CI-PREMIER PTE LTD
150 Orchard Road #07-14, Orchard Plaza, Singapore 238841.
Telephone: +65-6733 2922, Fax: +65-6235 3530
Company Reg. No. 4198/80

STUDY ON FIRE RESISTANCE IN TUNNEL FR CONCRETE LINING

Petr Prochazka*, Association of Czech Concrete Engineers, Czech Republic
Sarka Peskova, Czech Technical University, Prague, Czech Republic

35th Conference on **OUR WORLD IN CONCRETE & STRUCTURES:** 25 - 27 August 2010, Singapore

Article Online Id: 100035046

The online version of this article can be found at:

http://cipremier.com/100035046

STUDY ON FIRE RESISTANCE IN TUNNEL FR CONCRETE LINING

Petr Prochazka*, Association of Czech Concrete Engineers, Czech Republic
Sarka Peskova, Czech Technical University, Prague, Czech Republic

Abstract

Fiber reinforced concrete (FRC) exposed to extremely elevated temperature is of great concern in tunnel structures, for example. In this paper a theoretical and experimental study on behavior of FRC as the material for tunnel linings being subjected to fire of 1200^{0}C in duration of 2 hours is to be carried out. Theoretical considerations on this problem are presented in terms of free hexagon method and start with the experiments presented hereinafter. The procedure assumes a "soft contact" between hexagonal particles, i.e. springs simulate either tensile and shear contacts in the normal concrete or FRC, where fibers over-bridge possible cracks appearing during cooling process after removing the source of fire. Since the structure is loaded only by change of temperature and no other type of loading is considered (volume weight of the system is neglected), the "soft contact" is fully sufficient to describe the mechanical behavior of the material The formulation of the problem involves the change of porosity, degree of saturation of water, bulk modulus, and other relevant quantities appearing in the physical processes taking part in the FRC. Both the lining and surrounding rock are modeled by free hexagons; their mechanical properties are described by boundary elements. Formerly, the mechanical characteristics inside of the hexagonal elements were uniform during the processes envisaged. Now, the particles changes the properties according to the state equations and the interfaces obey also nonlinear laws, which are described by changing coefficients in generalized Mohr-Coulomb law. The results from numerical procedure are compared with accessible experimental data and the mechanical properties of the material are tuned accordingly.

Keywords: Tunnel lining, fire resistance, free hexagon method, coupled modeling

1. Introduction

The use of fibers in reinforcement of a brittle material can be traced back to Egyptian times when straws or horsehair were added to mud bricks. Straw mats serving as reinforcements were also found in early Chinese and Japanese housing construction, as well as in structures built up during the rule of Roman Empire. The modern development of steel fiber reinforced concrete may have begun around the early 1960s. Polymeric fibers came into commercial use in the late 1970s, glass fibers experienced widespread use in the 1980s, and carbon fiber attracted much attention in the early 1990's.

There are no standards issued for FRC exposed to high temperature, only standards for fire defense of plain concrete are available, [1]. Two recommendations were published in the frame of Eurocodes, which follow the latter standard and substitute the standars for FRC exposed to high temperature and are fully respected in this work.

After being subjected to different elevated temperatures, ranging between 105 °C and 1200 °C, the compressive strength, flexural strength, elastic modulus and porosity of concrete reinforced by 1% steel fiber (SFRC) the heated concrete have been investigated in [2]. 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 °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 °C.

In [3], the fiber pullout behavior being decisive for the overall material properties of the FRC was characterized and modeled. The effects of the firing temperature, the testing temperature and the inclination angle on the fiber pullout behavior were investigated by high temperature pullout tests and scanning electron microscopy observations. As a consequence, a decrease of the fiber pullout load was observed when the firing temperature increases. The high temperature tests showed an increase of the pullout mechanical performances. This phenomenon is induced by the development of a fretting pressure at the fiber-matrix interface.

