UHPC IN EXTREME CONDITIONS AND TEMPERATURE LOADING

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Abstract

Within a development and research of UHPC materials the wide public, academics and researchers deals mainly with a determinations of the basic physical-mechanical parameters as compressive strength and tensile strength at normal laboratory conditions. The UHPC materials are recently getting more common used not only for academic purposes but also for practical applications. Thus it is necessary to be focused on other parameters and other conditions of testing of this type of material. This paper is focused on extreme conditions and their impact to physical-mechanical parameters of UHPC. Bond behaviour after freeze-thaw cycling and strengths after exposing to high temperature loading are presented in this paper.

Résumé

Dans le cadre de la recherche sur les BFUP, le grand public, les enseignants et les chercheurs s'occupent principalement de déterminer les paramètres physico-mécaniques de base comme la résistance en compression et la résistance à la traction dans des conditions normalisées de laboratoire. Les BFUP sont de plus en plus utilisés, non seulement à des fins académiques, mais aussi pour des applications pratiques. Il est donc nécessaire de porter attention à d'autres paramètres et d'autres conditions d'essai de ces matériaux. Cet article se concentre sur les conditions extrêmes et leur impact sur les paramètres physico-mécaniques des BFUP. L'adhérence après des cycles de gel-dégel et la résistance après exposition à des températures élevées sont présentées dans cet article.

1. INTRODUCTION

Experimental research in the field of UHPC applications is very important. Based on current experience this fine-grained cement based material provides the possibility to optimize structural design as anchorage length of the reinforcement [1]. Excellent material properties of UHPC have very important effect at the bond between reinforcement bars and UHPC compared to bond behaviour at ordinary concrete. This effect was verified at previous experiments [2, 3]. Experimental verification of shear stress between prestressing strands and UHPC and also between strands and common used concrete C50/60 in extreme conditions, variable ambient temperature, are described in this paper. This ordinary concrete is used for bridge structures in the Czech Republic. The specimens were exposed to freeze-thaw cycling with temperature range from -20°C to + 20°C. The number of freeze-thaw cycles varied from 100 to 400 cycles. Degradation of material and related decline of material characteristics have very significant impact on values of the bond stress. The mutual comparison of the bond behaviour between reinforcement and UHPC or common used concrete is also very important.

Second part of presented research is focused on material properties of UHPC reinforced by a combination of steel and hybrid PP or PVA fibres exposed to extreme temperatures. Several types of mixtures (HPFRC, UHPFRC) were examined exposed to the extreme temperatures up to 200 – 1200 °C in the performed experiments. Residual parameters as flexural strength, compressive strength, fracture parameters of presented mixtures are presented in this article. The dependence of porosity of the matrix, sample damage and chemical analysis of samples exposed to extreme temperatures were also investigated. The dependence between basic material and physical properties of examined mixtures and elevated temperatures are presented. Presented results in this article are basis for further research and preparation numerical models for design of UHPC exposed to high temperatures.

2. BOND BEHAVIOUR OF UHPC EXPOSED TO THERMAL STRESS

Bond behaviour determining shear stress is one of the important factor in structures reinforced by conventional reinforcement, e.g. bars, prestressing strands etc. The tensile strength of the reinforcement is transferred to UHPC by the uneven shear stress at the contact zone between reinforcement and cement matrix. With respect to uneven shear stress development is used a simplification that is described by standards as uniform bond stress along the entire anchorage length. The average shear stress is given by the ratio of tensile force in reinforcement and contact zone between steel bar and UHPC [1].

Determination of the bond between prestressing strands and common used concrete is part of the standard ČSN 73 1333 – Testing of the bond between prestressing strands and concrete. According to this standard are used cubes with the edge 150 mm with axially placed reinforcement (Fig. 1). Anchorage length of the reinforcement is 140 mm. The standard allows for using of variable concrete classes for experimental purposes and it prescribes only preparation of testing samples according to scheme (see Fig. 1 and Fig. 2). Cubic samples made from ordinary concrete C50/60 and UHPC reinforced by prestressing strands were prepared. The UHPC samples were sets without subsequent compacting, samples made from concrete were compacted by steel bar. The samples were cured at normal laboratory condition after their demoulding. The mixture design of UHPC is shown at Tab. 1.

