during the standard fire. The soaking temperature is in the range of 20 to 1000 °C. After baking in the oven, the samples are tested on a strength machine. The authors carry out only pilot studies. Only results from destructive tests of compressive strength of a refractory concrete composite are presented. The simulation station for the fire impact is the PK-1100/5 high-temperature chamber furnace together with the control system and a computer station with temperature monitoring software. Samples are loaded with increasing temperatures, according to the "temperature–time" standard curve. The compressive strength test is used as a criterion for assessing the effectiveness of the aeration agent. Strength tests are carried out both on unheated and soaked conditions in different environments. This paper presents the results of laboratory tests that allow for the authors to determine the characteristics of the material being tested. The empirical data include, among others, testing of selected physical properties (water absorption of concrete) and mechanical properties (measurements of compressive strength before and after thermal load). Based on the results obtained, conclusions from the tests are formulated. The proposed considerations show that the modification of the composite by aeration is an effective preventive measure in relation to the phenomenon of explosive concrete spalling.

Keywords: structural concrete; concrete spalling; fire temperature; aeration admixture

1. Introduction

Concrete is a non-flammable material that does not spread fire. Despite the very high resistance to damage in fire conditions, its strength parameters are reduced [1–3]. The destructive processes occurring in concrete lead to the deterioration of its functional characteristics, and, in extreme cases, to its total destruction.

The first destructive process that occurs in cement composites that are exposed to high temperatures is the evaporation of chemically unbound water [4–7]. It starts at a temperature of around 100 °C. To a small extent, this phenomenon is beneficial. It contributes to the increase of the compressive strength of concrete. However, the evaporation process cannot be violent. The water contained in the capillary pores, with the sudden surge in temperatures increasing its volume, exerts pressure on the capillary pore walls in which it is located. The increasing vapor pressure induces local tensile stresses in their surroundings. As a result, if the tensile stress exceeds the tensile strength of the concrete, the composite structure might be damaged [8–11]. This phenomenon, especially in the case of high-strength concretes, is characterized by a gradual build-up of stresses. Initially, microcracks form, which at some point rapidly spread, causing the explosive chipping of concrete fragments known as spalling.

Dehydration in concrete generally occurs as the temperature rises and is clearly visible at a temperature of around 400 °C [1,9]. The process of dehydration of cement binder minerals causes a reduction in binder strength, which consequently weakens the concrete structure.

Decarbonation is another process causing volume changes of the binder. This phenomenon occurs at a temperature of approximately 700 °C. When the cementitious bond reaction (1) occurs:

$$CaCO_3 \rightarrow CaO + CO_2 \tag{1}$$

Calcium carbonate decomposes to calcium oxide and carbon dioxide under high temperature. The breakdown of the inorganic salt compound significantly weakens the concrete structure. During the fire, concrete is drenched with water. The water that is supplied after the rescue operation can also be very unfavorable for the construction, as the calcium oxide formed as a result of the reaction (2) is hydrated:

$$CaO + H_2O = Ca(OH)_2 \tag{2}$$

The resistance of concrete to high temperatures has importance in the selection of its components. The temperature limit for using aluminum cement results from the chemical reaction during heating. Calcium hydroxide (slaked lime) is stable up to a temperature of approximately 400 °C. Removal of chemically-bonded water occurs at approximately 500 °C. The calcium hydroxide is part of the crystal lattice that is formed during the binding, which then transforms into the free quicklime, which is capable of self-reattaching, as described in Equation (2). This phenomenon is accompanied by a strong increase in the volume of calcium oxide. The particles growing under the influence of water often violate the compact structure of the composite, and consequently cause its decay [8,12].

A new solution aimed at improving the properties of concretes at high temperatures is the use of special cements and waste ceramic aggregates for their production. Regarding results from the tests carried out so far [4–6], concretes made based on aluminum cement and waste ceramic aggregates due to the low content of CaO are not subjected to destructive reactions (1) and (2). The composite, at a slow temperature increase, maintains the invariance of the form and high strength parameters [4–6,9,12], even at temperatures of 1000 °C. Rapidly increasing temperatures, however, result in the destruction of concrete as a result of the thermal spalling of its fragments. The water that is contained in the capillaries of the concrete during boiling increases its volume, resulting in the formation of tensile stresses, causing explosive destruction [10,13,14].

There are many works in the literature that are devoted to changes in mechanical and physical properties, mortars, slurries, and concretes at high temperatures. Scientific research takes two directions. The first one is looking for materials that can work reliably in an environment with constantly increased temperature. The second one examines the behavior of materials for which the high temperature load is only an emergency situation, as it happens in the case of fires [15–18].

