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The influence of high temperatures on selected strength properties of fine-aggregate fiber composite

Wpływ wysokiej temperatury na wybrane cechy wytrzymałościowe drobnokruszywowego fibrokompozytu

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Abstract. The paper presents an analysis of the influence of high temperature on selected mechanical properties of finely aggregated mineral composite with dispersed steel reinforcement. The designed fibrecomposite has properties similar to or better than ordinary concrete and can be successfully used to make load-bearing reinforced concrete elements. The change in compressive strength and residual tensile strength during bending of the fibrecomposite was determined at room temperatures and determined according to the fire curve imitating the temperature build-up during a real fire. The research program also included the assessment of the weight loss of fibrecomposite samples annealed in the furnace. Studies have shown that the addition of steel fibers to the composite mix in the amount of 1.2% contributes to the preservation of its mechanical properties when exposed to temperatures up to 550°C due to fire, and thus is able to improve its structural stability at high temperature. Steel fibers significantly improve the fire-retardant properties of the fine-aggregate composite.

Keywords: fine-aggregate composite; mechanical properties; steel fibers; high temperature.

Streszczenie. W artykule przedstawiono analizę wpływu wysokiej temperatury na wybrane właściwości mechaniczne drobnokruszywowego mineralnego kompozytu ze stalowym zbrojeniem rozproszonym. Zaprojektowany fibrokompozyt charakteryzuje się właściwościami zbliżonymi bądź lepszymi niż beton zwykły i może być z powodzeniem wykorzystany do wykonywania nośnych elementów żelbetowych. Zmianę wytrzymałości na ściskanie i wytrzymałości resztkowych na rozciąganie przy zginaniu fibrokompozytu określono w temperaturze pokojowej i wyznaczonej wg krzywej pożarowej imitującej narastanie temperatury w trakcie rzeczywistego pożaru. Program badawczy obejmował także ocenę ubytku masy próbek fibrokompozytu wygrzewanych w piecu. Badania wykazały, że dodatek włókien stalowych do mieszanki kompozytu w ilości 1,2% przyczynia się do zachowania jego właściwości mechanicznych po wystawieniu na działanie temperatury do 550°C z powodu pożaru, a tym samym jest w stanie poprawić jego stabilność strukturalną w wysokiej temperaturze. Włókna stalowe znacznie poprawiają ognioodporność drobnokruszywowego kompozytu.

Słowa kluczowe: kompozyt drobnokruszywowy; właściwości mechaniczne; włókno stalowe; wysoka temperatura.

One of the most important advantages of concrete as a building material, compared to other construction materials such as steel or wood, is its behavior when exposed to fire and high temperatures. Destructive factors affecting concrete structures, i. e. the influence of static and dynamic loads, the effects of groundwater and weather conditions, have been well recognized and can be taken into account when designing structures. Partially researched factors include the influence of the temperature occurring during a fire on the strength parameters of building materials [1]. The influence of elevated and high temperatures on the operation of concrete structures is manifested in changes in the physical and strength properties of the heated material (concrete and steel) and the occurrence of deformations and thermal stresses [1, 2]. This means that the problem of fire safety of structures is one of the six basic requirements that buildings must meet in the light of applicable regulations. A characteristic phenomenon of high temperature affecting concrete structures is explosive spalling of concrete [2 – 5], which endangers people's lives during a fire. The reason for this is the occurrence of high water vapor pressure in the concrete pores and thermal stresses

In the 1980s, a positive effect of the addition of dispersed fiber reinforcement on reducing spalling was discovered [6, 7]. The study of fiber composites exposed to high temperatures is still a current topic in concrete construction. The analyzes concern primarily steel fibers and also in combination with polypropylene fibers (hybrid reinforcement), and to a lesser extent the use of only polypropylene fibers [8 – 12]. Many research centers are conducting work on the impact of fire and high temperature on various properties of fiber composites, e. g. Deshpande and his

