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IMPACT OF HIGH TEMPERATURE ON DIFFERENT COMBINATIONS OF FIBER REINFORCED CONCRETE

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Abstract. *Fire belongs to one of the most dangerous aspects of civil and underground engineering, mainly in the assessment of underground structures. The extensive use of concrete as structural materials of linings or envelopes of underground power stations has led to the need of full understanding the effects of fire. If concrete is subject to high temperature, its mechanical behavior, including the compressive and tensile strengths, Poisson's ratio and modulus of elasticity, etc., changes dramatically with the increase of temperature. On the other hand, these changes depend also on the peak temperature, the rate of heating, the fire duration (time at which the structure is exposed to the extreme temperature), on the type of concrete and the type of testing. The distribution of temperature inside of the concrete slabs (cubes) reveals to be a very important phenomenon, as the water inside there changes at a special temperature to a vapor, which, as superheated, can damage the surface of the concrete elements and lower their bearing capacity. A large scale of experiments has been carried out, which can, a.o., serve a possible improvement of the formulation of material properties and subsequent comparison with numerical results. Various combinations of fibers, such as a compound of PP and steel, also a carbon and steel combination and the normal concrete have been tested for temperature to 10000 C. Cubes with dimension of 7 x 7 x 7 cm3 serve as the test specimens, which are heated to 150, 500, 600 or 10000 C. This dimension is in full compliance with the existing norms. The loading is due to a one-sided heating, while the other sides of the cubes will be held at room temperature.*

1 INTRODUCTION

High temperatures, to which the fiber reinforced concrete is exposed, effect material deterioration and, consequently, the bearing capacity is obviously decreased and the failure is attained in the end of continuing fire.

Splitting and spalling of the parts of concrete is related with different thermal expansion of particular components of the concrete mixture and disturbed bonds between aggregate and stiff cement paste in consequence of physical and chemical changes has to be taken into account. Especially, this is an aftermath of the changes of quartz from triclinic crystal system to the hexagonal system in particular phases, which occurs during the increase of temperature to 570 - 575°C.

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This work is focused on the influence of extremely elevated temperatures in the problems of material behavior, namely in the shotcrete from the fiber reinforced concrete with selected fibers. It evolves from the chemo-mechanical and numerical analysis of the fiber reinforced concrete with basalt fibers, recently studied in [1, 2]. The main goal here is an application of experimental results to the mathematical formulation and numerical solution of this problem.

In [3], the effects of elevated temperatures on the compressive strength stress–strain relationship (stiffness) and energy absorption capacities (toughness) of concretes are presented. High-performance concretes (HPCs) were prepared in three series, with different cementitious material constitutions using plain ordinary Portland cement (PC), with and without meta-kaolin (MK) and silica fume (SF) separate replacements. Each series comprised a concrete mix, prepared without any fibers, and concrete mixes reinforced with either or both steel fibers and polypropylene (PP) fibers. The results showed that after exposure to 600 and 800^0 C, the concrete mixes retained, respectively, 45% and 23% of their compressive strength, on average. The results also show that after the concrete was exposed to the elevated temperatures, the loss of stiffness was much quicker than the loss in compressive strength, but the loss of energy absorption capacity was relatively slower. A 20% replacement of the cement by MK resulted in a higher compressive strength but a lower specific toughness, as compared with the concrete prepared with 10% replacement of cement by SF. The MK concrete also showed quicker losses in the compressive strength, elastic modulus and energy absorption capacity after exposure to the elevated temperatures. Steel fibers approximately doubled the energy absorption capacity of the unheated concrete. They were effective in minimizing the degradation of compressive strength for the concrete after exposure to the elevated temperatures. The steel-fiber-reinforced concretes also showed the highest energy absorption capacity after the high-temperature exposure, although they suffered a quick loss of this capacity. In comparison, using PP fibers reduced the energy absorption capacity of the concrete after exposure to 800 °C, although it had a minor beneficial effect on the energy absorption capacity of the concrete before heating.