It appears that very important role plays chemo-mechanical changes along the interface of the fibers and concrete matrix, [4]. The chemical processes basically influence the relations along the interface during the fire (extreme occurrence of entringite is registered) and the change of minerals supports debonding and, consequently, increases of the bearing capacity of the pull-out force. From this follows that the overall properties are also negatively affects.

Temperature also plays an important role in the use of concrete for shielding nuclear reactors. In [5], the effect of different durations (1, 2 and 3 h) of high temperatures (250, 500, 750 and 950 °C) on the physical, mechanical and radiation properties of heavy concrete was studied. The effect of fire fitting systems on concrete properties was investigated. Results showed that ilmenite concrete had the highest density, modulus of elasticity and lowest absorption, and it had also higher values of compressive, tensile, bending and bonding strengths than gravel or barite concrete.

An overview of the former fire in renowned tunnels and the experience from the observations are summed in a monograph, [6]. Also numerical examples based on finite elements are carried out and the results are compared with experimental, [7].

Free hexagon method serve as a numerical tool for assessment of local damage. The method is established in [8] and applied to the bumps occurrence in deep mines. It appears that the method can be used as a solution in very many other branches of civil and underground engineering problems. The results presented in this paper are fully utilized in [9] and the free hexagon method is the numerical tool for describing spalling in fiber reinforced concrete blocks.

2. Experimental

In order to go into the core of the problem of the concrete both non-reinforced and reinforced with basalt or hemp fibers exposed to a high temperature mechanical tests have been carried out. Distribution of temperature inside of a sample block the tests have been conducted with is brought into the open. Then the majority of this paper is devoted to the influence of this temperature on the pore pressure and other material properties due to the elevated temperature.

2.1 Temperature distribution thru the thickness of the sample block

In order to determine the temperature distribution thru the thickness of the concrete block coupled modeling has to be applied, as this is not an easy problem. To get comprehensive information about this a numerical procedure has to be prepared for coding in a computer. Such an approach is proposed in [8] in FORTRAN, for example. The results from that have to be tuned using an experimental study at various heating stages. The reason for this coupled modeling consists in the fact that positioning thermometers inside of the block is not fine enough to get complex and sufficiently complete data about the distribution of temperature inside the block.

In Fig. 1 distribution of temperature in the concrete reinforced by basalt fibers is shown for different distances from the heated face on a time scale. From the mechanical point of view an important process of degradation of compressive strength with degradation of modulus of elasticity as a function of temperature is depicted in Fig. 2, where the compressive strength at 520 ^{0}C fell at half in comparison with room temperature. The boundary conditions here are time dependent and obvious from the picture, where the heated side is left hand side of the picture.

