World Academy of Science, Engineering and Technology
International Journal of Structural and Construction Engineering
Vol:11, No:9, 2017

Stress-Strain Relation for Hybrid Fiber Reinforced Concrete at Elevated Temperature

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Open Science Index, Structural and Construction Engineering Vol:11, No:9, 2017 publications.waset.org/10008089.pdf

Abstract**—**The performance of concrete structures in fire depends on several factors which include, among others, the change in material properties due to the fire. Today, fiber reinforced concrete (FRC) belongs to materials which have been widely used for various structures and elements. While the knowledge and experience with FRC behavior under ambient temperature is well-known, the effect of elevated temperature on its behavior has to be deeply investigated. This paper deals with an experimental investigation and stress-strain relations for hybrid fiber reinforced concrete (HFRC) which contains siliceous aggregates, polypropylene and steel fibers. The main objective of the experimental investigation is to enhance a database of mechanical properties of concrete composites with addition of fibers subject to elevated temperature as well as to validate existing stress-strain relations for HFRC. Within the investigation, a unique heat transport test, compressive test and splitting tensile test were performed on 150 mm cubes heated up to 200, 400, and 600 °C with the aim to determine a time period for uniform heat distribution in test specimens and the mechanical properties of the investigated concrete composite, respectively. Both findings obtained from the presented experimental test as well as experimental data collected from scientific papers so far served for validating the computational accuracy of investigated stress-strain relations for HFRC which have been developed during last few years. Owing to the presence of steel and polypropylene fibers, HFRC becomes a unique material whose structural performance differs from conventional plain concrete when exposed to elevated temperature. Polypropylene fibers in HFRC lower the risk of concrete spalling as the fibers burn out shortly with increasing temperature due to low ignition point and as a consequence pore pressure decreases. On the contrary, the increase in the concrete porosity might affect the mechanical properties of the material. To validate this thought requires enhancing the existing result database which is very limited and does not contain enough data. As a result of the poor database, only few stress-strain relations have been developed so far to describe the structural performance of HFRC at elevated temperature. Moreover, many of them are inconsistent and need to be refined. Most of them also do not take into account the effect of both a fiber type and fiber content. Such approach might be vague especially when high amount of polypropylene fibers are used. Therefore, the existing relations should be validated in detail based on other experimental results.

Keywords**—**Elevated temperature, fiber reinforced concrete, mechanical properties, stress-strain relation.

I. Introduction

ALTHOUGH concrete is well-known for a high degree of fire resistance, high temperature seriously damages microstructure and mesostructure which results in generalized mechanical decay of a concrete composite [1]. As HFRC represents a complex material composed of various components with different response to high temperature, to determine its behavior and mechanical properties in fire is a demanding task. Recently, many comprehensive studies [2]-[11] have been undertaken with the aim to observe the mechanical behavior of FRC exposed to elevated temperature.

There are two fundamental types of a methodological procedure used for observing the mechanical properties of specimens at elevated temperature. Most of experimental investigations [1]-[8] were conducted on test specimens at ambient temperature after high temperature exposure and only a few was performed on heated test specimens [9]-[11]. Such approach to experimental testing is used mainly due to a simple way of testing as a test is easier to conduct on test specimens at ambient temperature. However, if the results obtained from the tests on specimens after high temperature exposure correspond enough to the mechanical properties of a tested material at a certain temperature level has not been still fully understood. Bamonte and Gambarova belong to authors who very intensively deal with such problem and state in their publications [12], [13] that the hot and residual (after high temperature exposure) behavior in compression are very close; the only difference was observed in case of the peak strain in compression which is larger on heated specimens in comparison with specimens after temperature exposure.

The fire response of concrete composites is closely associated with concrete composition, particularly with a type and content of concrete components used. Generally speaking, concrete made of siliceous aggregates, such as granite, shows unfavourable mechanical properties at high temperature compared to concrete composed of calcareous aggregates such as dolomite and limestone [14]. Recently, a lot of interest is also being paid on the possible use of metakaolin, fly ash and silica fume as partial cement replacement in concrete subject to high temperature [2], [15]. Owing to the silica fume and fly ash fineness, concrete composites with such additions have denser microstructure and as a consequence their explosive spalling tendency increases [15].