Publication [4] is focused especially on the shotcrete with fiber reinforced at extremely elevated temperatures with special respects for material behavior. It contains foundations of chemical, mechanical and numerical analysis of fiber reinforced concrete with basalt fibers.

In engineering practice, however, the highly non-linear temperature distributions in concrete members resulting from fire loading are commonly converted into (and replaced by) linear temperature distributions (given by the temperature T_m (°C) in the middle plane of the lining and a constant temperature gradient ΔT (°C/m) over the lining thickness). In contrast to the complex temperature distribution, T_m and ΔT can be easily considered in standard software tools developed for the (linear) analysis of beams and frames (see, e.g., [5, 6]).

After being subjected to different elevated heating temperatures, ranging between 105^0 C and 1200^0 C, the compressive strength, flexural strength, elastic modulus and porosity of concrete reinforced with 1% steel fiber (SFRC) and changes of color to the heated concrete have been investigated in [7].

The results show a loss of concrete strength with increased maximum heating temperature and with increased initial saturation percentage before firing. For maximum exposure temperatures below 400^0 C, the loss in compressive strength was relatively small. Significant further reductions in compressive strength are observed, as maximum temperature increases, for all concretes heated to temperatures exceeding 400^0 C. High performance concretes (HPC) start to suffer a greater compressive strength loss than normal strength concrete (NSC) at maximum exposure temperatures of 600^0 C. It is suggested that HPC suffers both chemical decomposition and pore-structure coarsening of the hardened cement paste when C–S–H starts to decompose at this high temperature. Strengths for all mixes reached minimum values at 1000 or 1100^0 C. When steel fibers are incorporated with 1% ratio, an improvement of fire resistance and cracking is lowered. Resistance as characterized by the residual strengths was observed. Mechanical strength results indicated that SFRC performs better than non-SFRC for maximum exposure temperatures below 1000^0 C, even though the residual strength was very low for all mixes at this high temperature.

Simple-to-use models are presented in [8] for determining the residual tension, compression and flexural properties of burnt fiber reinforced polymer composite materials following a fire. The post-fire mechanical properties are calculated using analytical equations that combine the properties of the fire-damaged (i.e. char) and undamaged regions of a composite. Fire tests were performed on composites containing carbon, glass or Kevlar fibers with an epoxy, polyester, vinyl ester or phenol resin matrix to assess the accuracy of the models. The composites were tested to a wide range of fire conditions with temperatures from 525 to 850^0 C for times up to 30 min. It is found that the post-fire properties drop rapidly with increasing heat flux and duration of a fire due to the thermal degradation of the polymer matrix. It is shown that the reduction to the post-fire properties of the burnt composites can be accurately determined using the models.

The relationship between heat release rate and other fire reaction properties of fiber reinforced polymer composite materials is investigated in [9]. The heat release rate and fire reaction properties of thermo set matrix composites reinforced with combustible fibers (aramid, extended-chain polyethylene) or non-combustible fibers (glass, carbon) were determined over a range of heat flux levels using the oxygen consumption cone calorimeter technique. The fire reaction properties that were measured were time-to-ignition, smoke density, carbon monoxide yield, carbon dioxide yield, mass loss rate and total mass loss. It is discovered that these reaction properties (apart from ignition time) are linearly related to the heat release rate for composites containing non-combustible fibers.

Mechanical and permeability performance of fiber reinforced high strength concrete after heat exposition was evaluated in [10].