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team [6] stated that the most favorable fiber content is 1 ÷ 2% in relation to the weight of the composite. We also used this share of steel fibers in our tests. Deshpande also studied the effect of high temperature (100 ÷ 800°C) on the anchoring of conventional reinforcement in fiber concrete and on the change of its mechanical properties [7]. He showed, among other things, that adhesion stresses decrease with increasing temperature. Ruano and his team [13] investigated the effect of high temperature on the mechanism of pulling steel fibers from the high-strength concrete matrix and the effect on the residual strength. It was found that the decrease in this strength results primarily from the weakening of the strength of steel fibers and friction forces as a result of high temperature. A reduction in the residual strength and tensile strength of the material was also observed. Temperature also influences the compressive strength and static modulus of elasticity of fiber concrete [14]. Researchers were also interested in the influence of high temperatures (400, 600 and 800°C) on the behavior of cracked fiber concrete elements subjected to bending [4].

The analysis of research works showed that in general there is a deterioration of the tested characteristics of fiber concrete at temperatures up to 100°C, while from 100°C to 500°C there is a gradual increase in the strength of fiber concrete, and at a temperature of 500°C it is even higher than that obtained on unheated samples. Generally, after exceeding 500°C, the tested features deteriorate. The use of fibers as dispersed reinforcement contributes to improving the resistance of fiber concrete at elevated temperatures, prevents spalling, limits dimensional differences, and maintains the cohesion of concrete. This beneficial effect of fibers on the properties and method of destruction of fiber concrete prompted us to analyze the impact of high temperature on selected properties of a fine-aggregate fiber composite using steel fibers and aggregate that is post-production waste. Previous research has shown that the developed fiber composite, registered with patent No. 239641, can be successfully used to make industrial floors, slabs and small-sized structural elements subjected to short-term and long-term loads, operating in moderate thermal and humidity conditions [15 – 17]. However, the behavior of such a fiber composite under high temperature conditions similar to the temperature occurring in a fire environment has not yet been recognized, which is the aim of the presented research. This is part of a larger experiment. The subject matter is consistent with current research trends related to the search for materials with increasingly better properties, produced using waste raw materials. Thus, it fits into the global trend of Sustainable Environmental Development.

Materials used in research

The subject of the research is a fine-aggregate cement composite with the addition of steel fibers in an amount of 1.2% (94 kg/m^3) in relation to the volume of the composite. To make the test elements, we used glacial sand obtained after the hydroclassification process, granulation up to 4 mm in an amount of 1570 kg/m^3, Portland cement CEM II/A-V 42.5R (420 kg/m^3), silica dust (21 kg/m^3), superplasticizer (16.8 kg/m^3) and water from the municipal water supply (160 kg/m^3). The dispersed reinforcement consisted of hook-shaped steel fibers with a slenderness of $\lambda = l/d = 62.5$ ($l = 50$ mm, $d = 0.8$ mm). The fiber content was determined based on the results of previous composite tests and was 0 – 2.5% [16]. The designed fiber composite is characterized by properties similar to or better than those of ordinary concrete (Table 1) and can be successfully used to make reinforced concrete elements reinforced with steel fibers, operating under bending and shear conditions [15, 17]. The procedure for dosing ingredients, conditions for sample preparation and their care are discussed in [15 ÷ 17].

Tests specimens and methodology

The aim of the research was to assess the effect of high temperature on the basic properties (compressive strength and residual flexural tensile strength) of a fine-aggregate mineral composite reinforced with steel fibers. Test elements (cubic samples with sides of 150 mm and beams with dimensions of 150 x 150 x 550 mm) were heated at temperatures of 20, 200, 300, 400, 500, 550, 600 and 800°C with an accuracy of ±1°C, in an electric medium temperature furnace. The sample heating process was carried out according to the so-called a fire curve imitating the temperature rise during a real fire [18]. The sample heating procedure was in accordance with RILEM guidelines [19]. The

Table 1. Mechano-physical properties of the analysed fiber composite and ordinary concrete