Changes in deformation in concrete take place relatively quickly. Thermal expansion of the material is influenced by the heat flow coefficient and swelling. The pressure causing swelling occurs as a result of the capillary tension of the water that is contained in the cement paste as a result of the temperature increase. The diffusion of moisture from the gel to the capillary pores is compensated to some extent by the phenomenon of contraction resulting from the loss of water through the gel as a result of drying the leaven.

A sharp increase in the so-called temperature thermal shock is an unfavorable phenomenon that occurs during a fire. It is difficult to obtain a composite characterized by failure-free operation during the operation of exceptional loads. The occurrence of explosive chipping of concrete fragments is particularly dangerous. The cause of spalling is the increasing pressure of water vapor that is contained in the free spaces of the composite. Under the influence of temperature, the water increases its density and causes pressure on the capillary pore walls. This leads to stretching stresses. When the stresses exceed the value of the tensile strength of the material, explosive detachment of concrete fragments takes place. This phenomenon applies mainly to concretes with high tightness, for which the downstream pair is not able to expand freely.

One of the innovative approaches for designing fire-resistant concrete is the use of aggregates made of sanitary ceramics and aluminum cement for production [4–6]. The resulting products from baked clays are resistant to high temperatures. However, research shows that not all types of ceramics are suitable to produce high-strength concretes, from which construction elements can be made. The authors developed a model of a concrete mix that was used to design concrete resistant to the phenomenon of spalling presented in this paper.

The research carried out is of great importance for science. Currently, materials are being sought that will be able to work in an elevated temperature environment and ensure the safety of evacuees and rescue teams. Due to the thermal load, which is characterized by a rapid temperature rise during a fire, it is difficult to obtain concrete with the ability to work without failure under this type of load.

The main purpose of the study is to design concrete that would be resistant to the phenomenon of spalling. It would maintain the strength parameters both during and after heating in temperatures simulating fire and extinguishing actions. An attempt is made to design a new cement composite by chemical modification. An aerating agent is used, and a binder of aluminum cement is used. Cement clay is characterized by a rapid increase in strength in the first days after use and increased resistance to high temperatures.

2. Materials and Methods

2.1. Materials

The experiment included the study of 45 cuboidal samples with standardized nominal dimensions of 10 × 10 × 10 cm and 30 samples in the form of cylinders with a diameter of 10 cm and a height of 20 cm. The samples were made of a concrete mixture based on ceramic aggregate and aluminum cement, which is in accordance with current standards [19–24]. The basic component of the designed composite was ceramic aggregate derived from post-production waste sanitary ware; those not suitable for sale ceramic products, 5–15 cm in size, had defects such as: cracks, enamel damage, or surface unevenness. These products underwent a crushing process in jaw crushers, whose work process allowed segregation of the aggregate into two granules: Fine grain size with a grain fraction from 0 to 4 mm and a thick grain fraction of 4–8 mm. Thicker grains were crushed again. A refractory hydraulic binder, GÓRKAL 70 aluminum cement obtained by grinding bauxite with a high content of aluminum oxide with limestone, was used for the binding component. Said cement is characterized by high strength and a short setting time. Due to the low content of CaO (about 30%) it is also used to produce refractory concretes.

The concrete mixture used tap water in accordance with the requirements of PN-EN 1008:2004 "Water for concrete. Specification of sampling, testing and evaluation of the mixing water".

As a modifier of the composite, Stachem's Microporan aerating agent was used. The mentioned admixture improves the workability of the concrete mix, reduces settling and release of cement milk, slightly plasticizes, and creates a system of air bubbles. This agent contains hydrophobic surface-active compounds, reducing the surface tension and making it possible to form a very fine-dispersive foam in the concrete mix, with a bubble diameter of about 20 μm. The bubbles in their main application interrupt the capillary pores in the concrete, lower the capillary rise of the water, and reduce the absorbability, thus increasing the frost resistance of the concrete. Potentially, they can also be a volume reservoir for increasing the volume of water in the pores during annealing.

Previous studies on ceramic aggregates have proven that the standard design methods did not give the expected results [4,5]. Porous grain structure and absorbability cause cement paste to not fill all the spaces between the aggregate. Therefore, the experimental method that is presented in this work brings valuable information to current literature, and the research is innovative. The results of laboratory research can be used in the future in industry. Conversely, the direction of research that is adopted by the authors is forward-looking.