In this part of the paper is thermal stress noted as a cycling of negative and positive temperatures, i.e. freezing and thawing cycles. Tested samples were exposed to the cyclic temperature loading from -20°C to +20°C. The bond behaviour was tested for reference samples made from concrete C50/60 and UHPC at several steps of freeze-thaw cycles. The samples were exposed to 100, 200, 300 and 400 freeze-thaw cycles. Samples were cycling at the age of 50 days, reference samples were placed in PE foil according to the standards. After cycling the bond behaviour was tested. Tensile forces were recalculated to average values of shear stress in the bond. Principal point of the experiment is the knowledge that there is no rupture of the structure and even no decrease of average stress in the bond in samples even after 400 cycles. Fine-grained structure of UHPC with excellent material parameters would resist on a long-term basis to extreme conditions represented undoubtedly by these freezing cycles. Results of average shear stress in the bond for samples made from UHPC and concrete C50/60 are detailed shown on the graph in Fig. 3.

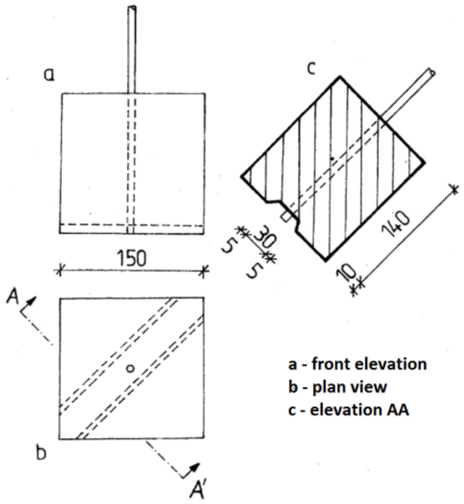

Figure 1: Scheme of the test sample production

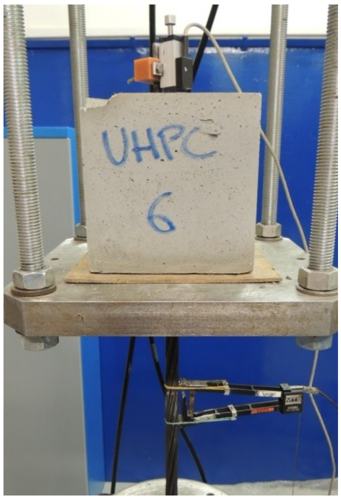

Figure 2: Specimen during the test

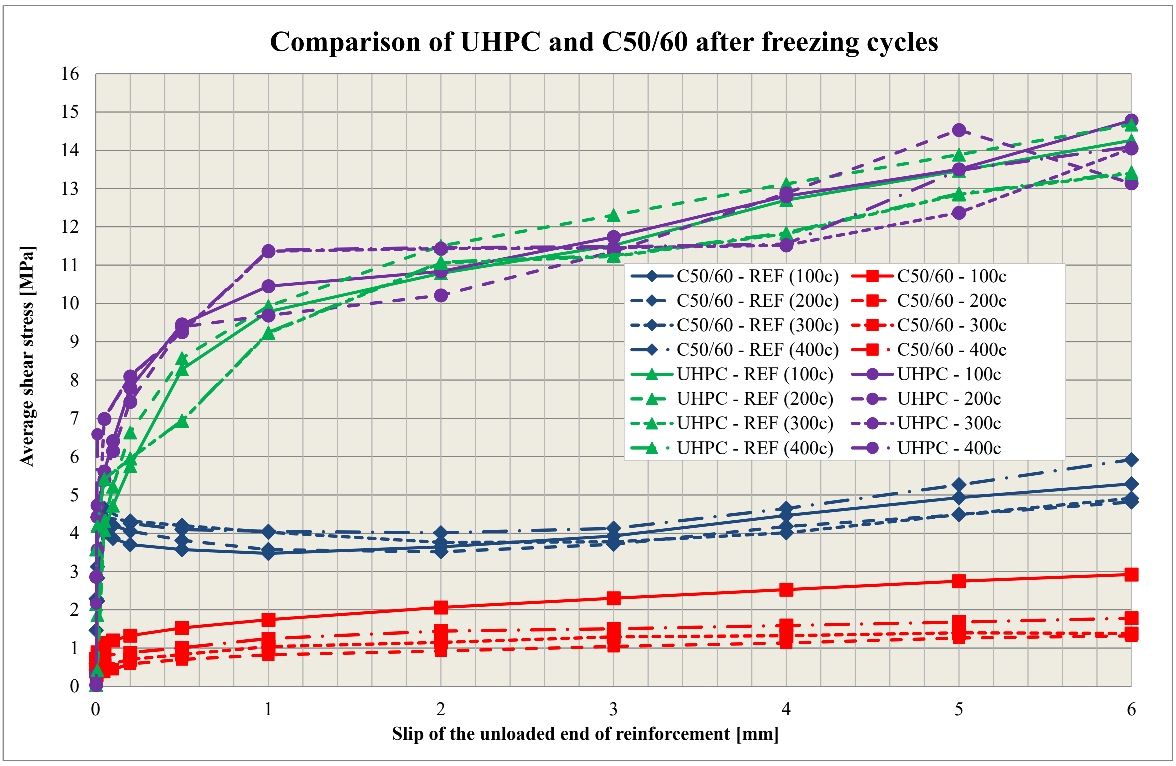

Figure 3: Overall comparison of UHPC and C50/60 after 100, 200 and 300 freezing cycles

Table 1: Mixture proportion of UHPC [kg/m^3]

cement	fine aggregates	water	fillers	silica fume	superplasticizer	fibres
