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EXPERIMENTAL INVESTIGATION OF THE FIRE RESISTANCE OF MODIFIED CONCRETE

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Abstract: *The paper presents results from large scale experiments on reinforced concrete panels obtained during an extensive experimental program aimed at possible application of cement reduced (fly ash replaced) concrete in the production of precast segmental linings for tunnels created by TBM. In particular, this paper is focused on the comparison of fire resistance of enhanced mixtures loaded by the RWS fire curve, which assumes 50 m^3 fuel tanker fire lasting for 120 minutes. The results from the experiments include spalling, overall damage of the surface, deformations during the fire exposure, temperature distribution and residual strength of the tested panels. The possibility of numerically approximate the deformations and time dependent temperature distribution throughout the specimens is evaluated. The paper also presents a description of a method proposed for the evaluation of the extent of spalling during the experiments as due to the extreme temperatures the direct observation of the exposed surface is excluded.*

Keywords: ***Fire resistance, Concrete, Spalling, Fly ash, PP fibres***

1. Introduction

Cement producing facilities are responsible for a significant portion of CO2 emissions which together with rising prices of cement leads to increased effort in a search for appropriate replacement. The idea of substituting cement for fly ash and thus reducing the heat from hydration has been successfully used in the past (e.g. Keil J., 1966) for massive concrete structures with low requirements on strength or strength increase rate. However only in past few decades an increased effort in the use of waste material powered by international agreements, increased taxation and subsidy from national and international agencies, and new challenges and improved standards on structural safety enabled incorporation of materials which so far have been used only under specific circumstances.

The results presented within this paper are part of an extensive experimental program aimed at possible application of cement free (alkali activated) or cement reduced (fly ash replaced) concrete in the production of precast segmental linings for tunnels created by TBM. The scope of this paper includes full scale fire resistance experiments of enhanced mixtures including large portion of fly ash, PP fibres and a protective layer. Requirements applied on mechanical parameters of tested mixtures correspond with concrete C45/55 with improved resistance against fire and hostile environment (mainly aggressive sulphate).

Due to very specific conditions are fire outbreaks in tunnels different from others especially in terms of peak temperature and rate of temperature increase which limits chances of survival of any living creature. Therefore unlike in case of fires in buildings the resistance of segmental tunnel lining is assessed in view of repair or replacement costs. In recent years a great deal of research has taken place internationally to ascertain the types of fire which could occur in tunnel and underground spaces. Such research has taken place in laboratory conditions as well as in disused tunnels. In the presented experiments the RWS curve which assumes 50 m^3 fuel tanker fire lasting for 120 minutes is modeled.

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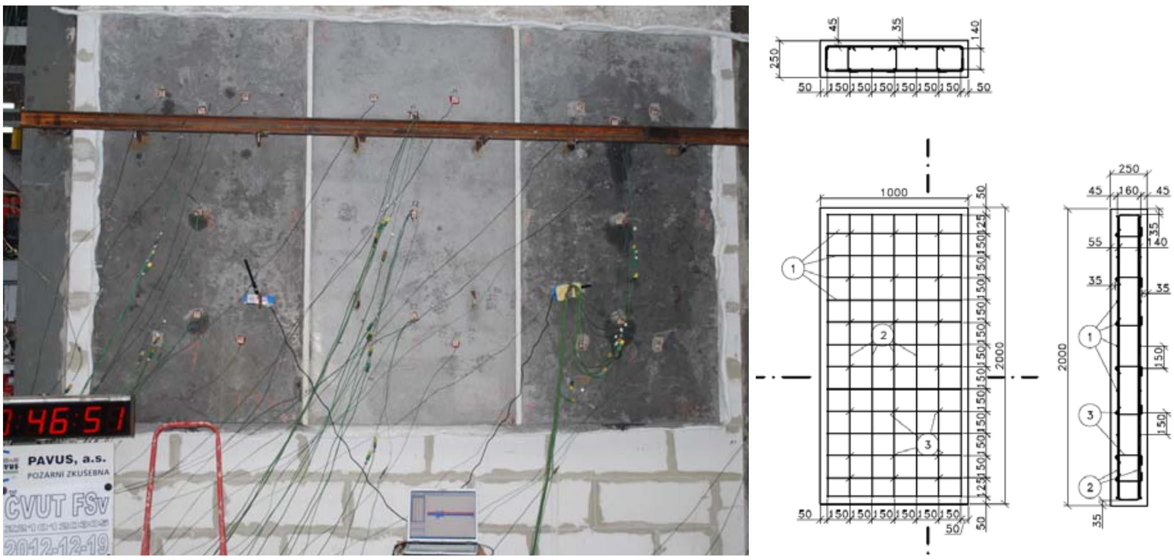
2. Experiment description