The combination of steel and synthetic fibers represents a promising alternative how to ensure good toughness of a concrete composite before heating and improve its residual mechanical behavior and spalling resistance as well as the ductility after heating [4]. Although a few contributions

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declare that a fiber cocktail does not have much effect on high temperature compressive strength [9], most of the presented works affirm that the incorporation of steel fibers can effectively improve the compressive properties of a concrete composite when exposed to elevated temperatures while polypropylene fibers enhance concrete spalling resistance [5], [8]. Specifically, the combination of steel fibers and polypropylene fibers shows positive synergy effect on the post-peak behavior of concrete composites before and after exposure to high temperature [4]. However, as synthetic fibers have a low melting point and ignition point, only steel fibers provide the stability and enhanced mechanical behavior to a concrete composite after exposing to elevated temperatures [7]. Considering steel to synthetic fiber content ratio, a concrete composite, containing 1% synthetic fibers and 1% steel fibers by volume, seems to produce the best results, balancing performance at high temperature with consideration of initial mechanical properties [10]. As a consequence, using HFRC (steel and synthetic fibers) might provide necessary safe guarantee for the rescue work and structure repair during and after a fire disaster.

TABLE I
NOMENCLATURE

d	Fiber diameter
f_{fc}	Compressive strength of concrete at ambient temperature
$f_{fc,T}$	Compressive strength of concrete at elevated temperature
$f_{fc,t}$	Tensile strength of concrete at ambient temperature
$f_{fc,t,T}$	Tensile strength of concrete at elevated temperature
l	Fiber length
FRC	Fiber reinforced concrete
HFRC	Hybrid (steel-polypropylene) fiber reinforced concrete
PC	Plain concrete
PFRC	Polypropylene fiber reinforced concrete
SFRC	Steel fiber reinforced concrete
T	Temperature
V_f	Fiber volume ratio

II. EXPERIMENTAL INVESTIGATION

A. Motivation

The state of the art review indicates several problems related to the HFRC performance at elevated temperature. The database of experimental results is very limited. While there is extensive experience with conventional plain concrete at high temperature [1], the effect of fibres on the behaviour of HFRC has not been fully understood. Particularly, very limited data are available when pre-cracking and post-cracking tensile strength of HFRC are considered. Therefore, it is desired to enhance the result database and subsequently validate or derive existing or entirely new stress-strain relations for such material, respectively. Moreover, most of the experimental investigations have been undertaken on specimens cooled down after a fire exposure to obtain material properties. Such methodological procedure likely considers further concrete deterioration in a cooling phase but is not capable to describe material properties at elevated temperature. Since the main objective of the presented experimental investigation was to obtain the properties of the material right at time of a fire, which will be subsequently used for a numerical simulation of steel-FRC composite columns at a fire, the proposed experiments were conducted on heated specimens.

B. Experimental Procedure

Considering the problems and gap in the field of HFRC performance, the following experimental investigation was developed. The whole experimental investigation was carried out by the team of researchers at Czech Technical University in Prague for one year. As the research was very extensive, the investigation was divided into several steps in the following order: Test specimen production, heat transport test, compression test, splitting tensile test and stress-strain relation analysis.

C. Test Specimens

All experimental tests were carried out on 150 mm cubes made of HFRC (Table II). The concrete composite was designed to be composed of easy available and widely used components which include Portland cement 42,5 R characterised by high early strength in accordance with CSN EN 197-1 [24], water and siliceous aggregate. The workability of fresh concrete mass was maintained by using plasticizer Sika Visco Crete 1035 that also enabled to reduce the content of used mixing water. The investigated HFRC also contains two types of fibres. Single hook end steel fibres Dramix RC-80/60-BN have tensile strength 1225 MPa and served as main reinforcement in the concrete composite whereas polypropylene fibres were added in concrete with the aim to reduce the risk of explosive concrete spalling which occurs at high temperature gradient [7], [25].

TABLE II
HFRC COMPOSITION

Concrete component	Content (kg/m^3)
Portland cement 42,5 R	490
Water	153
Fine aggregate 0-4 mm	890
Coarse aggregate 4-8 mm	100
Coarse aggregate 8-16 mm	745
Plasticizer Sika Visco Crete 1035	4.9
Steel fibers Dramix RC-80/60-BN	40
Polypropylene fibers Forta Ferro 54 mm	3

D. Heat Transport Test

As the compression test and splitting tensile test were conducted on heated specimens, first of all it was necessary to determine a time period required for the uniform heating of the specimens as well as to determine the rate of cooling in order to avoid excessive temperature loss during the tests. The heat transport test arranged particularly for this investigation was performed on three 150 mm cubes by using a system which consists of a control machine Mannings HTC 70 kW, ceramic pads and K-type thermocouples measuring temperature in a range from -200 °C to 1000 °C. The heat treatment of the specimens was performed for three different temperature levels – 200 °C, 400 °C, and 600 °C.