Tabela 1. Właściwości mechaniczno-fizyczne fibrokompozytu i betonu zwykłego

Property	Material	
	fiber composite (coefficient of variation)	regular concrete
Apparent density in a dry state ρ [kg/m^3]:	2290 (v = 0,7%)	2000 – 2600
Compressive strength $f_{c,cyl}$ [MPa]	64,4 (v = 6 %)	12 – 50
Compressive strength $f_{c,cube}$ [MPa]	67,6 (v = 3%)	15 – 60
Splitting tensile strength $f_{t,spl}$ [MPa]	7,3 (v = 8%)	3,0 – 3,7
Static modulus of elasticity E_{cm} [GPa]	36,7 (v = 7%)	29 – 37
Dynamiczny moduł sprężystości E_d [GPa]	45,9 (v = 1%)	$E_{cm} = 0{,}83\ E_d$
Creep ε_p [‰]	0,26 (v = 4%)	0,1 – 1,0
Shrinkage ε_{cs} [‰]	0,88 (v = 4%)	0,2 – 0,6
Abrasion resistance A [cm^3/50 cm^2]	9,0 (v = 7%)	1,5 – 22
Residual strength f_R [MPa]	f_{R1} = 9,3 (v = 13%) f_{R2} = 8,8 (v = 15%) f_{R3} = 7,9 (v = 15%) f_{R4} = 7,0 (v = 17%)	not applicable

temperature in the furnace increased to the temperature assumed in the research design at a rate of 1°C/min. The final (target) heating temperature was maintained for 60 min to ensure that the test elements reached the required temperature throughout the mass. The sample cooling process at a rate of 1°C/min was started after 60 minutes of heating. After cooling to room temperature, which simulates conditions after a fire, the samples were weighed to determine the mass loss, the change in their surface was macroscopically analyzed and their strength was tested. Before heating, some of the test elements were dried in a laboratory dryer at 60°C for 24 hours. The next samples were tested after cooling to room temperature.

The effect of high temperature on the properties of the fine-aggregate fiber composite was determined on the basis of testing the compressive strength determined on cubes (6 pieces each) according to PN-EN 12390-3 [20] and the residual bending tensile strength on beams (6 pieces each) in accordance with PN-EN 14651 [21], accepting them as the basic features used when designing cross-sections of fiber concrete elements. The compressive strength testing procedure was performed using a universal testing machine. The samples were continuously loaded to failure at a rate of 0.5 MPa/s.

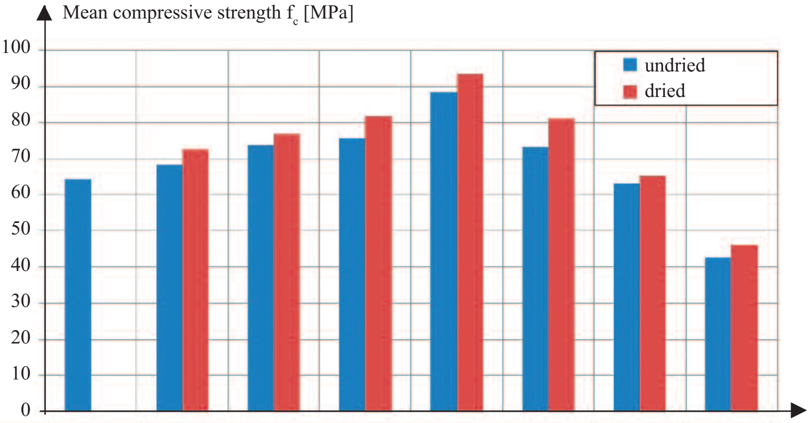
The relationship "Load – CMOD" determined in the residual strength test was used to determine the strength $f_{R,1}$, $f_{R,2}$, $f_{R,3}$ and $f_{R,4}$. The beams were placed on articulated supports (Photo. 1) at a spacing of 500 mm and loaded with concentrated force in the middle of the element span according to [21], continuously with variable speed. The increase in beam load speed was determined depending on the width of the CMOD crack opening. Initially, for a CMOD width of 0.1 mm, the load was applied at a rate of 0.5 mm/min. After exceeding this value, the load application speed was 0.2 mm/min. The test ended when the width of the CMOD crack opening reached a value greater than 3.5 mm. The crack width and beam deflection were monitored using the SAD256 data acquisition system, using inductive displacement sensors (two with rigid and two with articulated tips) and a sensor for measuring deflection. The measurement accuracy of the sensors was 1 mV/V. The limit value of beam deflection was determined in accordance with the PN-EN 14651 standard [21] so that all CMOD values could be achieved. Then, the residual strength ($f_{R,j}$) was determined for the appropriate value of CMOD, j, where j = 1, 2, 3, 4. The strengths $f_{R,1}$, $f_{R,2}$, $f_{R,3}$, $f_{R,4}$, mean the value of tensile stresses in cross-section at a given CMOD crack opening width of 0.5, 1.5, 2.5 and 3.5 mm, respectively.