750	1 000	180	200	200	20	200

The locally higher values reached at UHPC after freezing cycles could be explained by the method of samples treatment. Reference samples were casted in the humidity of 60% in PE foil, cycled samples were repeated watering thus there is a possibility to partially hydrating of cement and improve its mechanical parameters. The differences between concrete C50/60 and UHPC in the bond is evident and well seen at Figure 3. The extreme conditions and freeze-thaw cycling did not degraded the UHPC samples like in concrete C50/60, see Figure 4 and 5.

Figure 4: Samples from UHPC after 300 freezing cycles

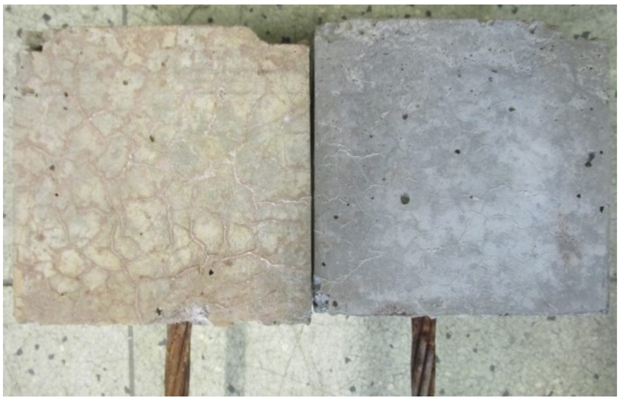

Figure 5: Samples from C50/60 after 300 freezing cycles

3. MECHANICAL PROPERTIES EXPOSED TO ELEVATED TEMPERATURE

The basic mechanical properties as compressive strength and tensile strength in bending (flexural strength) should be determined at normal laboratory conditions (mostly used for reference samples) and after high temperature loading. Mechanical properties of concrete exposed to high temperature have been studied as early as the 1950's. The results of studies constituted the technical basic for the provision and recommendations for determining concrete strength at elevated temperature in many existing codes [4 - 7]. These codes are focused on a normal strength concrete (NSC, $f_{c,\ cube} \leq 40$ MPa) and some of them also on high strengths concrete, e.g. [4]. The properties of UHPC exposed to the high temperatures could be determined at ambient temperature and also at hot state.