2 EXPERIMENTAL

Large scale of experimental tests has been carried out in the Czech Technical University in Prague. Our idea is to accommodate results from experiments mainly for underground structures, being collected for the time-dependent influence of changes of temperature together with moistening and pore pressure. The tests are divided to two parts. In the first part distribution of temperature from the heated face in normal concrete and fiber reinforced concrete is measured with various combinations of sets of fibers, such as PP and steel, carbon and steel and normal concrete have been tested for temperature to 1000^0 C. For the test specimens serve cubes with dimensions of 7 x 7 x 7 cm^3, which are heated to 150, 540 and 1000^0 C. The loading is due to a one-sided heating, with the other sides to be steadily held at room temperature. The matrix of these composites is always created as specific concrete mixtures prepared using Portland cement with basalt aggregate 4 - 8 mm. The masses of admixtures for creating the concrete samples are introduced in Table 1. The FRC contained 1% combination (half and half) steel fibers and PP fibers and in the next combination steel fibers and carbon fibers. These three types of concrete are studied under the temperature of 1200^0 C ceaseless for two hours.

Masses of constituents in dry aggregate concretes C40/50 composition	
Cement - CI 42,5 R Radotín	560 kg
Sand - DTK 0-4 mm Hostín	800 kg
Basalt aggregate - DTK 4-8 mm Hostín	820 kg
Plastificater - Chysofluid Optima 206	6 kg
Water	180 kg
Carbon fibers (first comp.) – TORAY, 1 um/15mm	10 kg
Steel fibers (first and second comp.) – HE 07/30 mm	10 kg
PP fibers (second comp.) – FIBREX PP, 0.45um/4mm	10 kg

Table 1. Concrete C40/50 composition

In Figure 1, the structure of FRC with combination carbon/steel at room temperature is illustrated for next comparison. In Fig 2 and 3 the same FRC is illustrated at temperatures 140 and 540^0 C which is exposed for 120 min to. In Figures 4 – 6, FRC with combinations carbon/steel and PP/steel and normal concrete loaded by an extreme temperature 1000^0 C changed their intrinsic structure (cracks, changes of material properties such as spalling, etc.). All samples from the experiments including thermometers are shown in Figure 7.

Fiure.1: FRC with carbon/steel without heating

Figure 2: FRC with carbon/steel under 140 ◦C

Figure 3: FRC with carbon/steel at 540 °C

Figure 4: FRC with carbon/steel at 1000 °C

Figure 5: FRC with PP/steel under 1000 °C

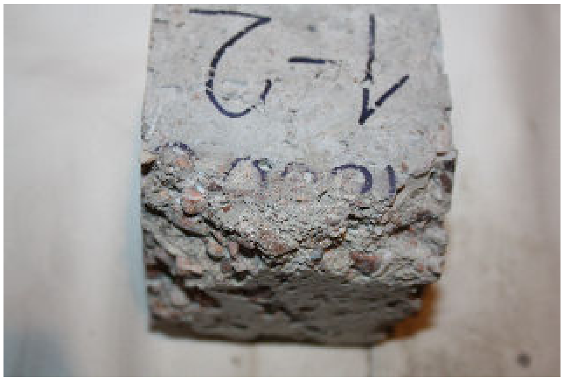


Figure 6: Normal concrete under 1000 °C

Figure 7: All samples from the experiments including thermocouples

Next three pictures describe the distribution of temperature inside of the trial sample cube in the time scale. The temperatures are measured at points with thermometers 1 cm from the heated surface, then at 2 cm etc. Hence, altogether five points are equidistantly distributed along the thickness of the trial cube. In Figure 8 the distribution of temperature in normal concrete is shown. The same temperatures are applied for the combination of reinforcement PP/steel. The loading is applied in such a way that in the first about 5 minutes the required temperature is attained and another 120 minutes the face is heated. In Figures 9 and 10 distributions of temperature posses a similar character for the concrete reinforced with carbon/steel and PP/ steel.

Different times for attained 1000 degrees in the three types of concrete may have different effects on mechanical and chemical resistance properties.

It remains to note and explain the obvious thickness of the curves introduced in the graphs. The measurement device measures the values at each 3 secs, which could lead to the loss of information in the pictures. This is why the measured values are aggregated, so that depicted values at 20 min are in reality collected from that time plus minus 15 secs. The selected times are then connected by Bezier polynomials to get the course presented.