The first step was to drill three holes in each cube which served for the thermocouples installation. Two 75 mm deep holes were positioned 10 mm from the edge, the last one at the center with the aim to measure temperature in the specimen core (Fig. 1). To ensure correct functioning of the thermocouples it was necessary to prepare the holes of the same diameter as the thermocouples had, otherwise any air void in the holes could affect the test results. Afterwards, two ceramic pads were attached directly to four of six specimen sides. The position of ceramic pads was secured by high temperature resistant glass wool insulation which was wrapped tightly around the pads together with a specimen. The insulation simulated so called thermo-box which ensured heat accumulation during the heat treatment. Subsequently, totally five thermocouples were installed in their position when three of them were inserted through the glass wool into the prepared holes and the other two were placed between the ceramic pads and a specimen to measure the surface temperature of the ceramic pads. The temperature of an unheated side was measured time to time by an infrared thermometer and compared with the temperature distribution at the depth of the specimen.

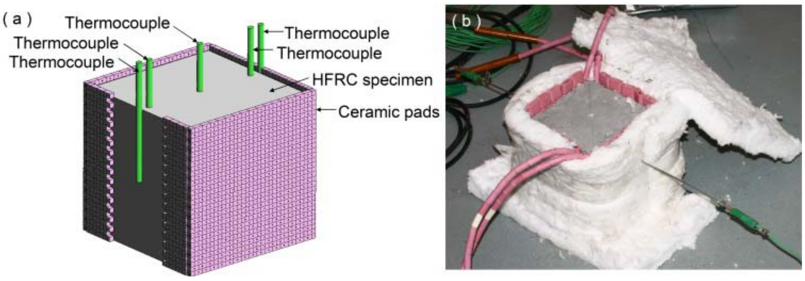


Fig. 1 Heat treatment: (a) model of specimen with thermocouples and ceramic pads, (b) specimen in thermo-box

The heat transport test was performed under the heating rate 200 °C/hour to determine the time period for the uniform heating up to 200 °C, 400 °C, and 600 °C. After the temperatures 250 °C, 450 °C, or 650 °C were reached at the interface between the ceramic pads and specimen surface, as the heat treatment went on, the ceramic pads temperatures were kept at the same level until the temperature in the specimen core reached 200 °C, 400 °C, and 600 °C, respectively. The increase in temperature on the heated sides of the specimen at the 75 mm depth was more rapid in comparison with the specimen core which was placed further from the source of heat. The temperature distribution at zero depth on the top unheated side observed using the infrared thermometer differs from the one obtained at the 75 mm depth of the specimens. However, as the temperature gradient decreases during the heat transport test, the difference in the temperature distribution at both depths ranges from 0 °C to 8 °C and consequently is negligible. Considering such heat treatment, the uniform heating of the specimens up to 200 °C, 400 °C, and 600 °C took approximately two, four and six hours.

When the intended temperature levels were reached, the heat treatment was stopped in order to observe specimen cooling in detail. First, the specimens were immediately removed from the thermo-box by using fireproof gloves, wrapped in new glass wool insulation and placed on steel plates. The intention of this process was to simulate the steps required for performing the compression test and splitting tensile test on heated specimens and consequently to precisely validate the rate of heat loss. While the temperature in the core was stabilized, the temperature on the sides of specimens decreased rapidly due to the low temperature of surrounding environment. The rate of heat loss was more significant at specimens heated up to higher temperature due to a higher temperature gradient. Based on the obtained data from the heat transport test, it was determined the maximum allowable time period for the compression test and splitting tensile test equal to 10 minutes.