Testing at ambient temperature is focused on a measuring of residual strength which is determined after heating of the sample to the temperature level T_{max}, then the sample is maintained at temperature level and after that are cooled down to the nature temperature (laboratory conditions, T_0 = 20°C). These samples could be tested at standard testing machine after heating, maintaining and cooling down. The results of this type of test are hereinafter referred as residual strengths.

On the other side there is a possibility to test samples at hot state. It means testing after first two steps (heating and maintaining). The cooling down is done after the tests. This type of test is well known as a hot state testing, but the testing procedure should be divided into two test types. The first test type, easier and cheaper, is focused on heated sample at furnace and after reaching maximal temperature T_{max} is sample removed from the furnace and putted and tested at common used testing machines. This kind of test is most often used to lower temperature T_{max} = 400°C. The second test type is focused on testing in one machine combined furnace and loading testing machine. This type of test was performed at Laboratory of Klokner Institute and it is used for testing normal strengths concretes and lightweight concretes. Nowadays the testing procedure and boundary conditions are optimized for UHPC testing. The differences between ambient temperature testing and hot state testing is noted at Figure 6.

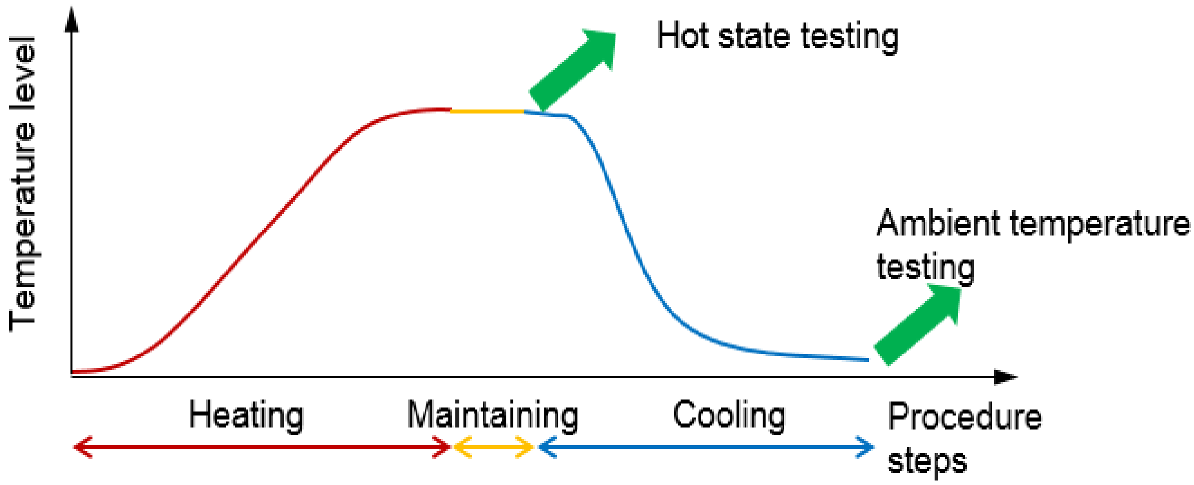

Figure 6: Procedure steps for testing at high temperature

At high temperatures occur in the concrete extreme stress which especially in naturally wet concrete leads to explosive delamination and damaging of the surface layers of concrete. Delamination and cracking of concrete is due to several factors. The first factor is heat transferring between different components of the matrix. According to a different thermal expansion of binder component and aggregate leads to uneven deformation and to local tensile forces in the cement based materials. These forces may result in cracking of the concrete [8, 9]. Hydrothermal process in which this transition occurs bound water to steam is another major influence on the damage of concrete exposed to high temperatures. Due to low porosity of UHPC there is sufficient space for water vapour expansion. This extreme pressure of water vapour affected tensile stress, spalling and material damage.