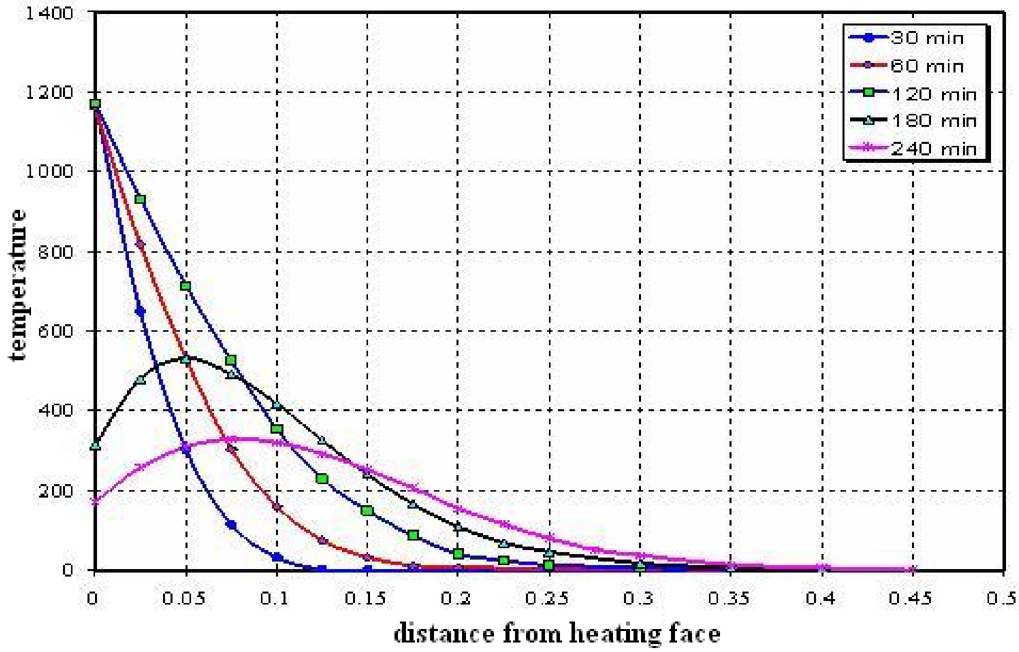

Fig. 1. Temperature distribution in concrete lining reinforced by basalt fibers

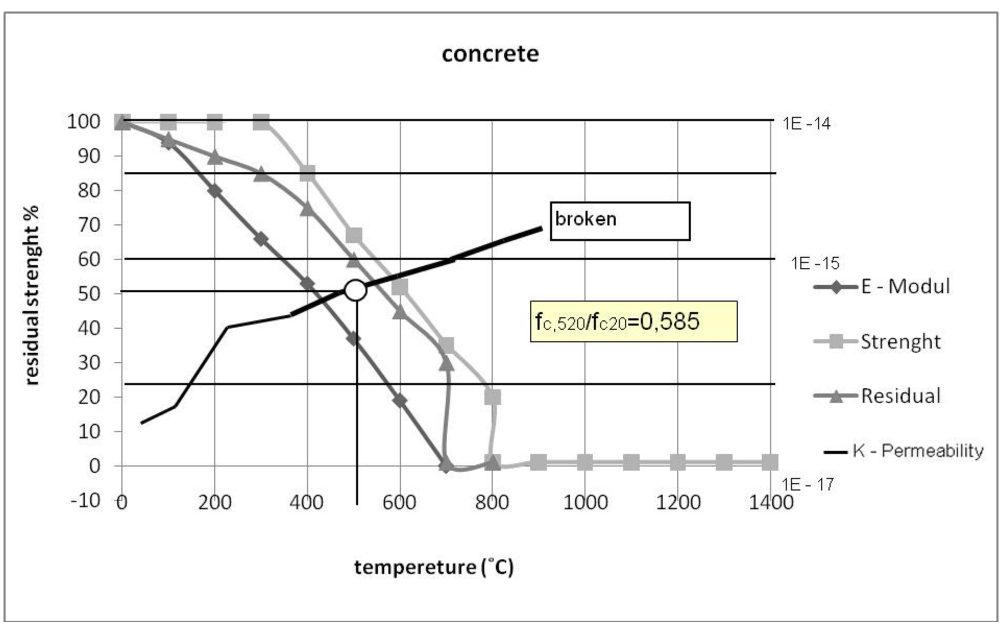

Fig. 2. Process of degradation of compressive strength in dependence on temperature.

2.2 Hygromechanical

As the application is aimed to the tunnel lining attacked by an extraordinary temperature load, extreme level of the temperature is ranged to 1200^{0}C, according to the European standards. For a closer view of the mechanical behavior of the normal concrete and that reinforced with basalt or hemp fiber reinforcement the experiments were carried out in a blast furnace with approximate dimensions 1400 x 2200 x 1300 mm and concrete samples with dimensions 800 x 600 x 500 mm. Three samples were tested in this experiment namely a standard concrete and FRC with basalt and hemp fibers were used. In Fig. 3 a typical sample fiber reinforced concrete block being equipped with analog instruments and thermopiles are shown.

Fig. 3. Furnace with a typical FRC block.