E. Compression Test and Splitting Tensile Test

The concrete compression test and splitting tensile test were conducted on thirty-six 150 mm cubes under 20 °C, 200 °C, 400 °C, and 600 °C in accordance with CSN EN 12390-3 [26] and CSN EN 12390-6 [27]. First, the whole set of the specimens was divided into four groups according to the intended temperature level during testing. The specimens tested under elevated temperature were heated up to the intended temperature following the procedure used for the heat transport test. The specimens, in this case with no holes drilled in them, together with two ceramic pads were inserted into the thermo-box of glass wool (Fig. 2) and then two thermo-couples were placed between the specimen and ceramic pads with the aim to control and monitor the temperature of the ceramic pads. The time and heat treatment were identical to those obtained from the heat transport test. Heating up to 200 °C, 400 °C and 600 °C took 113 min, 235 min and 370 min, respectively.

Fig. 2 HFRC specimens during the heat treatment

After the intended temperature in the specimen core was reached the compression test and splitting tensile test were performed in a testing machine Inova 200F. The time of an experimental test of each sample had to be kept under 10 minutes in order to avoid excessive temperature loss. The test was driven by deformation 0.02 mm/s in the range of 0-5 mm and 0.1 mm/s for deformation greater than 5 mm. The obtained data from the tests were used for generating stress-displacement diagrams which describe the material behavior at various temperature levels.

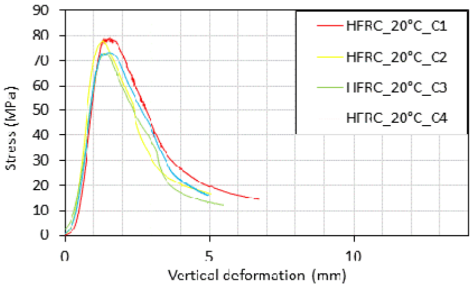
III. STRESS-STRAIN RELATION

A. Compressive Stress-Strain Relation

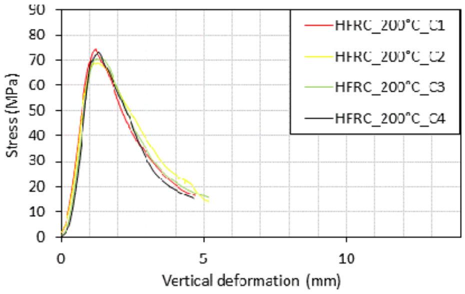
The stress-displacement diagrams (Fig. 3) show the mechanical performance of HFRC specimens at different temperature levels, mainly the peak and residual (post-peak) strength of the investigated material. The presented results do not exhibit any significant deviations caused by either incorrect conducting the experimental tests or poor-quality manufacturing technology. The diagrams correspond to the typical behavior of concrete in compression. In the opening phase the compressive strength of the material increases linearly until concrete starts yielding and ultimate compressive strength is reached. The modulus of elasticity defined by the slope of the linear part of the curves significantly decreases with increasing temperature. This phenomenon is caused by the specimen structure significantly damaged by cracks resulting from both the high temperatures and pore pressure. Moreover, the material structure at elevated temperature is also more porous as the polypropylene fibers melts due to the low melting point of the material [28]. All such phenomena also affect the peak compressive strength of the material and its ductility. While the material ductility increases with the temperature, the peak strength decreases rapidly.

The peak compressive strength of HFRC at 200 °C, 400 °C, and 600 °C corresponds to 98%, 88%, and 45% (solid circle), respectively, of its initial strength at ambient temperature (Fig. 4). The relative compressive strength diagram shows that such values are placed at the interface between normal HFRC (blank circle) and reactive powder HFRC (blank square) whose compressive strength slightly increases up to 400 °C in general. That might be caused the composition of reactive powder concrete and low porosity of such material.

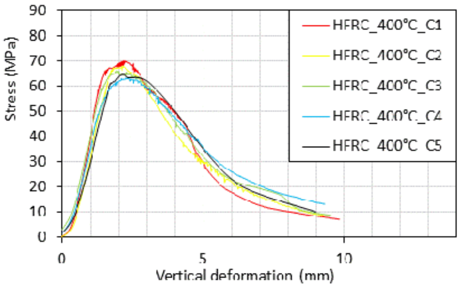
There are only several relations between relative compressive strength and temperature which have been developed for either PC [21]-[23] or FRC so far, in particular most of them for SFRC [18]-[20] and only few for HFRC [5], [9] and PFRC [17]. In order to make the relative compressive strength diagram clear, only the most relevant relations are presented. Zheng et al. [5] developed two relations for reactive powder HFRC which are based on results obtained from compressive tests on cubic specimens (1) and prismatic specimens (2). While the second