The microcracks reduction and improvement of material parameters can be achieved by adding a suitable amount of dispersed reinforcement (steel, glass, composite). Application of different types of scattered reinforcement in common used concrete is ordinary matter nowadays. The fibres are used for reducing shrinkage cracks elimination, improvement of fracture parameters etc. Adding dispersed reinforcement to UHPC matrix gain significantly better mechanical properties, e.g. higher modulus of rupture, behaviour after first crack, reduction of cracks formation and distraction. The type and size of the fibre varies for different applications. The most commonly used fibre reinforcement in the UHPC are steel fibres (length of 6 –12 mm). The purpose of the combination of fibres of different types can improve not only mechanical properties but also change the structure of the matrix to improve the resistance of concrete at high temperatures [10, 11, 12]. The mixture proposition for testing are shown at next Tab. 2.

Table 2: Mixture proportion of tested mixtures [kg/m^3]

Mixture	cement	fine aggregates	water	fillers	silica fume	PCE	steel fibres	PVA fibres	PP fibres
REF	700	1250	165	80	100	40	120	-	-
PP 0.1	700	1250	165	80	100	40	120	-	0.9
PP 0.2	700	1250	165	80	100	40	120	-	1.8
PVA 1	700	1250	165	80	100	40	120	1.3	-
PVA 2	700	1250	165	80	100	40	120	2.6	-
PVA 3	700	1250	165	80	100	40	120	5.2	-

Table 3: Residual mechanical properties of mixtures with different type of fibres

Temperature of heat loading	Mix	Bulk density [kg/m^3]	Compressive strength [MPa]	Flexural strenght [MPa]	Mix	Bulk density [kg/m^3]	Compressive strength [MPa]	Flexural strenght [MPa]
laboratory	REF	2330	149.5	21.3	PVA 1	2370	152.8	22.1
200		2290	157.2	19.6		2260	159.9	20.3
400		2170	148.4	16.6		2180	144.0	14.1
600		2190	112.1	10.6		2160	109.7	12.0
800		2140	61.6	5.7		2150	54.7	5.1
1000		2010	13.9	1.4		2070	13.9	1.3
1200		1960	9.4	1.3		2030	12.0	1.9
laboratory	PP A	2310	148.5	22.6	PVA 2	2360	151.8	20.9
200		2210	157.2	17.7		2260	149.5	19.3
400		2210	134.2	14.4		2190	148.0	12.5
600		2170	96.5	8.8		2190	102.7	10.3
800		2110	50.4	4.4		2150	52.1	4.8
1000		2020	11.7	1.1		2070	13.6	1.4
1200		1940	9.6	1.2		1950	10.0	1.7
laboratory	PP B	2310	148.3	23.4	PVA 3	2370	157.6	22.5
200		2190	148.4	17.8		2260	155.9	21.5
400		2150	134.2	13.3		2180	134.2	14.9
600		2130	91.5	9.2		2130	107.1	10.9
800		2060	45.8	5.1		2150	51.6	5.2
1000		2030	13.9	1.3		1990	11.1	1.3
1200		1920	9.5	1.5		1900	8.4	1.2

3.1 Ambient temperature testing of UHPC exposed to high temperatures

For the tests of the residual parameters were made a cube size of 100 mm and small prism beams size of 160/40/40 mm. Samples were left for 24 hours in the mould of guaranteeing a highly humid environment approx. RH = 98%. After removal from the mould, the samples were stored for 27 days in water conditions at 20 °C. After 28 days from the production, the samples were removed from the water and placed in laboratory conditions (RH = 30 ± 5%, T = 20 ± 2 °C). At the age of 90 days all samples were sequentially moved into a drying furnace and dried at 105 °C until constant weight. Immediately after drying, the part of the prepared specimens (each set of three specimens) was placed in an electric furnace without openings.