2.2. Research Methods

The conducted research entitled "Modification of refractory concretes with aeration agents as a method of protection against the phenomenon of spalling" was carried out in the Laboratory of Mechanics and Strength of Materials at the Main School of Fire Service, where the appropriate measuring station is located. The measuring station includes an electric furnace and a testing machine adapted to test the compressive strength of concrete.

To heat the concrete samples, a medium-temperature electric chamber furnace type PK-1100/5 was used together with a control system, a computer station with appropriate software for temperature monitoring, and control of the heating process. The diagram is shown in Figure 1. The program was prepared and written in the Visual Studio 2008 environment for temperature simulation. The furnace is made of sections and stainless steel. The insulating layer is a chamotte brick and a mat of ceramic fibers. The heating element of the furnace are spirals made of Kanthal A1 retaining wire. The upper part of the furnace has chimneys for draining steam and a thermocouple.

Figure 1. View of the PK 1100/5 chamber furnace with instrumentation.

Strength tests were carried out with the Controls Adventest 9 hydraulic press with a console and computer, along with the software. The view of the machine adapted for compressive strength testing with the force sensor installed is shown in Figure 2.

Figure 2. View of the Controls Advantest 9 hydraulic press adapted to test compressive strength.

The process of heating the samples proceeded according to a standard curve showing the temperature rise during a real fire. The temperatures that were used in the tests ranged from 20 to 1000 °C. The temperature was measured using an external thermocouple and internal thermocouples, Figures 3 and 4. During the research, the aim was to make the temperature distribution close to the thermal conditions of a standard fire, which can be represented by a normalized "temperature–time" curve showing the thermal conditions in the test furnace. The temperature distribution was assumed on the surface of a standard concrete slab, which can be determined by means of the empirical relationship described by Formula (3) [8].

$$T_p = 1250 - (1250 - T_o) \cdot erf \frac{K}{2 \cdot \sqrt{t}} \tag{3}$$

where:

K—material factor, depending on the material density,
t—duration of fire [h],
T_o—the initial temperature of the plate surface [°C],
T_p—surface temperature of the plate from the heating side [°C], and
erfx—Gaussian error function, not having finite decomposition into elementary functions, essentially:

$$erf x = \frac{2}{\pi} \int_o^x e^{-x^2} dx \tag{4}$$

Figure 3. View of cylindrical samples before temperature loading, thermocouple fixing.

Figure 4. View of cubic samples before temperature loading, thermocouple fixing.

The testing program assumed compressive strength tests on cubic and cylindrical samples. The samples were made based on aluminum cement and ceramic aggregates. Samples were stored until testing under laboratory conditions. They were then subjected to rapid heating in the PK-1100/5 electric chamber furnace. The process of forming and testing samples was in accordance with the standard requirements. Samples before baking in the furnace are shown in Figures 3 and 4.

The compositions of the concrete mixtures were differentiated in terms of the amount of aerating agent. The samples were divided into three lots. Samples of batch A were made without an aerating agent using the composite that is shown in [4]. Batch sample B used 0.5% by weight of the aeration agent in relation to the cement mass. Regarding batch sample C, 1% by weight of the aerating agent in relation to the cement mass was used. Subsequently, for batches of samples A, B, and C with respect to 1 m^3 of concrete, the amount of admixture was, respectively, 0.00 kg, 2.4 kg, and 4.8 kg. The composition of the concrete mix, the basic batch A without the additive, is given in Table 1.

Table 1. A composition for a mix of lot A used to make samples.

No.	Mixture Component	Component Weight	Ingredients on 1 m^3
1	Fine aggregate	44.87 kg	997.14 kg
2	Coarse aggregate	17.95 kg	398.86 kg
3	Alumina cement	21.96 kg	488.00 kg
4	Water	8.96 kg	199.00 kg

Molds for making samples after filling with a concrete mix were vibrated and placed in a climatic chamber. The following day, the samples were dissected and subjected to further maturation. Samples were kept in the climatic chamber for 28 days [22–24]. Strength tests were carried out (depending on the type of samples) in stages that simulated the fire conditions. Tables 1–4 present the test program for the designed concrete composite.

The first part of the experiment included measuring the absorbability and compressive strength tests for cubic samples (10 × 10 × 10 cm). Samples were randomly selected from each batch, which were not subjected to annealing, and were to constitute the control samples in research works. Then, four samples were selected from each batch (1, 2, 3, 4, 16, 17, 18, 19, 31, 32, 33, 34) and then subjected to annealing. To analyze what effect the moisture content has on the concrete during high fire temperatures, the remaining samples (5, 6, 7, 8, 20, 21, 22, 23, 35, 36, 37, 38) were immersed in water for 24 h. The conditioning of samples in such conditions was supposed to simulate concrete work in wet conditions like a tunnel. The samples after removal from the molds and the numerical designation are shown in Figure 5.