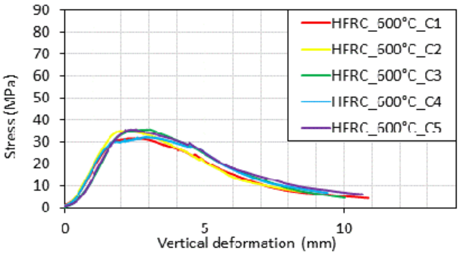
(a) Stress-displacement diagram of HFRC at 20°C



(b) Stress-displacement diagram of HFRC at 200°C



(c) Stress-displacement diagram of HFRC at 400°C



(d) Stress-displacement diagram of HFRC at 600°C

Fig. 3 Stress-displacement diagrams of HFRC in compression

$$f_{fc,T} = f_{fc}\begin{Bmatrix} 0.99+0.44\left(\frac{T}{1000}\right) & 20^{\circ}C \le T \le 400^{\circ}C \\ 1.09+1.44\left(\frac{T}{1000}\right)-3.1\left(\frac{T}{1000}\right)^2 & 400^{\circ}C \le T \le 800^{\circ}C \\ 0.06+0.24\left(\frac{T}{1000}\right) & 800^{\circ}C \le T \le 900^{\circ}C \end{Bmatrix} \quad (1)$$

$$f_{fc,T} = f_{fc}\begin{Bmatrix} 0.96+2.09\left(\frac{T}{1000}\right)-8.71\left(\frac{T}{1000}\right)^2+6.06\left(\frac{T}{1000}\right)^3 \\ 20^{\circ}C \le T \le 900^{\circ}C \end{Bmatrix} \quad (2)$$

While (2) seems to be very inaccurate in comparison with the result database for reactive powder HFRC, (1) might able to describe precisely the mechanical performance of reactive

HFRC when exposed to elevated temperature. The other relation (3) shown in Fig. 4 was developed by Khaliq et al [9].

$$f_{fc,T} = f_{fc}\left\{\begin{matrix} 1.0 & 20°C \\ 0.99-0.002\,T & 100°C \le T \le 200°C \\ 0.73-0.0005\,T & 200°C \le T \le 800°C \end{matrix}\right\} \qquad (3)$$

for general self-consolidating FRC based on linear regression analysis. However, the relation seems to be inconsistent at the temperatures 100 °C and 200 °C. Moreover, the relation shows a poor agreement with the data from the experimental investigation as well as with the actual result database for HFRC. Considering only the presented experimental investigation, the best agreement is evident with CSN EN 1992-1-2 [29] which recommends to use 95%, 75%, and 45% of the initial compressive strength of concrete with siliceous aggregates for the temperatures 200 °C, 400 °C, and 600°C, respectively. However, this recommendation is particularly applicable to plain concrete and does not take into account the effect of fibers. Such problem is also associated with the other three relations (1), (2), and (3). None of them consider a fiber type or even fiber content. However, such approach might be vague, especially when high content of polypropylene fibers is used. They melt very shortly at low temperature and as a consequence might significantly increase the porosity of a material which can result in the deterioration of mechanical properties. Nevertheless, firstly this thought must be experimentally validated.