From the mechanical experiments some concrete results are presented in this paper. The results are attained under the time dependent boundary conditions applied on the heated surface of the sample from a concrete blocks and the distribution of temperature inside of the block in time scale, see Fig. 1. Although the time regime is obvious from Fig. 1, recall that the boundary conditions are selected in such a way that in the first 30 minutes the temperature of 1200 degrees is successively, but very rapid, attained and another 90-120 minutes this boundary temperature is hold. Then the source of heating is removed and a natural cooling process is initiated until the room temperature is accomplished. About 15 minutes after triggering the experiment a vapor escaping from the concrete block was observed, see Fig. 4, and then in duration of another 15 minutes hot water was registered extravasations out of the unheated surface. In Fig. 4 the left block is reinforced by the hemp fibers (almost no vapor escaping) while the right block is not reinforced. In Fig. 5, also position of the gas heater OLYMP 3520 is shown.

Spalling and cracking at the heated face of the normal concrete, see Fig. 6, left picture, and that of reinforced concrete, right picture, is depicted after cooling time. It appears that the saturated water in pores is changing rapidly into overheated vapor, which is damaging after fast increase of temperature in the normal concrete, while different situation is observed for appropriately reinforced concrete. For the hemp and basalt fibers reinforcement the lower face of the block exposed to a high temperature no obvious damage is seen, the right picture of Fig. 6.

Comparing the normal concrete and that with fiber reinforcement one sees that the cracks are suppressed in the case of fiber application. It appears that standard melting point of basalt is about 1100^{0}C, but in case fibers in concrete are used the melting point decreases. Consequently, the basalt fibers are very supporting the suppression of tensile cracks during the curing process, but they melt at higher temperature. From this standpoint application of such fibers to concretes exposed to a high temperature seems to be promising. On the other hand closer investigation is necessary, as not only mechanical behavior is decisive, but also chemical analysis of the neighborhood of the heated surface can bring about new views of the problem. Even more efficient are hemp fiber, when applied as reinforcement in the fiber reinforced concrete. They burn out at relatively low temperature and make free space, corridors, or holes, at their locations. In this manner the overheated vapor is given way to escape and do not tear the concrete in full extent. Both hemp and basalt fibers play their basic role at room temperature during curing process, when they bridge the fissures being created because of the shrinkage due to the dehydratation. The most efficient for this goal appear the fibers of the steel or glass type. Since they do not burn out (because very high melting point) if the temperature rise, they do not make free above mentioned corridors inside of the concrete matrix and the vapor has low chance to escape quickly.

Fig. 4. Vapor escaping from the above surface

Fig. 5. Gas heater OLYMP 3520 and escaping water

Fig. 6. Spalling of the surface previously heated – normal concrete and fiber reinforced concrete

3. Free hexagon method

First we briefly recall basic ideas of the free hexagon method. Free hexagon method provides a particle small displacements model, similar to classical PFC (Particle Flow Method) embracing the following assumptions:

- Generally non-linear material behavior is assumed inside of each particle, which is uniformly distributed and boundary element method describes it.
- The contacts occur along the sides between two adjacent elements and are modeled by springs.
- Overcoming of the tensile strength is not admitted in the normal direction, in the shear direction the Mohr-Coulomb's law is applied along the contacts.
- All particles are hexagonal, and either regular division of the domain into non-overlapping hexagons can be considered or the hexagons possess arbitrary shape.

In Fig. 7 situation describing the adjacent elements is depicted together with the basic denotation.