With respect to a significant progress in numerical modelling allowing for estimation of damage in concrete structures exposed to fire load the large scale experiments still play irreplaceable role in the assessment of the impact of fire. In addition, results obtained from specimens with enhanced mixtures and applied protective layer combined with temperatures that are close to the melting point of grains in concrete could certainly improve the current constitutive models or to provide necessary data for calibration.

Three specimens, which had very similar thickness and other properties such as reinforcement used in tunnel linings (except for the shape), are built in the fire chamber. In fact they present one of the sides of the fire chamber as shown in Fig. 1 (a). The fire chamber is block shaped with a height and one side length equal 3.4 m and the depth equal approximately 1,2 m. Four computer controlled gas burners with 650 kW power output are responsible for keeping the temperature inside the chamber at the designed level. The temperature inside the chamber is measured by 7 plate and 2 shell thermometers.

The temperature distribution inside the specimen is measured in 3 points (upper third, middle, lower third) located on the middle vertical line. Points in upper and lower third contain 3 thermocouples positioned 50 mm, 125 mm (centre) and 200 mm from the inner surface. The measuring point in the middle has 5 thermocouples located 10 mm, 30 mm, 50 mm, 125 mm (centre) and 200 mm from the inner surface. Another seven thermocouples were used to measure the temperature of the outer surface of each specimen.

Specimens are held in place by a steel beam welded to specimens' handling reinforcements. The beam is anchored to the sides of the chamber; see Fig. 1 (a). The deflection of the specimen is measured in seven points located by three in three horizontal lines (top, middle and bottom) against a parallel vertical plane created by a rotational laser beam. All measured values are plotted against time, counting form the start of the experiment.



(a) *(b)*

Fig. 1: Full scale experiments: (a) Specimens built-in the fire chamber, (b) Reinforcement of the panels

3. Specimens and mixtures

Uniform distribution of temperatures in the fire chamber allows for simplification of the problem by straightening the tunnel lining into panels with dimensions 2000x1000x250 mm. Major reinforcements present steel bars 10 mm in diameter at 150 mm distance in both directions and surfaces. The cover distance is 40 mm. Shear reinforcement bars are 6 mm in diameter. Position of the reinforcement is clear from Fig. 1 (b). Although the panels could seem to be over reinforced the governing idea of the specimen geometry and reinforcement selection was to get as close to the one used in tunnels as possible and only alternate the concrete mixtures.

Three different mixtures were tested to allow for general qualitative description of the effect of increased amount of fly ash in the mixture, the possible enhancement by plastic fibres and the 25 mm thick protection layer made of PROMATEC-T material. The grain distribution remains the same for all the mixtures and is presented in Tab. 1.

Tab. 1: Grain distribution in mixtures

Grain fraction (mm)	**Amount** (kg/m^3 of mixture)
0 / 4	705
4 / 8	130
8 / 16	865

Substituting brown coal fly ash for cement in concrete is one of the main aims of the experimental program. Based on the previous experimental results one mixture with replacement of 30% and two mixtures with replacement of 70% of the cement were suggested. The improvement of long term behaviour is expected due to Pozzolanic reaction of the fly ash that runs more slowly but for longer time than of the pure clinker cement as described by (e.g. Helmuth, 1987 or Fraay, Bijen and de Haan, 1989). One of the mixtures was further modified by adding 0.5% of volume of polypropylene monofilament 54 mm long fibres Forta-Ferro. Table 2 shows the amounts of materials used for mixtures in specimens for full scale experiments. The amount of grains is clear from Table 1.