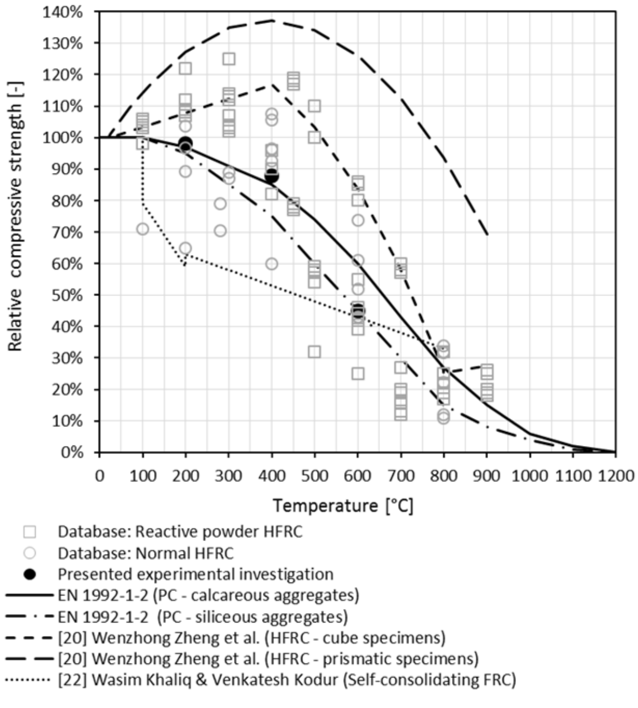


Fig. 4 Relative compressive strength diagram

B. Tensile Stress-Strain Relation

Fig. 5 demonstrates the tensile behavior of the investigated concrete composite at various temperature levels, in particular the peak and residual (post-peak) splitting tensile strength. The structural performance described by the presented diagrams corresponds to the typical mechanical behavior of FRC. In the opening phase, the splitting tensile strength raises almost linearly until the peak strength is reached. The investigated HFRC is characterized as FRC with a tension softening curve [30] as their residual strength decreases after the first macro-crack occurs. The regions with short-term increase in residual strength result usually from fibers which are gradually activated with increasing loading until they are fully activated. While both polypropylene fibers and steel fibers ensure the ductility of the material at ambient temperature, only the steel fibers contribute to the residual strength including the ductility of the material at elevated temperature as the polypropylene fibers burn out with increasing temperature and their influence on the concrete composite strength is negligible.

The critical problem relates to the poor result database for HFRC in pension because only few experimental investigations have been conducted so far. Therefore, no stress-strain relations have been developed particularly for HFRC up to date and thus the stress-strain relations for SFRC [16], [18] and PFRC [17] are presented (Fig. 6). The relations derived by Aslani et al. for PFRC (4) and SFRC (5), are

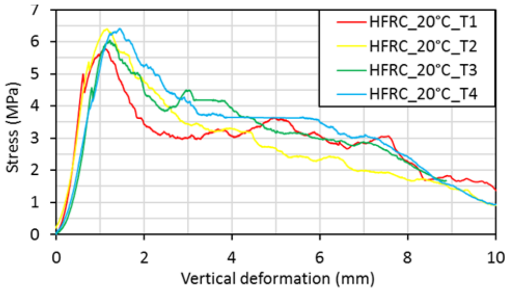
$$f_{fc,t,T} = f_{fc,t}\left\{\begin{matrix} 1.0 & 20°C \\ 1.0237-0.00107\,T+10^{-7}T^2 & 100°C \le T \le 800°C \end{matrix}\right\} \qquad (4)$$

$$f_{fc,t,T} = f_{fc,t}\left\{\begin{matrix} 1.0 & 20°C \\ 0.98-0.0005\,T-5\times10^{-7}T^2 & 100°C \le T \le 800°C \end{matrix}\right\} \qquad (5)$$

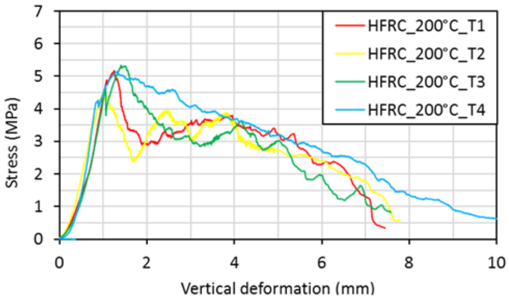
They follow the pattern of the result database for conventional HFRC (blank circle). However, both of them are inconsistent at 200 °C and 400 °C. The other empirical relation (6) for SFRC based on a regression analysis was

$$f_{fc,t,T} = \left[\left(\left(0.0008\frac{l}{d}-0.03\right)V_f - 0.113\right)T+100\right]f_{fc,t} \qquad (6)$$

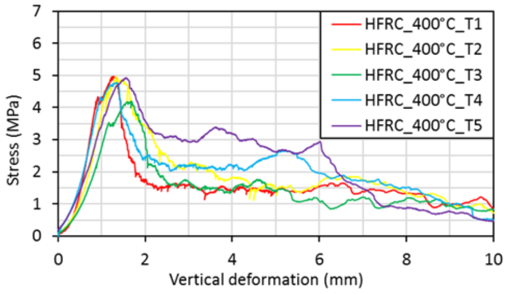
as developed by Kim et al. [16] and is in a good correlation with the result database. This relation also takes into account the influence of fibers on tensile strength at elevated temperature. However, when it is used for the investigated HFRC, obtained values (dashed line) are in a poor agreement with the experimental results (solid circle). Nevertheless, the poor result database does not enable to accurately validate the stress-strain relations proposed so far. First, it is still necessary to enhance the result database for tensile behaviour of HFRC. Even a result database for FRC in tension is very poor and should by updated. After that, it might be possible to either validate the existing stress-strain relations or propose new relations which could precisely describe the structural behaviour of HFRC in tension at elevated temperature. The relations should also take into account the content and a type of fibres used, especially when polypropylene fibres considered. However, the effect of fibres on the behaviour of HFRC at elevated temperature has not been still fully understood.