Photo 1. The stand for testing residual bending tensile strength

Fot. 1. Stanowisko do badania wytrzymałości resztkowej na rozciąganie przy zginaniu

Rest results and analysis

The change in the compressive strength of the fine-aggregate fiber composite as a function of the heating temperature is shown in Figure 1. An increase in the strength of the fiber composite up to a temperature of 500°C was observed, both in the case of samples subjected to drying and those not subjected to this cycle, and then there was a decrease in the value of this feature. It was found that the composite with the addition of steel fibers in the amount of 1.2% in relation to its volume retains mechanical properties after exposure to a temperature of 500°C, and thus demonstrates high-temperature structural stability. The use of steel fibers significantly improves the fire resistance of the fiber composite. The increase in compressive strength with increasing temperature, in relation to the strength of 64.4 MPa after thirty days of maturation of the fiber composite, was 6, 14, 17, 37%, respectively (Figure 1). In the case of samples subjected to preliminary drying, greater increases in compressive strength were recorded, namely by 12, 20, 27 and 45%. At temperatures above 550°C, a reduction in compressive strength was already observed, but only in comparison to the strength corresponding to a tempe-



T [°C]	20	200		300		400		500		550		600		800	
s [MPa]	4,1	3,42	2,91	2,93	3,01	4,27	6,39	1,67	1,68	3,14	3,62	4,88	7,94	7,28	8,82
v [%]	6	5	4	4	4	8	6	2	2	4	4	8	12	17	19

Fig. 1. Compressive strength of fine-aggregate fiber composite as a function of heating temperature

Rys. 1. Wytrzymałość na ściskanie drobnokruszywowego fibrokompozytu w funkcji temperatury wygrzewania rature of 500°C. This strength, compared to the initial strength of 64.4 MPa, was higher by approximately 14% in the case of non-dried samples and 26% in the dried samples. At the same time, at a temperature of 550°C, small surface scratches of the samples were observed (Photo 2a). As the temperature increased, the extent of damage increased (Photos 2b and c) and the compressive strength decreased. Samples heated at 600°C achieved compressive strength close to the initial strength (thirty days). At a temperature of 800°C, there was a very large decrease in compressive strength compared to the initial strength and reached a level of approximately 28% in the case of pre-dried samples and 33% in the undried samples. **An increase in temperature to 550°C can therefore be considered a limit value.**

The increase in compressive strength at temperatures of 200 – 500°C should be attributed to the hydration of unhydrated cement under high temperature conditions [22]. The increase in surface forces between the cement gel layers is another factor responsible for the increase in strength [23]. By increasing the temperature from 550°C to 800°C, chemical reactions and microstructure degradation intensify, resulting in a significant reduction in strength at 800°C.

Studies on the microstructure of cement mortars, described in [24, 25], showed that the peak intensity of the C-S-H phase is almost constant up to 400°C and decreased significantly at 800°C. The use of steel fibers enables easy heat transfer inside the concrete, which reduces thermal stresses and limits the occurrence of scratches. However, the rate of improvement in compressive strength decreases at temperatures of 550 – 800°C. This can be attributed to the effect of high temperature on the loss of bonding properties. Moreover, the significant elongation of steel fibers under the influence of temperature causes radial cracks surrounding the fibers [13], which is another cause of strength loss. A similar relationship was observed in the flexural tensile residual strength test (Figure 2). The residual strength of the fiber composite exposed to a temperature of 800°C was not determined due to the destruction of the samples (Photo 3).