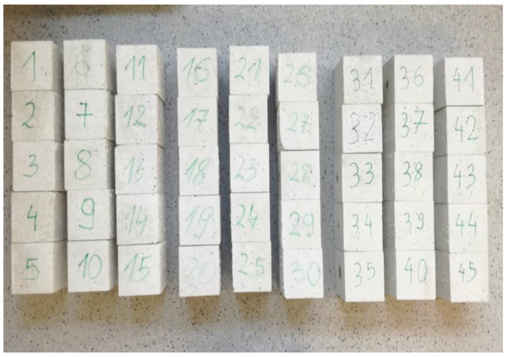

Figure 5. Samples for strength tests, Lot A (No. 1–15), B (No. 16–30), and C (No. 31–45).

The process of heating the samples from the moment the furnace was switched on was recorded. Figure 6 shows the view of the samples after temperature loading. The results are depicted on the graph (Figure 7) using the "temperature–time" standard curve. The concrete was subjected to annealing up to approximately 1000 °C for 120 min. The temperature increase in the furnace took place a bit slower than it was visualized by means of a standard (cellulose) curve. These differences are small, and it can be concluded that the increase in furnace temperature reflected the increase in temperature in the fire conditions.

Figure 6. View of samples after temperature loading.

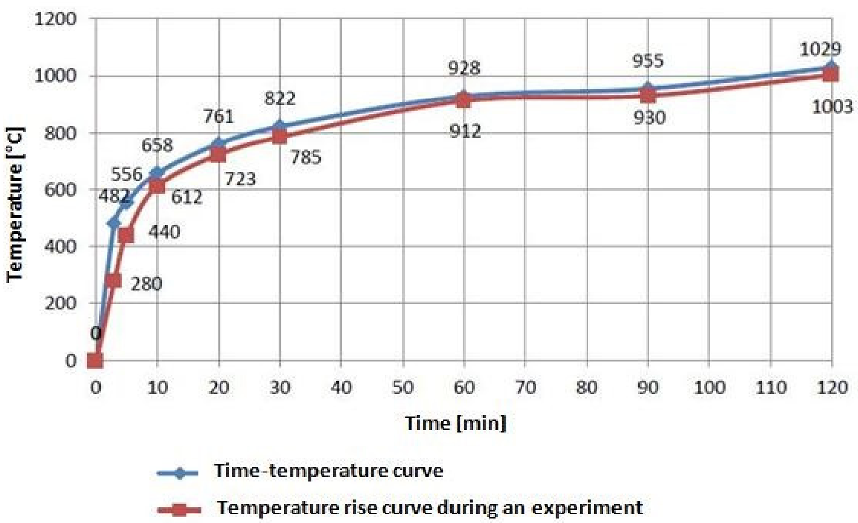

Figure 7. Curve showing the temperature increase in the furnace during the test.

All of the samples of different lots A, B, and C subjected to annealing, non-heated and conditioned in different environments, moisture and compressive strength tests were carried out. The moisture content was estimated as the mass of water contained in the sample in relation to the weight of the dry sample and expressed as a percentage. Compressive strength tests were carried out on a Controls strength machine. They were conducted in accordance with the standard procedures [25–27].

The second part of the experiment included tests of cylindrical samples with nominal dimensions of 10 × 20 cm. The investigators randomly selected samples that were the reference point. The remaining ones were moistened by immersion in water for 24 h. The samples were then placed in an oven and thermocouples that are attached to them (Figure 3). Later in the study, the samples were not wetted. Some of them were subjected to annealing, previously placed in steel covers to avoid damage caused by concrete chipping. The next stage of the study provided the simulation of fire conditions for samples with different humidity. Compressive strength tests were carried out after exposure to high temperatures. The last step involved compressive strength tests of the cylindrical shaped reference samples.

To test the compressive strength, the authors prepared 30 cylindrical samples that were adapted for testing under fire conditions. They were made based on aluminum cement. Samples were divided into three batches (A, B, and C) due to the degree of aeration (0%, 0.5%, and 1% by weight of aeration agent in relation to mass cement). The samples were then treated after conditioning. Following 28 days of maturation, the samples were stored under air-dry conditions for a further 30 days. Then, 10 reference samples were selected from each batch. The remaining ones were thermally loaded using a chamber furnace. Samples were loaded at 400 °C and 800 °C.