It is of importance to note that only carbon/steel FRC possesses the results from all six termometers. In the other two cases the most exposed position is excluded from the evaluation as the gauges fell out due to the local spalling.

In the second part deformation - controlled test of concrete and FRC with carbon/STEEL or combination PP/steel is carried out for loading of 0 to 1000 centigrade at room temperature after natural cooling process; these result are illustrated in Figures 11 - 13.

The second test shows that normal concrete achieves very good results of the strength and deformation till 540 centigrade; after reaching 1000 centigrade the situation worsens rapidly. From Figures 11 and 13 it is obvious that the FRC exhibits a better mechanical behavior than the normal concrete at 1000 centigrade.

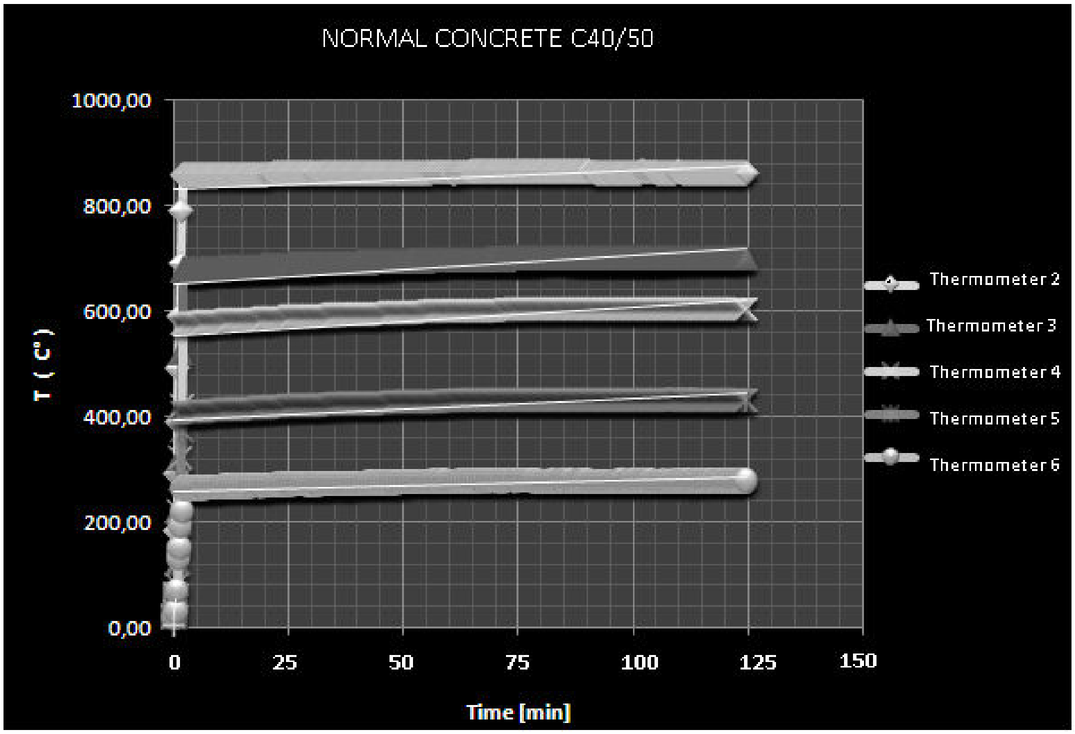


Figure 8: Temperature distributions in normal concrete from the heating side

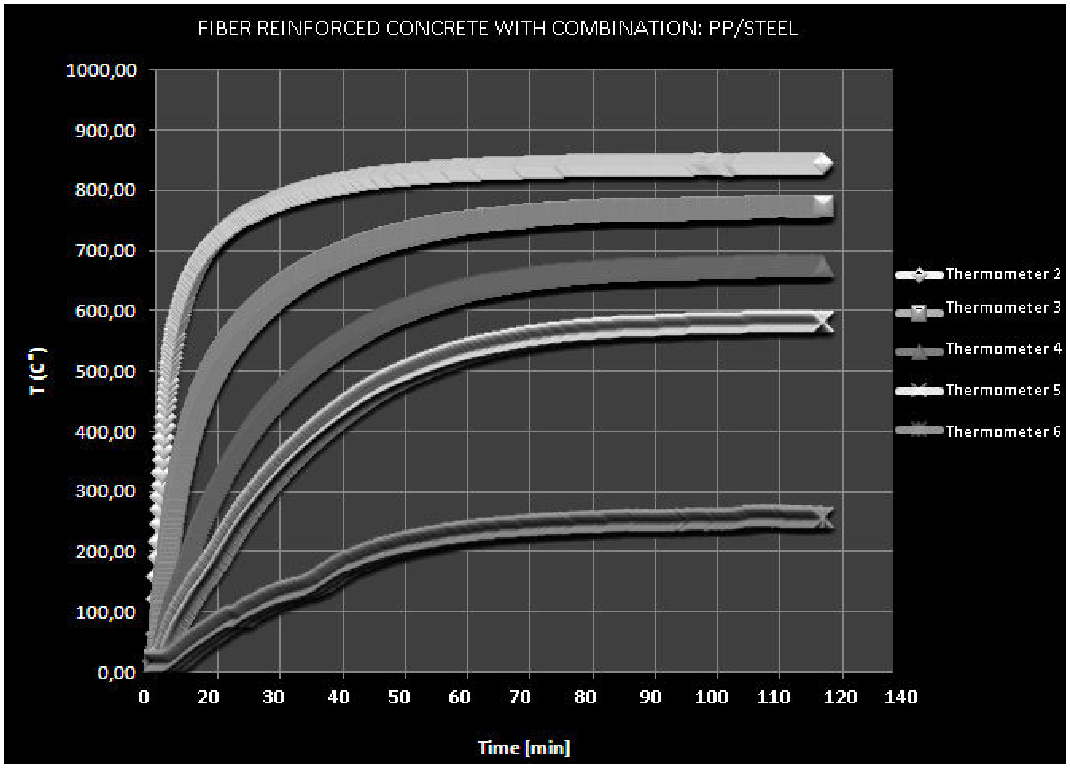


Figure 9: Temperature distributions in FRC with combination PP/steel from heating side