Tab. 2: Tested mixtures

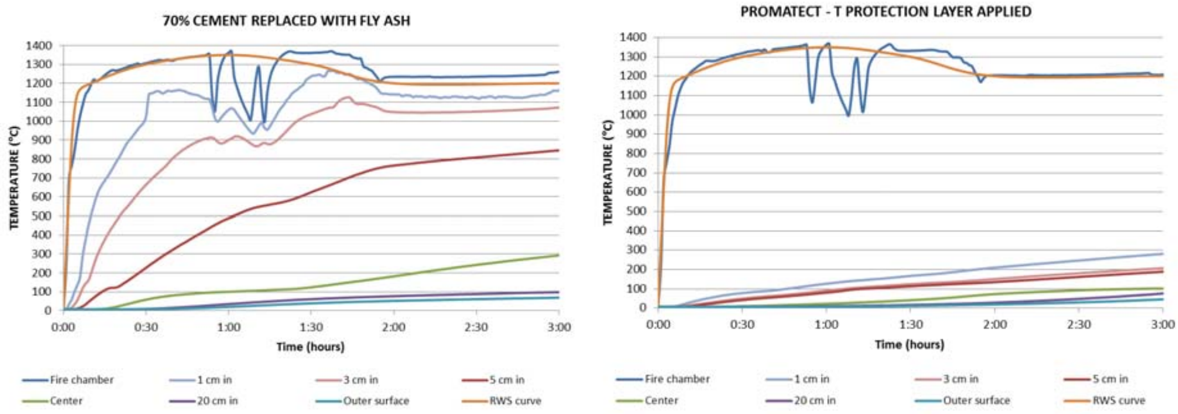
Mixture	**FAC1+PRO**	**FAC3**	**FiFAC3**
Material	Amount (kg/m^3 of mixture)		
CEM I 52.5 R	322	138	138
Fly ash (Melnik I)	138	322	322
Water	150	187	187
Limestone powder	40	40	40
Gleanium ACE 40	4.2	4.2	4.2
FORTA-FERRO fibres	0	0	4.5

4. Results

Under normal circumstances the entire heating system of the fire chamber is driven by a special computer code. Even though the RWS curve is within the safety limits of the chamber, the code evaluated the situation in the chamber as potentially dangerous and run an emergency procedure which shuts down the heating system 3 times before being disconnected. From that point, i.e. from 73rd minute, the heating system was controlled manually which caused insignificant discrepancies between the required and measured loading curve. As all emergency shut downs, took place long time after spalling, see Fig. 2, and the decrease in temperature was of short duration their influence on the results is nearly negligible.

4.1. Temperatures

The temperature distributions along specimens during loading are shown in Fig. 2 (a) for the FAC3 mixture and in Fig. 2 (b) for the FAC1+PRO mixture. Although after 180 minutes the heating stops and the fire chamber begins to slowly cool down, within the specimens the temperatures keep on rising. Table 2 summarizes the peak temperatures which are higher than temperatures at the end of the fire loading.



(a) *(b)*

Fig. 2: Measured temperatures: (a) FAC3 specimen, (b) FAC1+PRO specimen (protection layer)

The specimen equipped with protection layer experienced lowest temperatures and as the only one sustained the fire loading without visible damage. Only this specimen fulfilled the general accepted limit values of 250°C for temperatures in concrete adjacent to reinforcements.

Even though the mixture enhanced by plastic fibres (FiFAC3) did not fulfil the temperature requirements it experienced significantly lower temperatures in the surface areas than the mixture without (FAC3) during the entire experiment and also during cooling. This fact also influences the damage of the surface areas and amount of scrap due to spalling. When comparing the obtained results with experimental data on mixtures with smaller amount of fly ash content (Šejnoha et al, 2012), significant decrease in temperatures can be observed for mixtures having large portion of cement replaced.

Tab. 3: Temperatures in °C inside specimens

Mixture	**FAC1+PRO**	**FAC3**	**FiFAC3**
Location	End of fire loading (T = 180 min)		
30 mm from inner surface	208	1073	---*
50 mm from inner surface	189	847	703
Centre of the specimen	102	293	197
Location	Peak temperature (time differs)		
30 mm from inner surface	222	1125	---*
50 mm from inner surface	208	852	710
Centre of the specimen	122	352	273

* The sensor in this location malfunctioned.

4.2. Spalling

Fast increase of pore pressure due to vaporization is generally accepted as the main cause of spalling of the concrete structures exposed to fire loading. The process is mainly influenced by the temperature increase rate and the peak temperature in the exposed zones. A positive effect of the polypropylene fibres that burn out and therefore create additional “space”, due to which the pore pressure increase is smaller and spalling is also less likely to occur or be of less magnitude, was experimentally proved several times in the past (e.g. Kodur, Cheng, Wang and Sultan, 2003). The specimen with added fibres indeed shown better behaviour during fire loading but the fibres also influence other mechanical parameters and such mixtures are also more demanding with respect to technological discipline.