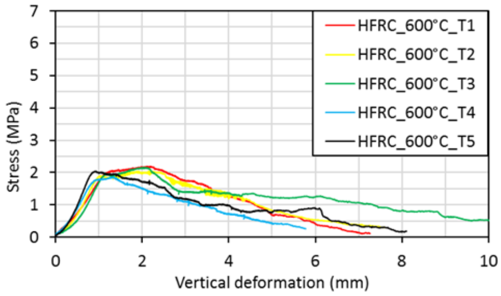
(a) Stress-displacement diagram of HFRC at 20°C



(b) Stress-displacement diagram of HFRC at 200°C



(c) Stress-displacement diagram of HFRC at 400°C



(d) Stress-displacement diagram of HFRC at 600°C

Fig. 5 Stress-displacement diagrams of HFRC in splitting tensile strength

IV. CONCLUSION

The paper deals with stress-strain relations for HFRC at elevated temperature and the experimental investigation conducted with the aim to enhance the result databases. The compression test and splitting tensile test were conducted on 150 mm cubes of HFRC heated up to 200 °C, 400 °C, and 600 °C by using special heat treatment. Based on the obtained findings the following statements have been concluded:

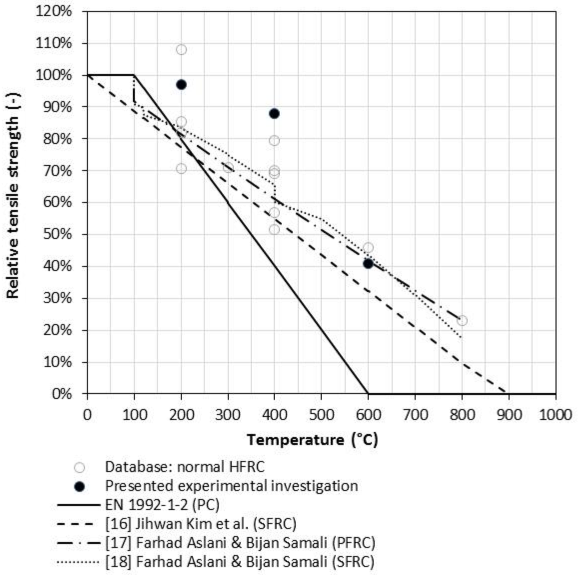


Fig. 6 Relative splitting tensile strength diagram

- Stress-strain relations should by proposed independently for conventional HFRC and reactive powder HFRC as the structural behavior of such materials in compression at elevated temperatures differ significantly.
- The results from the presented compression test as well as the result database for conventional HFRC show a good agreement with CSN EN 1992-1-2, in particular with the recommendations for concrete with siliceous aggregates.
- The empirical relations developed by Khaliq et al. [9] and Aslani et al. [17], [18] seem to be inconsistent at 100 °C, 200 °C and 400 °C.
- The content and a type of fibers used are usually not considered in the existing stress-strain relations for HFRC. From our point of view, excluding such parameters might lead to a poor correlation with experimental data, especially when HFRC with high amount of polypropylene fibers is used.
- There is a critical need to enhance the existing result database for HFRC in order to either validate the existing stress-strain relations or propose new relations which could describe the mechanical behavior of such material at elevated temperature with high accuracy.

The other step in the ongoing scientific project is to enhance the result database for HFRC and find out the effect of various contents of polypropylene fibers on the fire response of HFRC. As an outcome, new stress-strain relations will be developed which could describe the structural performance of general HFRC at elevated temperature.

ACKNOWLEDGMENT

This work was supported by the grant Models of steel and fiber composite columns exposed to fire, No. GACR 15-19073S, from the Grant Agency of the Czech Republic (GACR).

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