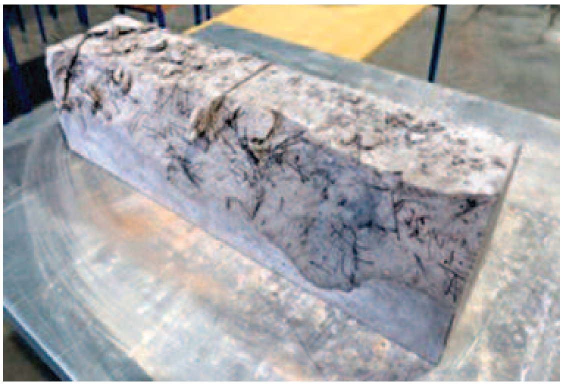
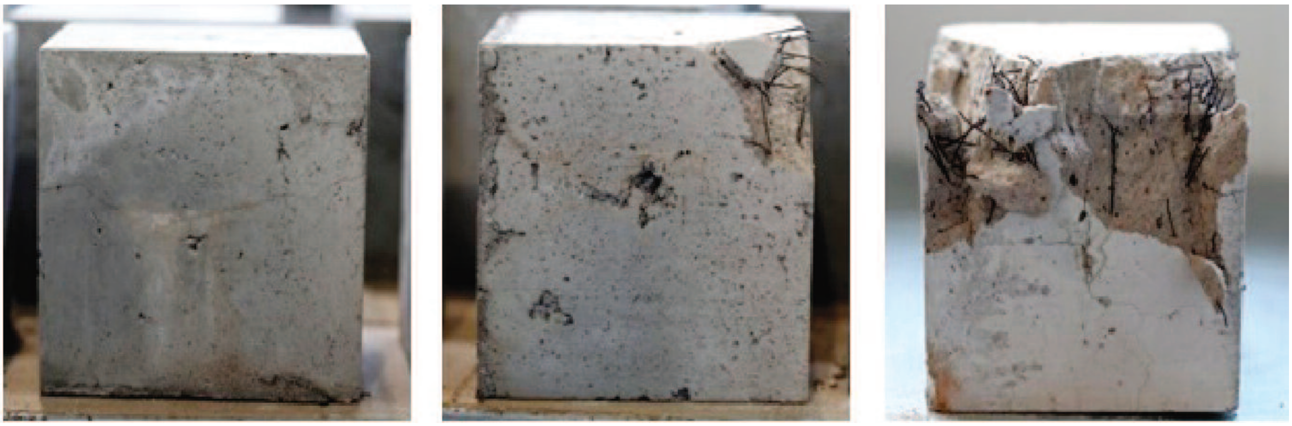


Photo 3. The sample image of beam specimen after heating at a temperature of 800°C

Fot. 3. Przykładowy obraz próbki belkowej po wygrzewaniu w temperaturze 800°C

The obtained results of residual strength tests at 20°C (Figure 2) clearly indicated the ductile nature of the tested material. The shape of the graphs presented in Figure 2 indicates that in the case of a fine-aggregate composite, a slow decrease in the destructive force is observed with an increase in the CMOD value after the crack appears. The use of dispersed reinforcement means that the composite does not undergo sudden destruction, as in the case of ordinary concrete or composite without fibers. Heating the test elements has a significant impact on the level of loading force and, therefore, on the residual strength compared to specimens tested at 20°C. However, a higher heating temperature was not always associated with a greater decrease in residual strength (Table 2). In the case of undried specimens (Figure 2a), a loading force level of approximately 7 kN was observed at each CMOD crack width, and in the case of dried samples (Figure 2b), the loading force in the initial stages of cracking reaches values similar to those for beams tested at a temperature of 20°C, which is a clear difference compared to non-dried samples. The drying effect disappeared after exceeding the crack width of 2.5 mm, where the strength drop was similar to that in the case of undried elements.