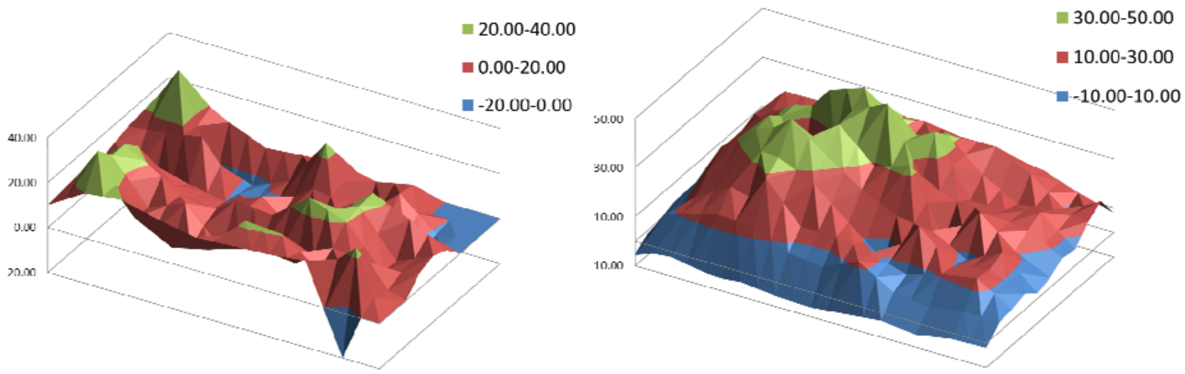
The protection layer prevents the temperatures inside the specimen to rise quickly and also significantly decrease the peak values. The specimen equipped with protection layer was completely spared from the effect of spalling though the protection layer itself was damaged and as shown in chapter 4.3 it was not spared from the impact of heat to the compressive strength.

Thanks to the increased amount of fly ash, the tested specimens did not experience heavy spalling resulting in large areas of exposed and deformed reinforcement which is typical of non protected concrete surface (Šejnoha et al, 2012). In case of FAC3 a FiFAC3 specimens, the high temperatures however caused the entire cover layer of concrete above the reinforcement to delaminate – see Fig. 3 (a). The top 100 mm of the panels was severely damaged and could not be included into further analysis. The strength of this 100 mm is considered to be close to zero and the reinforcement must also be excluded for the residual strength purpose. Athough the specimen with PP fibres was damaged less, the delamination was aslo observed and top 100 mm had to be considered as completely destroyed.

(a) *(b)*

Fig. 3: Specimens after an experiment: (a) FiFAC3 mixture, (b) FAC3 mixture - detail

The following figure shows surfaces of the FAC3 and FiFAC3 specimens plotting measured points. Measurement was carried out at each node of the proposed rectangular mesh against the selected parallel plane on specimens without any further treatment. That is important mainly due to the presence of large “bubbles” with very thin shell covering most of the surfaces. As a result of the extremely high temperatures the surface material is close to the melting point and when the pore pressures increase due to vaporization of water they “inflate” some areas of the surface which are therefore higher than the original surface due to these bubbles.



(a) *(b)*

Fig. 4: Measured surface after an experiment: (a) FAC3 mixture, (b) FiFAC3 mixture

Table 4 summarizes the effect of fire loading on the specimens. Missing weight i.e. the difference between the weight before the experiment and the weight after the experiment plus the weight of the scrap is vaporized water. It is clear from the measured values, that the amount of vapored water is in overall the same for specimens without protection layer. Unlike in case of pure clinker cement mixtures or mixtures with small portion of fly ash as a binder the total amount of vaporised water is smaller than included in the mixture. Therefore it can be stated that chemically bonded water in tested specimens have not all vaporised during the fire loading with RWS curve as it would have without mixture enhancement or protection layer application.