The authors carried out only pilot studies. The article presents only results from destructive tests of compressive strength of a refractory concrete composite. In the future, to broaden the approach to the subject, the experimental program will be extended—testing the tensile strength of a concrete composite and further statistical analysis.

3. Results and Discussion

Following test performance in accordance with the previously established research program, the subsequent results are presented in the form of diagrams (Figures 8 and 9) and tables (Tables 2–4) describing the behavior of the composite that is made of 100% recyclable aggregate and the moisture content of the samples subjected to soaking. Table 2 illustrates the water content in individual samples and the percentage of moisture content in subsequent batches. Absorption was tested on cubic cubes. Four samples from each series were tested. The samples were immersed in water and remained in it in order to determine their mass. Samples that passed the baking process positively were weighed to determine the moisture that is contained in them. The moisture content of the samples was calculated as the ratio of the amount of water the concrete was able to absorb to the mass of dry concrete expressed in percent and the obtained results were averaged. Samples that were not included in Table 2 were not soaked or were burned as a result of annealing.

The average moisture of all the samples was 8.70%. The samples that were ripened in the laboratory room conditions had an average humidity of 6.74%. The moisture content of these samples tested for each series was almost the same and was equal to A: 6.67%, B: 6.99%, and C: 6.59%.

Samples that were submerged in water for 24 h after ripening were subjected to annealing and had an average humidity of 10.90%, while the humidity that was tested for each series was A: 11.30%, B: 11.02%, and C: 10.39%. It was observed here that, as the amount of aerating agent increased, the samples had slightly lower humidity despite conditioning under the same moisture conditions. The described method of moistness represented the conditions of samples in moist conditions, like tunnels.

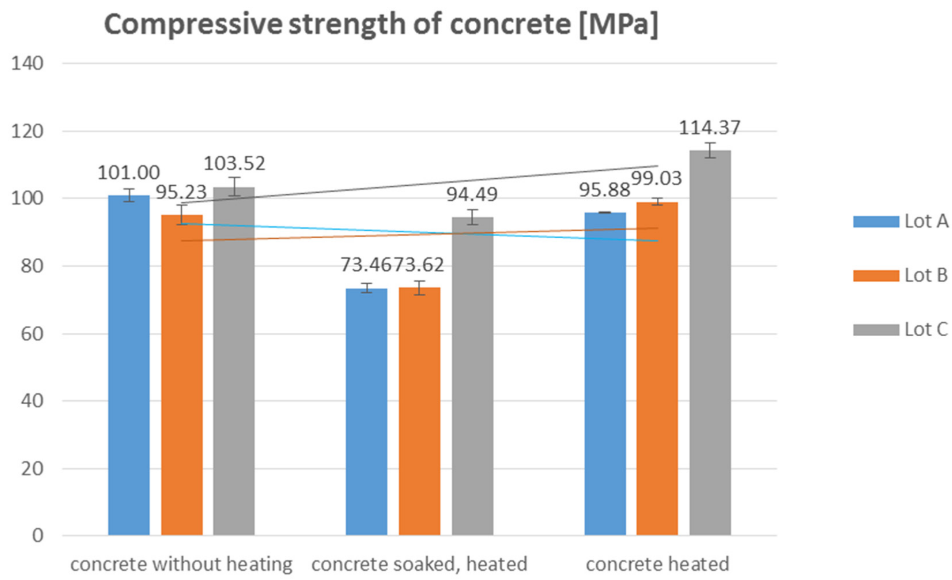

Figure 8. Average compressive strength of individual parts of the concrete mix, including aerated admixture—lot A (0%), lot B (0.5%), lot C (1%).