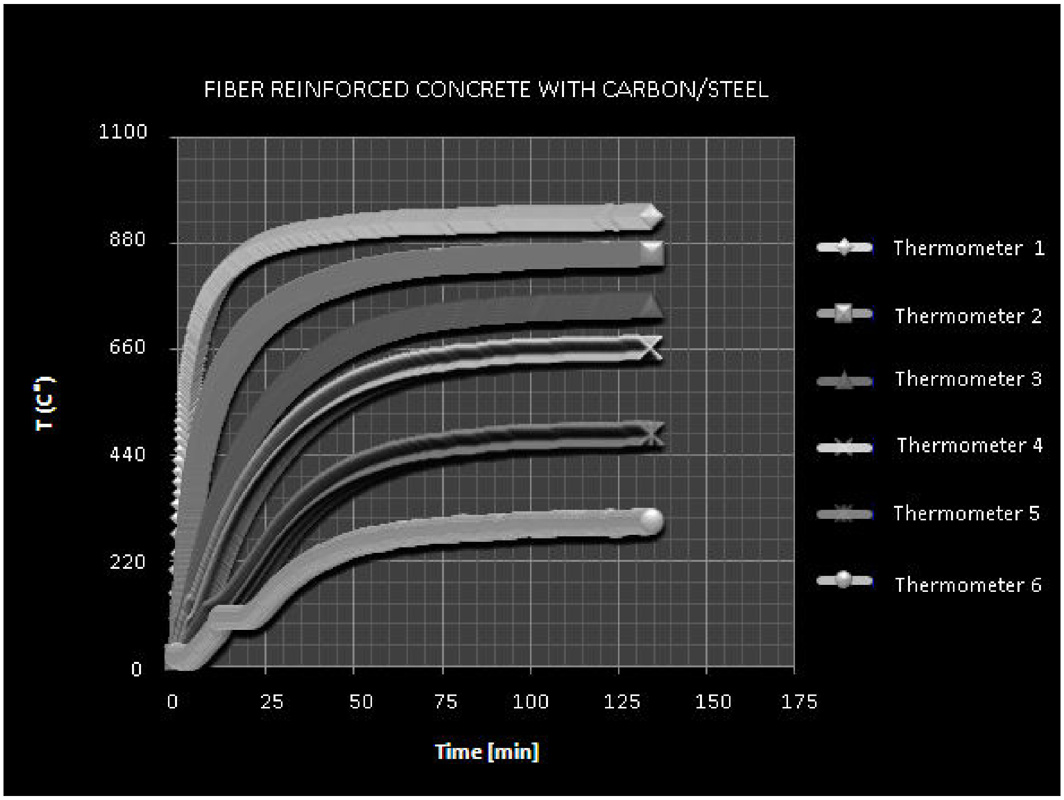


Figure 10: Temperature distributions in FRC with combination