The heating rate was 1 °C / min [13]. The maximum temperature exposure of the samples was 200 °C, 400 °C, 600 °C, 800 °C, 1000 °C and 1200 °C. Specimens were loaded by high temperature for each set from low to high temperature. Maximum temperatures were kept for 60 minutes. Before testing residual properties, the samples were cooled to laboratory conditions. Cooling of the specimens has not been controlled electronically.

All sets were tested uniformly in order to eliminate age related to final strength. The prism beams without notch were tested at three point bending test with span of 100 mm. Due to the drying of the samples before exposition to high temperatures the hydration of the cement and thus the concrete curing was almost stopped - time intervals were eliminated. After all the tests, the specimens were stored for subsequent analysis. In the following Tab. 3 are the results for bulk density, compressive strength and flexural strength, one for each mixture and the temperature to which the samples were loaded. The results of fracture energy are noted at graph at Fig. 7.

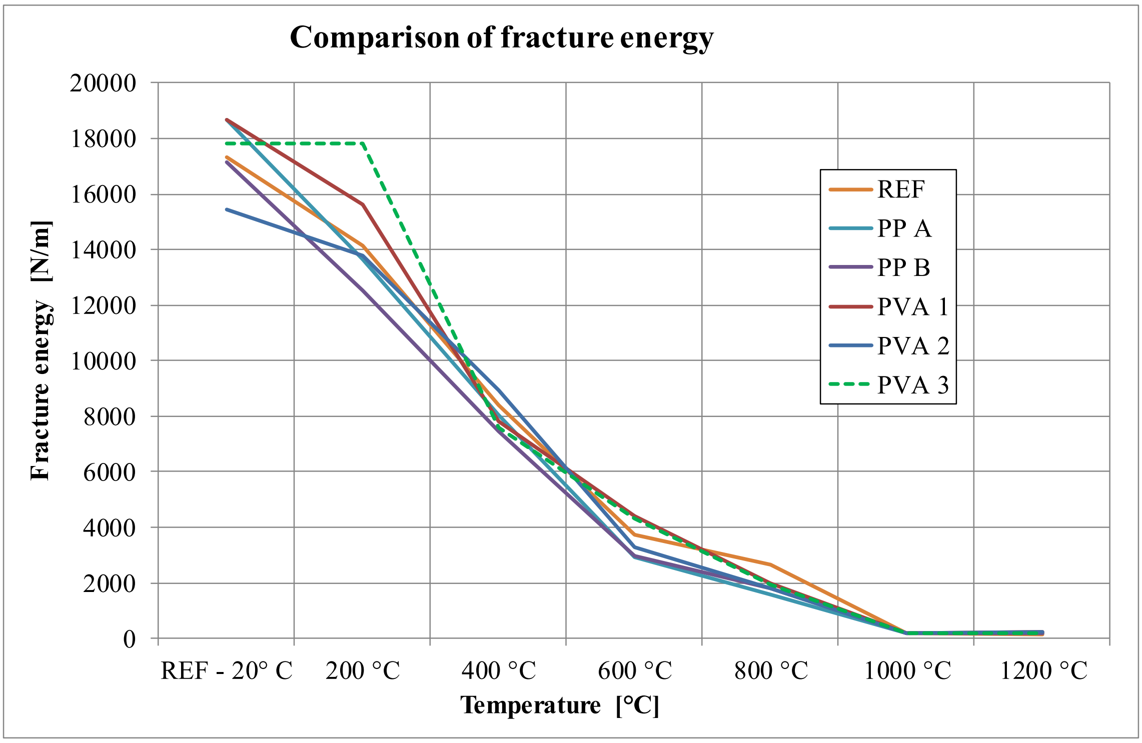

Figure 7: Overall comparison of fracture energy measured at ambient temperature

3.2 Hot state testing

Second experimental part of testing material at hot state was performed at small prism beams size of 160/40/40 mm without notch. Samples were moulded and storage like samples at chapter 3.1. Immediately after drying one of each three specimens was placed in split tube electrical furnace with openings at the top and bottom to allow the loading rams transmit load from test machine to samples. Samples were exposure to temperatures from 200°C to 1200°C and were tested at three point bending test with span of 100 mm. Some of the results are presented at Tab. 4. More results will be presented at next papers because the test at hot state is more time consuming than test at ambient temperature.