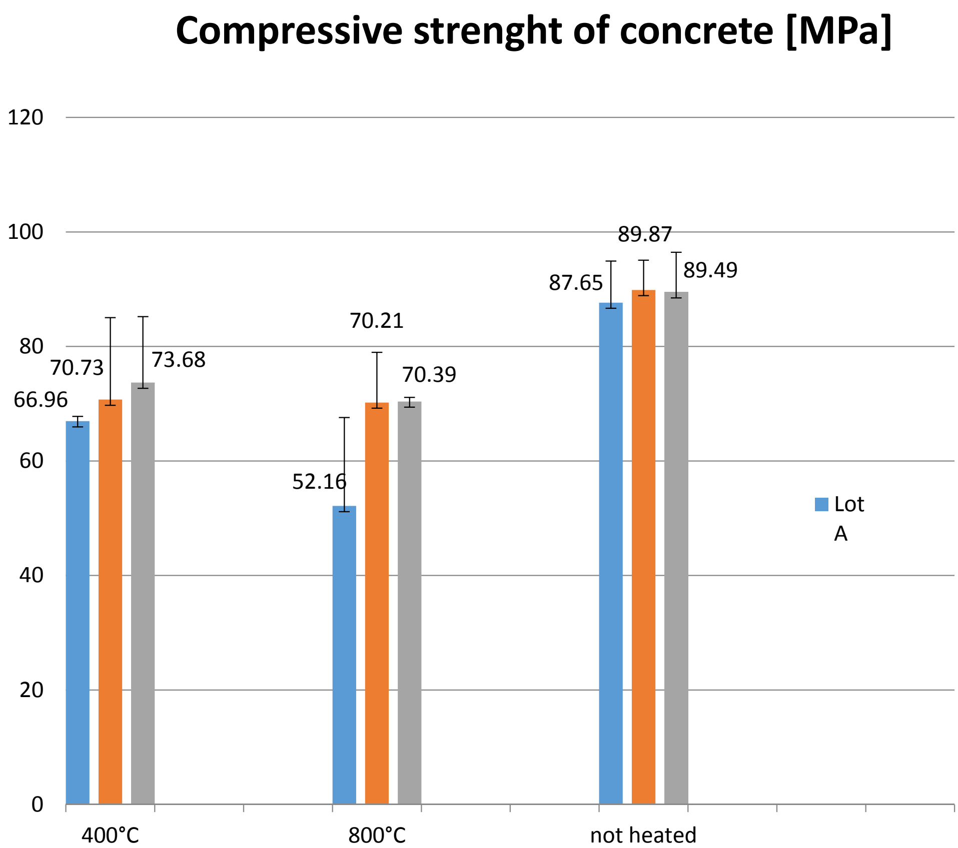

Figure 9. Average compressive strength (cylindrical samples) of individual lots of concrete mix including aeration admixture—lot A (0%), lot B (0.5%), lot C (1%).

Table 2. Moisture samples subjected to soaking.

The Share of Aeration Admixture	Sample Number	Weight of the Wet Sample [kg]	Weight of the Dried Sample [kg]	Water Weight [kg]	Moisture Share [%]	Average Humidity [%]
0%	7	2.28	2.01	0.27	11.42	11.30
	8	2.29	2.03	0.26	11.18	
	14	2.28	2.11	0.17	7.80	6.67
	15	2.29	2.17	0.12	5.53	
0.5%	20	2.14	1.9	0.24	10.85	11.02
	21	2.18	1.92	0.26	11.46	
	22	2.11	1.89	0.22	10.72	
	23	2.14.	1.9	0.24	11.03	
	26	2.11	1.98	0.13	6.30	6.99
	27	2.16	2.01	0.15	7.46	
	30	2.16	2.01	0.15	7.20	
1%	35	2.18	1.95	0.23	10.20	10.39
	36	2.16	1.94	0.22	10.05	
	38	2.12	1.88	0.24	10.93	
	39	2.13	1.95	0.18	9.25	
	41	2.22	2.1	0.12	5.73	6.58
	42	2.20	2.06	0.14	6.54	
	43	2.18	2.07	0.11	5.06	
	44	2.21	2.07	0.14	6.51	
	45	2.17	–	0.13	6.37	
Average humidity:						8.70
Average humidity of samples in laboratory conditions:						6.74
Average humidity of samples after submersion in water:						10.90

The results of compressive strength tests of samples are presented in a tabular manner (Table 3) and in bar graphs (Figure 8). The average strength of the A batch concrete without the aeration addition, which was not subjected to previous dipping and soaking, was approximately 101.00 MPa. Samples that underwent only annealing obtained an average strength of 95.88 MPa. The compression strength of the samples, which before bending were submerged in water to 9.29% moisture and decreased to 73.46 MPa, decreased the most. However, it is worth noting that in this batch there was an explosion of two samples during the soaking. Samples of lot B under the conditions that are described above reached a strength of 95.23 MPa, 99.03 MPa, and 73.62 MPa, respectively. The last series of tests was carried out on C samples. The average strength of the standard samples for this series was 103.52 MPa. Conversely, the samples that were subjected to self-heating and compression reached the value of 114.37 MPa. The lowest compression strength (94.49 MPa) was achieved by water-immersed and heat-treated samples.