According to the guidelines of the Model Code 2010 standard [26], the



T = 550°C T = 600°C T = 800°C

Photo 2. The sample image of cubes specimens after heating

Fot. 2. Przykładowy obraz próbek sześciennych po wygrzewaniu

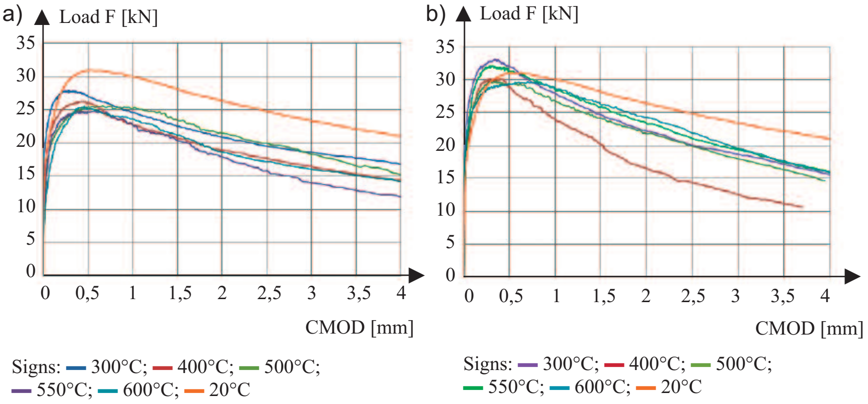


Fig. 2. The relationship between the average loading force F and the crack opening width CMOD as a function of the heating temperature for samples: a) non-dried; b) dried

Rys. 2. Zależność średniej siły obciążającej F od szerokości rozwarcia rysy CMOD w funkcji temperatury wygrzewania próbek: a) niesuszonych; b) suszonych

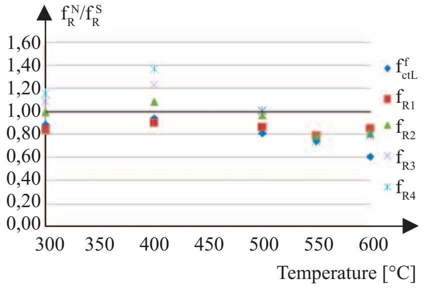


Fig. 3. Residual flexural tensile strengths determined on non-dried f_R^N and dried f_R^S samples, as a function of heating temperature

Rys. 3. Wytrzymałość resztkowa na rozciąganie przy zginaniu, określona na próbkach niesuszonych f_R^N i poddanych suszeniu f_R^S, w funkcji temperatury wygrzewania

class of the fiber composite tested at a temperature of 20°C can be marked as 7b (letter "b" determined on the basis of the f_{R3}/f_{R1} relationship). This means that the material is characterized by a high f_{R1} value (range 1 – 8) and a post-crack softening feature. As the heating temperature increased, the ductility of the material changed. At temperatures up to 300°C, the tested fiber composite is still class "b", and at higher temperatures it is classified as class "a". This indicates a lower ability to transfer tensile stresses after cracking compared to beams tested at 20°C. It should be noted, however, that at temperatures of 400 – 600°C, the ductility remains at a similar level (similar slope of the F – CMOD curves in the graphs and similar f_{R3}/f_{R1} values oscillating at approximately 0.65).

Figure 3 shows the dependence of the residual strength, determined on dried and non-dried samples, as a function of temperature. Drying of the samples influenced the value of residual strength in the case of cracks of small CMOD width. The analysis of Figure 3 shows that the proportionality limits, as well as the residual strength f_{R1}, are lower in the case of undried specimens by 10 – 20%. At high heating temperatures (550 and 600°C), the difference in proportionality limits is significant and at 600°C it amounts to 40%. This is due to the appearance of large cracks during the heating stage of non-dried samples. A different trend was observed for the residual strength in the case of large crack widths (f_{R3} and f_{R4}). It was higher in the case of undried elements at low heating temperatures (300 and 400ºC by approximately 15 and 30%), but lower in the case of high temperatures (550 and 600ºC by approximately 20%). In our opinion, the drying effect has a negligible impact on the residual strength f_{R3} and f_{R4}. The described trend results from the random arrangement of the fibers and their anchoring in the composite (which is decisive for the large width of CMOD cracks) rather than from the initial scratch resulting from heating.