carbon/steel from heating side

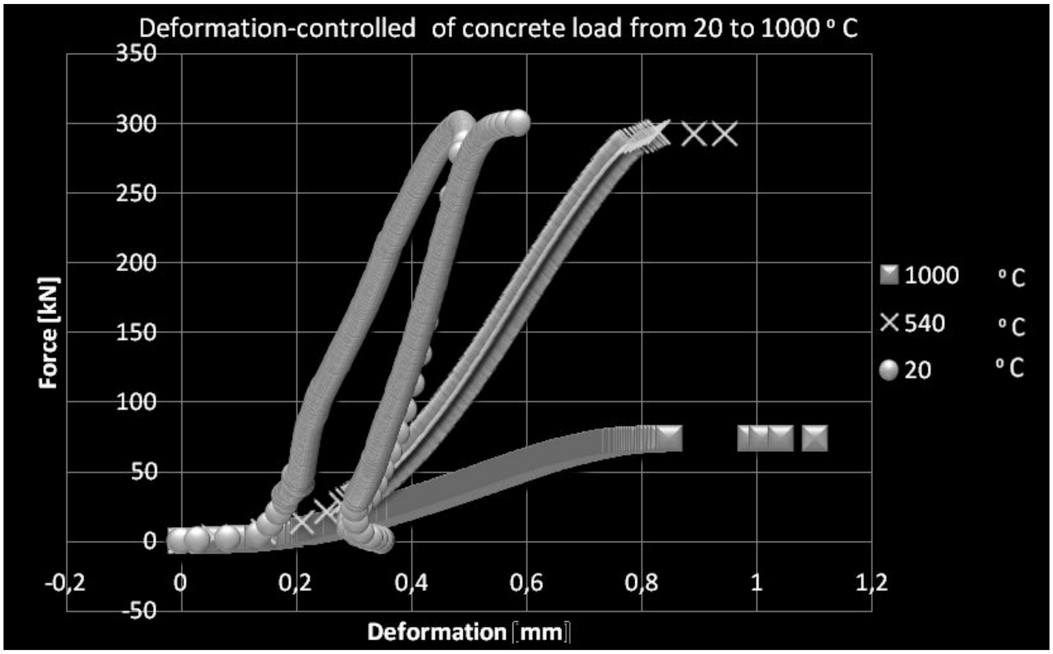
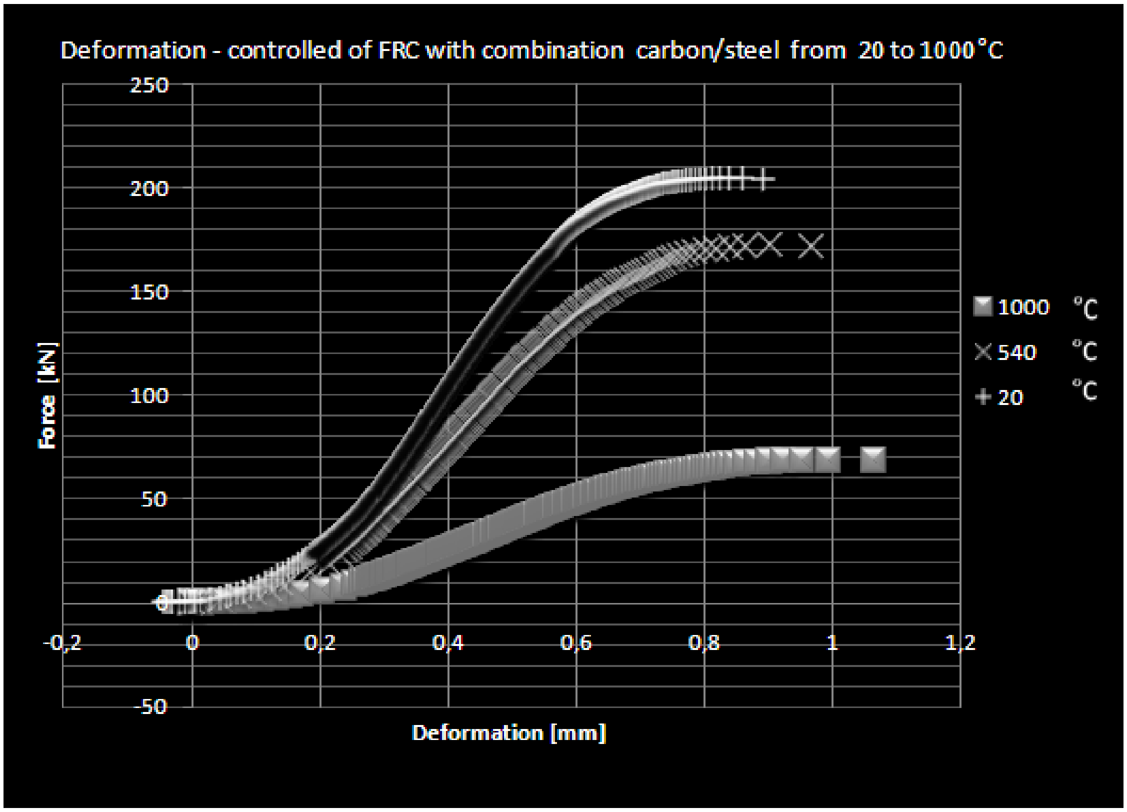