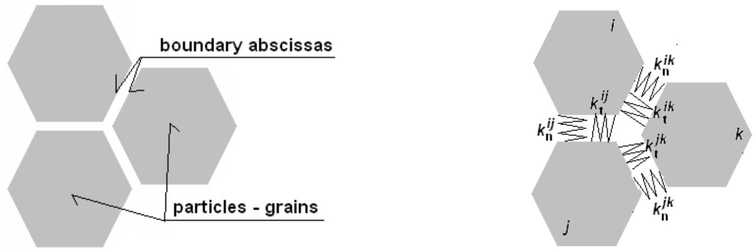

Fig.7. Geometry and basic denotation of adjacent particles

3.1 Penalty formulation

Setting $p_n = k_n[u]_n$, $p_t = k_t[u]_t$, where k_n, k_t are normal spring and tangential spring stiffnesses, [.] means the jump in displacements u, p are interfacial tractions, and subscript n or t denotes normal or tangential direction. Following Fischera's conditions we get:

$$\Pi = \frac{1}{2}\sum_{\alpha=1}^{N} a_\alpha(\boldsymbol{u},\boldsymbol{u}) - \int_\Gamma \overline{\boldsymbol{p}}^{\mathrm{T}} \boldsymbol{u}\,\mathrm{d}\boldsymbol{x} + \sum_{\beta=1}^{n}\int_{\Gamma_\beta} \{k_n^\beta([u]_\mathrm{n}^\beta)^2 + k_n^\beta [u]_\mathrm{n}^\beta\,|[u]_t^\beta| + k_t^\beta([u]_t^\beta)^2\}\,\mathrm{d}\boldsymbol{x} -$$

$$- \sum_{\beta=!}^{n}\int_{\Gamma_\beta}\{(p_n^+)^\beta \kappa(p_n^+ - p_n^\beta)[u]_n^\beta + c^\beta\,\kappa(p_n^+ - p_n^\beta)\,|[u]_\mathrm{t}^\beta|\}\mathrm{d}\boldsymbol{x}$$

where the first two terms in the latter expression express the classical Langrange's principle, the last two describe the situation on adjacent particle boundary abscissas, N is the number of hexagonal elements, n is the number of boundary abscissas being in mutual contact, κ is the Heaviside function. Very weak formulation leads us to boundary elements, which describe the material behavior inside of each element. They relate interfacial tractions linearly with boundary displacements and then iteration is applied to solve the multi-contact problem. It appears that if the division of the domain is regular, the solution is very fast.

For details on the free hexagon method see [8].

3.2 Results

516 hexagonal particles are used for covering the domain of the sample blocks. At the room temperature and in elasticity Young's modulus $E = 160$ MPa, and that in plasticity is 120 MPa; its value at the peak stress is 110 MPa and bilinear interpolation is used. The residual value of E is 30 MPa. Poisson's number ν in room temperature is 0.16 and its residual value is 0.35. Tensile strength along the crack $p^+ = 1$ MPa, inside the domain the shear strength is 3 MPa, in plasticity is 2.5 MPa and residual value is 0.5 MPa. The coefficient of friction is 13 and in plasticity is 32 while in residual state is 11. The above values are implemented to the models for normal concrete. In case the hemp fiber reinforced concrete is used the similar development of internal parameters is assumed as that published in [10].

Similarly, splitting and spalling of the parts of concrete on the heated surface are consequences of different thermal expansion of particular components of the concrete mixture; debond between the volume changing aggregate and the cured cement paste, and additional physical and chemical changes. Particularly, it is the phase change of quartz from triclinic crystal system to the hexagonal system, which happens during the increase of temperature to 570-575°C. Also pore pressure is involved into these processes. It is necessary to take into consideration very rapid change of temperature on the heated surface and a restructuralization of particles inside of the short layer being close to that surface.

In Fig. 8 movements of particles after 30 minutes of heating from below are seen. Although expansion due to the elevated temperature causes small disturbances along the particles, the temperature inside of the blocks is not yet aggressive enough to provoke flaws along the heated face. Since the pictures are small and the movements are hardly recognized, also vectors of the movement are depicted in all forthcoming pictures. They indicate that a compression of the particles takes place; small deflections are registered even at the upper boundary of the block but no decisive destruction of any part or the whole structure appears.