Analyzing the results of the research, a significant influence of aeration addition on the strength parameters of concretes was noted. Introducing it to the concrete mix at the level of 0.5% by weight in relation to the cement mass caused the strength of the concrete subjected to self-heating to increase by approximately 3.15% in comparison with the pre-heated and non-aerated concrete. Regarding the case of 1% addition of the aeration agent in a weight ratio to the cement mass, an increase in the strength of the concrete by 18.49% was observed. The obtained test results show that increasing the degree of aeration of concrete translates into an increase in the compressive strength of concrete, subjected to high fire temperatures.

The uncertainty of measurement for a testing machine for evaluating building materials Controls was determined in accordance with document EA-4/02 M: 2013: Determination of uncertainty of measurement during calibration. The specified uncertainties in the calibration certificate issued by the accredited laboratory are extended uncertainties with the probability of expanding to approximately 95% and the expansion coefficient k = 2. Due to the calibration, it was found that the testing machine met the standard requirements and was qualified to accuracy Class 1 in the measurement range from 100 kN to 3000 kN for tensile strength in bending. The indication error, according to the calibration certificate, is for 300 kN, 600 kN, and 900 kN, respectively, 0.04%, 0.14%, and 0.41%. However, when the testing machine worked in the range of 10 kN to 250 kN for compressive strength, the indication error for forces of 60 kN, 100 kN, and 150 kN is 0.05%, 0.67%, and 0.63%, respectively. The expanded uncertainty in both cases is 0.25%.

Table 3. Results of current research. Compressive strength.

Type of Lot	Medium Durability [MPa]	Standard Deviation [MPa]	Volatility Indicator [%]	Measurement Uncertainty MPa
Test without dampness and without heating				
A	101.00	2.02	2.00	3.45
B	95.23	2.88	3.02	4.11
C	103.52	2.80	2.70	3.77
Test without humidity after heating				
A	95.88	0.30	0.31	2.24
B	99.03	1.08	1.09	2.58
C	114.37	2.27	1.98	4.08
Test after moisture and after heating				
A	73.46	1.33	1.81	2.16
B	73.62	2.09	2.84	2.96
C	94.49	2.36	2.49	3.54

The average compressive strength (cylindrical sample) of individual lots of concrete mix is shown in Table 4 and Figure 8.

Table 4. Results of current research. Compressive strength of cylindrical samples.

Sample Type	Medium Durability, MPa	Standard Deviation, MPa	Volatility Indicator %
Test without heating			
A	87.65	7.27	8.29
B	89.87	5.18	5.76
C	89.49	6.97	7.79
Test at 400 °C			
A	66.96	0.83	1.24
B	70.73	14.30	20.22
C	73.68	11.52	15.64
Test at 800 °C			
A	52.16	15.42	29.56
B	70.21	8.76	12.48
C	70.39	0.71	1.01

The standard deviation for bending tensile strength is very diverse. The tested samples at 400 °C were characterized by different deviations, and the coefficient of variation of strength for concrete samples with differentiated aeration content was more than 20 times (B series) and 15 times (C series) higher than samples to which no aeration addition was introduced. Regarding the case of cylindrical samples that were subjected to annealing to the temperature of 800 °C, the index of variation depended on the amount of aeration agent that was added. However, for samples not subjected to annealing, the coefficient of variation was similar. The calculated value of the coefficient of variation indicated a small variation of the analyzed strength trait because it did not exceed 50%.

The analyses of the results prove that the change in the degree of aeration of the concrete mix affects compressive strength. As the aeration addition increased, the strength of the element grew.

Conversely, the strength of concrete exposed to high temperatures decreased correspondingly to non-heated samples. Cylindrical samples heated at 400 °C reached a strength of 66.96 MPa, 70.73 MPa, 73.68 MPa for lots A, B, C. Similarly, samples were heated at 800 °C—52.16 MPA (A), 70.73 MPa (B), and 70.39 MPa (C).

The greatest threat to the natural environment is waste. The priority of waste management is to find ways to reuse it, which will be economically justified. Utilization is the most effective method of their management. Thanks to recycling, people can again use materials from ceramic cullet with a small expenditure for their processing. It allows for people to protect natural resources that are used for their production and subsequent processing. The research shows that one of the directions of processing of inorganic raw materials, such as waste sanitary ware, is to use them to produce building materials. Wastes from sanitary ceramics are biologically neutral and they do not threaten the environment after crushing. This waste might be a substitute for natural aggregates that are popularly used to produce cement composites. The authors in their research work have designed the so-called "green concrete", with an aggregate that was made of white ceramics and aluminum cement. Recovery of recyclable materials has a doubly beneficial effect on the environment: It reduces the amount of waste and reduces the extraction of aggregates from natural resources. Searching for alternative aggregates based on industrial waste is, therefore, not only in line with economic trends, but is also ecologically justified. Ceramic aggregate that was obtained from cullet need not be processed in a particular way. As a result, the process of producing a concrete mix from recycled material is similar to traditional methods. While carrying out the research, the authors attempted to utilize waste from sanitary ceramics. Recovering unconventional aggregates in the future might result in great interest due to the cost of manufacturing and the increase in the price of traditional aggregates.