Table 4: Mechanical properties of mixtures with different type of fibres at hot state

Temperature of testing	Mix	Flexural strenght [MPa]	Mix	Flexural strenght [MPa]	Mix	Flexural strenght [MPa]
laboratory	REF	20,9	PP A	22,0	PP B	23,2
200		18,0		16,9		17,4
400		16,1		15,2		11,6
600		9,0		7,0		6,7
800		3,1		1,8		3,5
1000		1,0		1,3		1,4

4. CONCLUSIONS

Extreme climatic conditions (higher temperatures, freezing and thawing) require high durable material. Good mechanical properties of UHPC leads to a significant increase of the bond between the reinforcement and cement matrix. For bond behaviour cubic samples with prestressed strands were tested. The samples were cycled between frost (-20°C) and water (+20°C) before the pull out tests was one part of the experimental research work presented in this paper. Samples were exposed up to 400 cycles. The reference specimens which were not be exposed to cycling temperature were also tested at the same age as exposed samples and all the results were compared.

At samples made from concrete C50/60 a severe surface degradation was observed and values of bond stress had a decreasing character. In contrary, the samples made of UHPC did not prove any surface degradation of material and in all cases even after 400 cycles their measured shear stress values were identical or higher than values of reference samples. The obtained experimental data serve as basis for further systematic experimental or numerical verification and more accurate information about the bond significantly higher values of UHPC with the prestressing strands so as to enable efficient design of prestressed elements.

The second goal of this paper was to describe the basic material parameters exposed to high temperatures that may have a fatal effect on the damage of the concrete element, and especially due to expansion of water vapour, the formation of tensile stress in relation to the porosity of the matrix and different values of thermal expansion of each matrix components. Using the concept of UHPC normally obtain high levels of compressive and tensile strength, which is achieved thanks to the high homogeneity and low porosity matrix. For initial experiments was elected one recipe of UHPC to which were added a hybrid fibres and has studied their impact on the residual parameters.

Significant decrease in compressive strength and flexural strength was seen in all sets of up to 800 °C. For samples exposed to 600 °C was reached about 50% of the values of reference samples. Samples exposed to temperature of 1000 °C and 1200 °C, completely lose their resistance and the difference between such extreme temperatures is negligible. This dependence was very similar for all investigated sets, with both PVA and PP fibres. This result has been predictable due to the high volume fraction of steel fibres $V_f = 1.5\%$, where conversely hybrid reinforcement were dosed from 0.1 to 0.4%. Due to the drying of the sample before high temperature exposition to avoid explosive material behaviour and allow these residual parameters - at the moment the reference, to determine.

These information are valuable to the next stages of research, and in the future they will be comparable with the results of mechanical parameters directly tested during high temperature exposure and also to tests carried out under normal (wet) conditions. These tests are currently underway and will be a subject to subsequent publications.

ACKNOWLEDGEMENTS

The research work presented in this paper has been supported by the Grant Agency of the Czech Republic, in the framework of grant No. 15-05791S “Analysis of physical and chemical processes in hybrid-fiber reinforced high performance cement-based composites induced by high-temperature loading” and part of experiments were supported by Student grant of CTU in Prague SGS16/196/OHK1/2T/31 “Properties of fiber reinforced cement-based composite materials exposured to high temperatures”. All tests were carried out in laboratory of Klokner Institute, Czech Technical University in Prague.

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