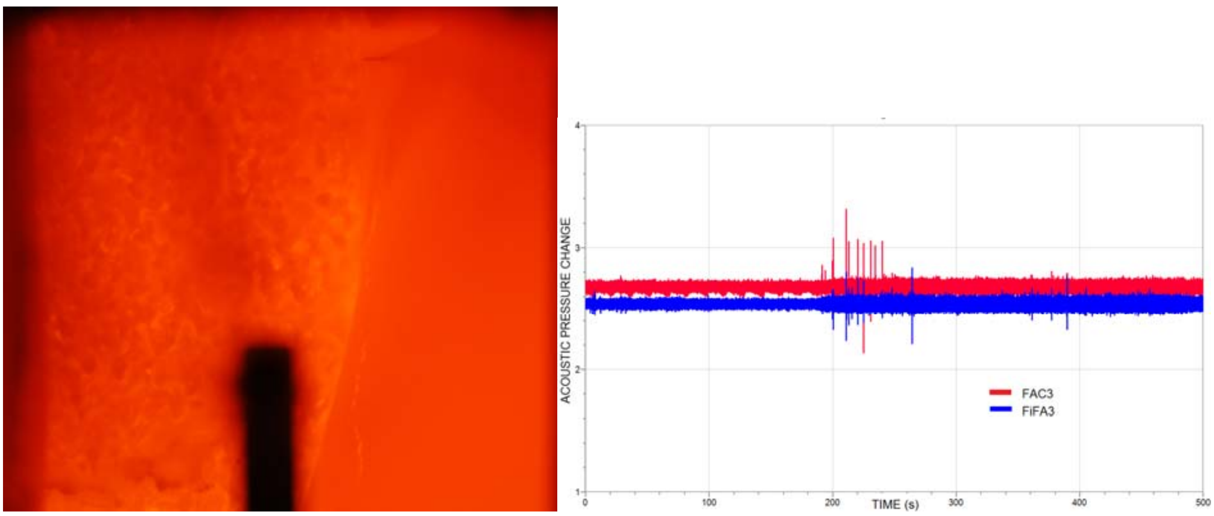
Tab. 4: Spalling

Mixture Value	FAC1+PRO	FAC3	FiFAC3
Weight before experiment (kg)	1230	1165	1150
Weight after experiment (kg)	1178	1066	1080
Weight of the scrap (kg)	0	30	5,2
Scrap in % of weight	0	2.6	0.5
Average scour depth (mm)	0	-18.6	-9.5
Exposed reinforcement	not directly; delaminated	not directly; delaminated	no visible damage

4.2.1 Observation and acoustic pressure

The temperature distribution along one specimen during experiment and the overall damage caused by spalling together with the shape of the damaged surface and weight of the scrap provide very good but incomplete information about the spalling phenomenon. A direct observation of the exposed surface is however severely limited due to extreme temperatures inside the fire chamber, which are high enough to melt steel. Therefore, an indirect observation method based on the acoustic pressure changes was proposed to depict the time – spalling – temperature relation and to separate the recorded sounds from different specimens. The last mentioned issue result from economic aspects of the experiment that support the idea of more specimens being tested during a single experiment.

It should be mentioned that the RWS curve represents fire loading with the highest temperatures among other generally accepted fire loading curves, only theoretical modified hydro carbon curve reaches temperature 1300°C, and also that the RWS curve was experimentally confirmed (Ingason and Lönnermark, 2003) . Fig 5 (a) presents a view into the fire chamber during the experiment when the temperature dropped to 1200°C. The specimen’s surface can be seen on the left part while on the right side deformed special plates made of mineral fibres separating the specimens can be observed.



(a) (b)

Fig. 5: Spalling observation possibilities: (a) direct visual, (b) indirect acoustic pressures

An acoustic pressure measurement combined with a sound record or in this case a video record allows for attributing appropriate sounds to each specimen at the exact time allowing for completing information set for description of spalling phenomenon. The obtained experimental data are further used to enhance the current constitutive relations for concrete at very high temperatures (Li et al, 2006), (Tenchev et al, 2001) or (Beneš and Mayer, 2007).

4.3. Residual strength

In order to evaluate the impact of heat exposure on the tested specimens, bores with 150 mm inner diameter were drilled into the specimens after the experiment and the residual compressive strength was measured.