In Fig. 9 the final stage of the process of heating is shown for fiber reinforced concrete. In this case and also in the care of normal concrete the pressure from the inside of the block due to overheated vapor causes more extensive damage in the block. Since in the reinforced concrete by polypropylene fiber implies better and faster escape of the overheated vapor, the spalling is almost negligible on the heated boundary. According to the vectors of movement one can even see that the bending does not touch the whole structure, the movement of the above boundary is even smaller that that in Fig. 8. Not distinct cracking leading to spalling is seen along the lower boundary.

This is not the case of normal concrete. The situation is in the final stage of the test described in Fig. 10. Since there is a small chance of escaping the overheated vapor the movement of the whole body attains the movement of the entire structure, bending is now obvious and all the rows of the particles move principally. Also cracking and separation of the rows on the heated boundary is obvious. This will lead to the spalling along the lower boundary of the tested plain (normal) concrete block.

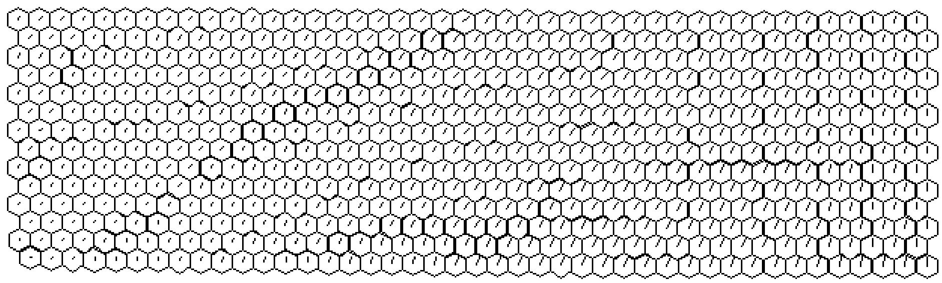

Fig. 8. Movements of particles after 30 minutes of heating from below.

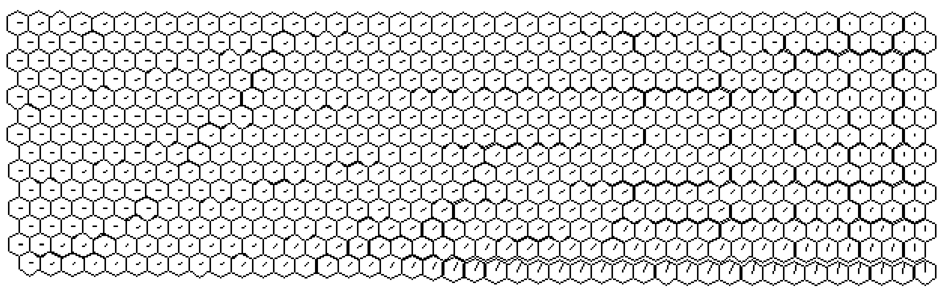

Fig. 9. Spalling appearing after cooling along the lower boundary of the block – FR concrete

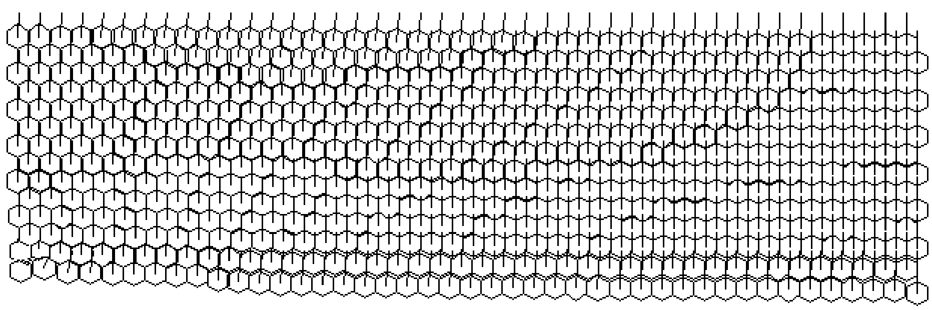

Fig. 10. Spalling appearing after cooling along the lower boundary of the block – normal concrete

4. Conclusions

This work is focused on the influence of extremely elevated temperatures on the change of impact of pore pressure due to vapor created inside of the pores in plain (normal) concrete and in fiber reinforced concrete. Principally the effect of the value of pore pressure inside of the material to the overall behavior is tested. In order to do this, extensive experiments have been carried out in the Czech Republic and in Austria at TU Innsbruck, in which the second author took part during her stay there.