Figure 11: Deformation - controlled of concrete with load from 0 to 1000 centigrades



Fiure 12: Deformation - controlled of FRC with carbon/STEEL load from 0 to 1000 degrees

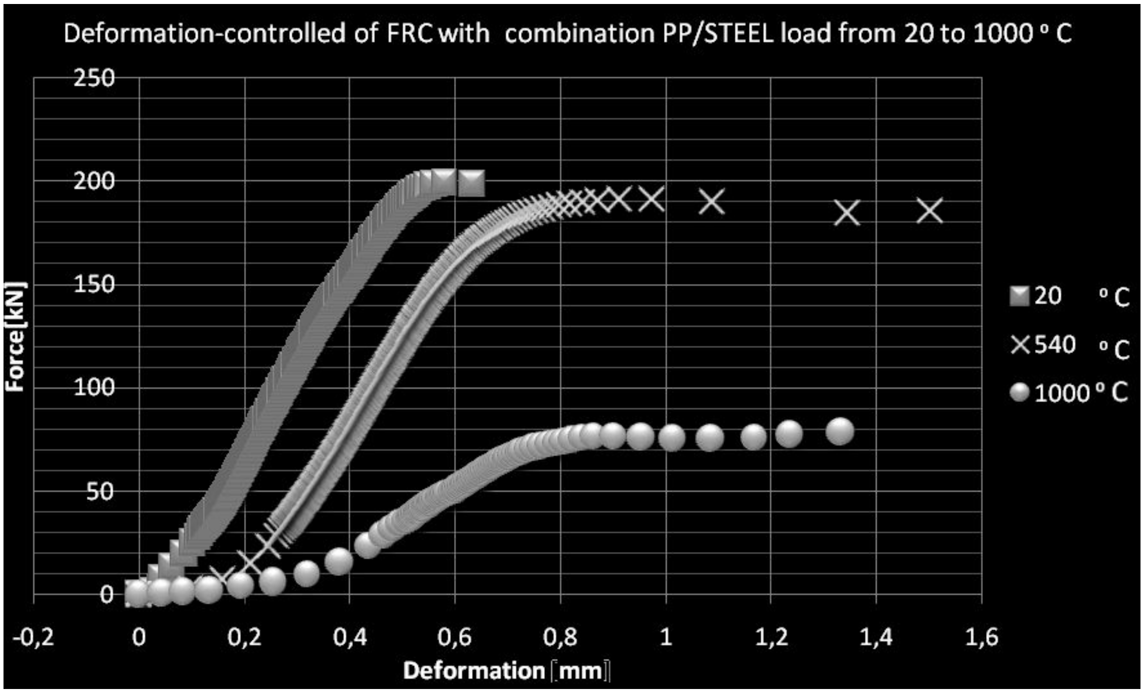


Figure 13: Deformation - controlled of FRC with PP/STEEL load from 0 to 1000 degrees

3 DISCUSSION AND CONCLUSIONS

Large scale of experimental tests has been carried in the Czech Technical University in Prague. In the first step the idea is to collect results from experiment with FRC and a normal concrete. The tests are mostly oriented to underground structures. The time-dependent change of temperature together with moistening and pore pressure are traced. The test is divided to two parts. In the first part measured distribution of temperature from the termal source at one surface of the trial cube, hence the influence of heated face in normal concrete and fiber reinforced concretes with various combinations of fibers are observed. The second part contains complete mechanical tests such as compression tests, for example. As a side product certain chemical changes of concrete and FRC have been evaluated and will be published elsewhere. All results from the tests can serve in theoretical improvement of knowledge on the material behavior of FRC.

Coming back to Figures 8 – 10, where the temperature at the points inside of the cube is traced, one can see that in case the normal concrete is observed, the temperature at the measured point is attained very fast and remains at this temperature all the time of heating. The heating of FRC with the combination PP/steel and carbon/steel records a similar character, the curves are monotonic and only for the lowest temperatures the curves are wavy in character during 40-50 min, say. Next three pictures are devoted to the strain controlled tests with the same material as that used for the temperature time-development. For all cases the diagram force – displacement is one-to-one mapping, so that it is possible to expect that the stress controlled tests deliver the same results. In normal concrete relatively large displacement belongs to a zero force, in case the temperature of 1000^0 C is reached this length is about 0.3 mm. Surprising is the behavior of the concrete at the room temperature after unloading. There is no toughness and the descending part of the curve is creates with ascending one an A model (one would expect V behavior). It seems an interesting observation in the maximum force of the normal concrete and carbon/steel reinforced concrete. They both attained the same maximum force at 1000^0 C.

In the displacement – force diagrams it is of interest that the first stage of applied deformation very small force appears. Note that for stress controlled tests this is not so and the slopes of the curces are mostly the steepest in the entire range of the observed intervals. In the strain controlled tests very resonable behavior is attained. For example, the highest temperature enables the largest displacement before failure. This is a consequence of high porosity in the material, which is exposed to the highest temperature.

It has been shown here that the tests are necessary for new theoretical formulations, which are not clear, although certain recommendations have been issued is some countries. This seems not to be sufficient and it is necessary to continue in testing larger samples, mainly because of obvious big influence of various combination of fibers and they volume ratio.

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