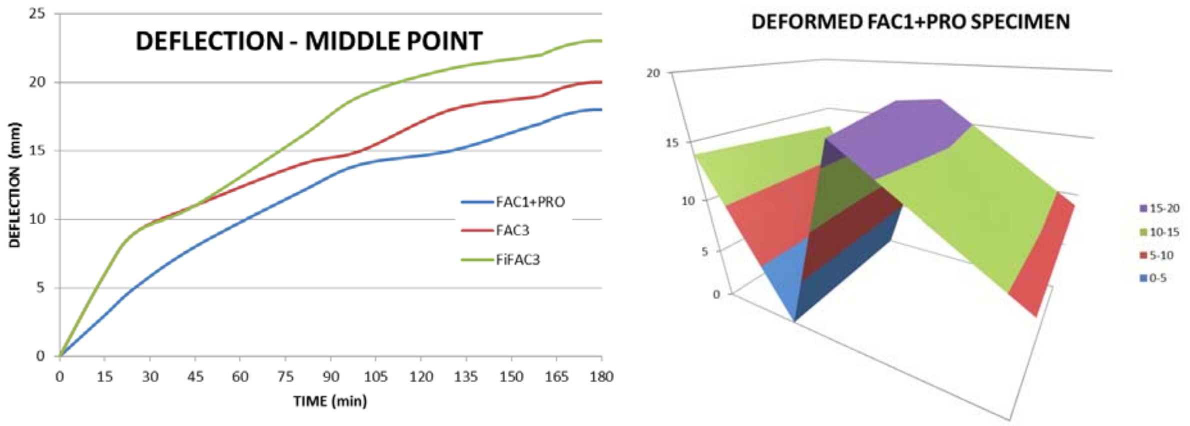
Table 5 summarizes the impact of fire by comparing cubic compressive strengths measured on undisturbed cubic samples and cores from boreholes. The height of samples from FAC3 and FiFAC3 specimens was approximately 150 mm while the height of samples from the FAC1+PRO specimen was 240 mm. A dramatic decrease can be observed even for the panel with protective layer which was without a visible damage. Also the coefficient of variation rises significantly. For specimen FAC1+PRO it should be pointed out that when using only 150 mm high samples as in the case of other specimens, the mean cubic compressive strength after the experiment rises to approximately 39 MPa. Therefore we conclude that even though the temperatures did not rise over the limiting value in this particular case it still heavily influence the mechanical parameters of the specimen in undesirable way and the concrete would not comply the with required class C45/55.

Tab. 5: Residual strength

Mixture / Value	FAC1+PRO	FAC3	FiFAC3
$f_{c,cube}$ (28 days) – mean (MPa)	58.6	29.0	26.4
$f_{c,cube}$ (28 days) – CV (%)	4.4	0.5	0.4
$f_{c,cube}$ (after experiment) – mean (MPa)	33.9	14.3	17.8
$f_{c,cube}$ (after experiment) – CV (%)	11.1	13.6	16.7

4.4. Deflection due to fire loading

Seven measuring points on every specimen were used to describe the change in the deflection over time. The welded points are assumed to have zero displacement. Due to the position of the supporting beam the deformed shape is more complex but the measured data can still be used for numerical modelling as a calibration or confirmation source. Fig. 6 presents deflection of the central point for all three specimens over time and also the deformed shape of the FAC1+PRO specimen at the end of fire loading.



(a) *(b)*

Fig. 6: Deformation of the specimens: (a) middle point displacement over time, (b) deformed shape of the FAC1+PRO specimen – linear interpolation

5. Conclusions

The paper summarizes results obtained from large scale fire resistance experiment with three models of flat TBM segment linings made of enhanced concrete mixtures. Increased amount of fly ash replacing cement proved to have positive influence on the fire resistance which is, however, still unsatisfying.

Although temperatures inside specimen covered with protection layer made of 25 mm of calcium-silicate material (PROMATEC-T plate) did not exceed generally accepted limit values and no visible damage was observed on the specimen, residual mean compressive strength measured on columns drilled from the specimen was less than 60% of the mean compressive strength after 28 days.

Specimen with added plastic fibres showed better behaviour in terms of spalling and temperature distribution but the compressive strength was smaller by more than 10% when compared to the specimen without fibres.

Proposed method of acoustic pressure measurement proved the capacity to relate spalling which takes place in closed fire chamber with time and temperatures inside the specimen, when combined with appropriate audio or video capturing device, and also to distinguish between several specimens tested within one experiment. Direct observation of the exposed surface is due to extremely high temperatures very limited.

Acknowledgement

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