Selected remarkable results and comments are listed below:

- the deterioration of the face of lining is very rapid after during the cooling process as the temperature increased inside of the tested blocks. It is obvious that steel and glass fibers support the stiffness, but due to the high temperature and the water (vapor) and air expansion, change of their density and other phenomena extreme stresses are attained, which cannot be overtaken by the material; better material behavior appears when using natural fibers, or basalt fibers, which are annealed and the space remaining after them is filled by the vapor and the air. After some time of applying the high temperature at the face of the concrete specimens, extravasations of condensed water were observed on the unheated surface of the block.
- Even from the small range of tested fibers one can deduce that the stiffer the better fibers are during the curing process of concrete. On the other hand the softer the better fibers are expected for decreasing the pore pressure due to a sudden change of temperature. This assertion can be extended also for loading, as is the impact load, for example. Probably the best behavior can be expected for combination of stiff and soft fibers and the optimal combination should be searched for. This assertion seems easy to fulfill but there are very many side effects if temperature increase, like condensation of water along the steel fibers, their debond from the concrete matrix, etc.

ACKNOWLEDGEMENT: Thanks are due to Technical University of Innsbruck, personally to Professors Swoboda and Paulini, for fruitful cooperation and enabling Dr. Pešková to conduct certain experiments using their blast furnace. This work has been prepared under support of grant projects of the Grant Agency of the Czech Republic No. P104/10/1021. The financial support of CIDEAS at CTU Prague is gratefully acknowledged. The second author was financially supported also from a post doc project of the Grant Agency of the Czech Republic No. 103/09/P541

5. References

[1] EN 1992-1-2. 2003. Eurocode 2, Bemessung und Konstruktion Von Stahlbeton- und Spannbetontragwerken, Teil 1-2: Allgemeine Regeln und Tragwerksbemessung für den Brandfall. Europäisches Komitee für Normung.

[2] Lau, A., Anson, M. 2006. Effect of high temperatures on high performance steel fiber reinforced concrete. Cement and Concrete Research. Volume36, Issue 9, 1698-1707.

[3] Cailleuxa, E., Cutardb, T., Bernhart, G. 2005. Pullout of steel fibers from a refractory castable: experiment and modelling. Mechanics of Materials. Volume 37, Issue 4, 427-445.

[4] Prochazka, P., Machovic, V., Peskova, S. Chemical and mechanical changes of basalt reinforced concrete exposed to a high temperature. To be published in Silicates and Composites.

[5] Sakr, K., Hakim, E. 2005. Effect of high temperature or fire on heavy weight concrete properties. Cement and Concrete Research. Volume 35, Issue 3, 590-596.

[6] Peskova, S., Prochazka, P.P. 2008. CTU Reports 1, Vol. 12, pp. 150.

[7] Krejčí, T., Nový, T., Sehnoutek, L., Šejnoha, J. 2001. Structure - subsoil interaction in view of transport processes in porous media. CTU Reports, Vol. 5, pp. 125.

[8] Prochazka, P.P. 2004. Application of discrete element methods to fracture mechanics of rock bursts. Engineering Fracture Mechanics 71, 601–618.

[9] Prochazka P.P., Peskova, S., Valek M. 2010. Study on spalling of extremely heated FRC by free hexagons. To appears in Key Engng. Mat.

[10] Prochazka, P.P., Trčková, J., Dolezel, V. (2010) Cement mixture reinforced by polypropylene fibres under higher temperature conditions . To appear in Proceedings of OWICS 2010