The results of the relative weight loss of fiber composite samples depending on the adopted heating temperature are shown in Figure 4. After heating the samples at 200°C, the highest

Table 2. Summary of the mean values of the residual strength of the fiber composite $f_{R,j}$ determined on dried S and non-dried samples N and the standard deviation values s

Tabela 2. Zestawienie średniej wartości wytrzymałości resztkowej na rozciąganie przy zginaniu fibrokompozytu $f_{R,j}$ określonej na próbkach suszonych S i niepoddanych suszeniu N oraz wartości odchylenia standardowego s

Heat tempe-rature	Type of spe-ci-ment	f_{fctL} [MPa]	s [MPa]	CMOD = 0,5 mm		CMOD = 1,5 mm		CMOD = 2,5 mm		CMOD = 3,5 mm		Category acc. to [26]	
				f_{R1} [MPa]	s [MPa]	f_{R2} [MPa]	s [MPa]	f_{R3} [MPa]	s [MPa]	f_{R4} [MPa]	s [MPa]	f_{R3}/f_{R1}	
300ºC	S	8,25	1,19	10,22	1,81	7,24	0,64	6,18	0,20	4,92	0,37	0,75	cat. b
	N	7,35	0,88	8,61	1,22	7,21	1,24	6,25	1,17	5,68	0,99	0,73	cat. b
400ºC	S	6,70	1,73	9,21	1,91	6,43	1,12	4,59	1,15	3,59	1,19	0,50	cat. a
	N	6,31	1,31	8,30	1,10	7,00	0,43	5,65	1,02	4,91	1,02	0,68	cat. a
500ºC	S	6,90	1,26	9,39	1,69	7,72	2,30	6,37	2,12	5,23	2,00	0,68	cat. a
	N	5,60	0,30	8,15	2,36	7,50	2,06	5,54	1,78	5,29	1,67	0,68	cat. a
550ºC	S	7,29	1,69	9,99	1,92	8,26	1,87	6,74	1,43	5,59	1,42	0,67	cat. a
	N	5,44	2,12	7,88	0,54	6,53	0,27	5,07	0,23	4,12	0,74	0,64	cat. a
600ºC	S	7,40	2,50	9,37	1,63	8,37	1,59	5,62	1,75	5,63	1,63	0,60	cat. a
	N	4,50	0,74	8,05	1,17	6,79	1,24	5,51	0,24	4,85	0,31	0,68	cat. a

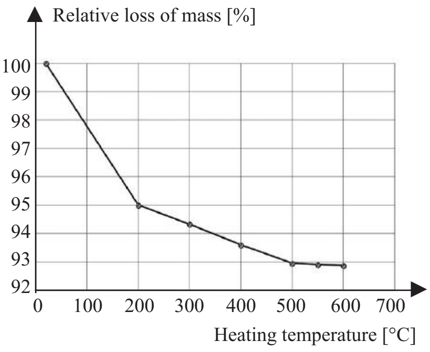


Fig. 4. Relative mass loss of fine-aggregate fiber composite as a function of heating temperature

Rys. 4. Względny ubytek masy drobnokruszywowego fibrokompozytu w funkcji temperatury wygrzewania weight loss of 5% was recorded, and stabilization was observed from a temperature of 500°C. The weight loss at temperatures lower than 500°C is due to the loss of physically adsorbed and chemically bound water. Studies published by other authors [27, 28] are convergent on this issue.

Conclusions

The research focused on the effect of high temperature on the compressive strength and residual flexural tensile strength of fine-aggregate fiber composite reinforced with 1.2% steel fiber. Based on the results presented in the article, the following conclusions were drawn:

1) the addition of steel fibers ensures good compressive and tensile strength of the concrete composite against exposure to high temperatures, but also improves its continuity, plasticity after heating and resistance to spalling (eliminates the tendency to spall);

2) fine aggregate fiber composite with 1.2% fiber content retains its mechanical properties when exposed to temperatures up to 550°C due to fire and is thus able to improve its structural stability at high temperature. The use of steel fibers in mineral materials significantly improves their fire-resistant properties. The fine-aggregate composite with dispersed steel reinforcement has the ability to withstand mechanical loads under fire conditions and thus contributes to the safety of the structure;

3) the addition of steel fibers to the fine-aggregate composite changes its behavior from brittle to pseudoplastic, and thus ensures a slight deterioration of mechanical properties at high temperature;

4) the tensile strength of concrete has a significant impact on the properties of structures, especially structures exposed to high temperatures. Adding steel fibers to concrete is one way to recover the loss of tensile strength.

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