4. Conclusions

The main goal of the experiment was to analyze the influence of temperatures occurring during fire on the change of strength parameters of the concrete composite and to analyze the effectiveness of introducing pores in the concrete to eliminate explosive concrete spalling in fire conditions.

The analysis of the literature shows that there is a lack of work that is related to testing the properties of modified concretes subjected to thermal shock and physical and chemical changes affecting the material properties occurring during cement hydration. There is a lack of sources in the literature on how to assess the type of cement, whether the type of additive or admixture affects evaporation of concrete water and clustered structures on its surface (areas on the surface of the sample are limited by scratches or edges of the sample), and for unfavorable dropping of particles of construction material. It should be emphasized that the conducted research requires very high accuracy at every stage of the technological process. The process starts with the preparation of a cement mix and it ends with heating the samples. Any inaccuracies as a result of deviation from the initial assumptions at any stage affect the accuracy and correctness of the results.

Modification of the concrete with an aerated admixture is an effective procedure in the design of concrete resistant to suddenly rising temperatures, as demonstrated by the study results. Aeration of concrete using an aeration agent is particularly advantageous. Following heating, this concrete, despite sudden temperature increases, was characterized by high strength parameters. Its composition is considered as the concept for a new, ecological cementitious composite that is able to carry loads even in fire conditions. Its use in constructions that are exposed to the threat of high temperatures in humid conditions, such as tunnels, can significantly increase the safety of both users and the people carrying out rescue operations.

Based on macroscopic observations with the unaided eye of concrete samples subjected to annealing at fire temperatures (from 20–1000 °C) and comparably ripening at 20 °C, the following can be stated:

1) The advantage of using aluminum cement is a rapid increase in strength and resistance to high temperatures.

2) Particularly noteworthy is the innovative approach that is expressed using ceramic aggregate that is derived from the recycling of sanitary ceramic waste. Until now, concrete has been studied in the world literature with the addition of recycled aggregate. The authors, in their research, proposed a complete conversion of the aggregate into recycled aggregate.
3) The strength properties of a concrete composite are irreversibly reduced at high temperatures. At a temperature of 800 °C, the strength of the concrete drops by 20% to 40%, in relation to the measured strength of the standard samples.
4) A significant influence of aeration admixture on the increase of strength of fire resistant concrete in high temperatures was noted. When introduced into the air bubble mixture, the average compressive strength increased by approximately 35% when the element was heated to 800 °C. However, the air bubbles in the heated composite up to 400 °C caused an increase in strength by approximately 10%.
5) When changing the moisture of the samples, the authors noticed that the content of aeration admixture in the amount of 1% in relation to the cement mass increases the compressive strength of concrete up to approximately 28%.
6) Cooling of the structure during fire-fighting is also of great importance. Watering the structure with water lowers the compressive strength of the structural element. The current analysis has shown the heating of the moist samples.
7) The heating of the samples at 800 °C results in scratches and the weakening of the concrete.

The authors carried out only pilot studies. This article only presents the results of destructive tests of compressive strength of a refractory concrete composite, which contained aluminum cement and aggregate obtained from sanitary ceramic waste. As part of the next stage of the experiment, to broaden the approach to the subject, a number of tests will be carried out to check the tensile strength of samples with dimensions of 50 × 10 × 10 cm, in addition to further statistical analysis.

A thesis was made, which assumed that the arrangement of air bubbles in the composite, which would be a volume reservoir for increasing the volume of water, would be a way to eliminate the destructive phenomenon occurring in the concrete. The results of the tests prove that the modification of the composite by aeration is an effective means of eliminating spalling. Similar research with the use of unconventional waste ceramic aggregates in the literature has not been recorded. The results that will be obtained in future research will be necessary to assess the occurrence of explosive concrete spalling, working in the actual building structure under operating conditions. The performed tests prove that the combination of alumina cement with aggregate from ceramic cullet is suitable for composing high temperature-resistant concrete. The presented experimental results lay the foundations for continued future research.

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