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RESISTANCE OF CONCRETE WITH FLY ASH CONTENT UNDER THE RWS CURVE FIRE LOADING

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Abstract: *The first part of the paper presents the results obtained from large scale fire experiments on reinforced concrete panels 1.5 x 3.0 meters and small scale high temperature experiments on cubes with a side length equal to 0.15 meters. Concrete mixtures with large content of fly ash as a binder were selected for large scale experiments whereas cubes were made of cement based mixtures as well as of alkali activated fly ash mixtures. The influence on polypropylene fibres, added into half of the specimens, on the fire resistance is also described. Second part of the paper is focused on the numerical modelling of the effect of fire using a simplified numerical approach. Experimental data are used for calibration of the models as well as for the comparison of results. The loading is governed by RWS Curve which assumes 50 cubic meters of petrol or oil fire in the tunnel.*

Keywords: ***Fire resistance, Heat transfer, Spalling, Fly ash, PP fibres***

1. Introduction

Increased effort in use of waste material as well as in decrease of CO_2 emissions powered by international agreements, increased taxation and subsidy from national and international agencies, and new challenges and improved standards on structural safety enable incorporation of materials which so far have been used only under specific circumstances. The idea of substituting fly ash for cement 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.

Presented results 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. In particular, this topic is focused on fire resistance of enhanced mixtures including large and small scale experiments as well as numerical simulations of large scale tests. Requirements applied on mechanical parameters of tested mixtures correspond with concrete C50/60 with improved resistance against fire and hostile environment (mainly aggressive sulphate).

Fire outbreaks in tunnels differ from others especially in terms of peak temperature and rate of temperature increase. 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, RWS curve, which assumes 50 m^3 fuel tanker fire which last for 120 minutes, is considered.

The results from the physical experiments including spalling, overall damage of the surface and deformations of the tested panels are presented. The possibility of numerically approximate the deformations and time dependent temperature distribution throughout the specimens is evaluated.

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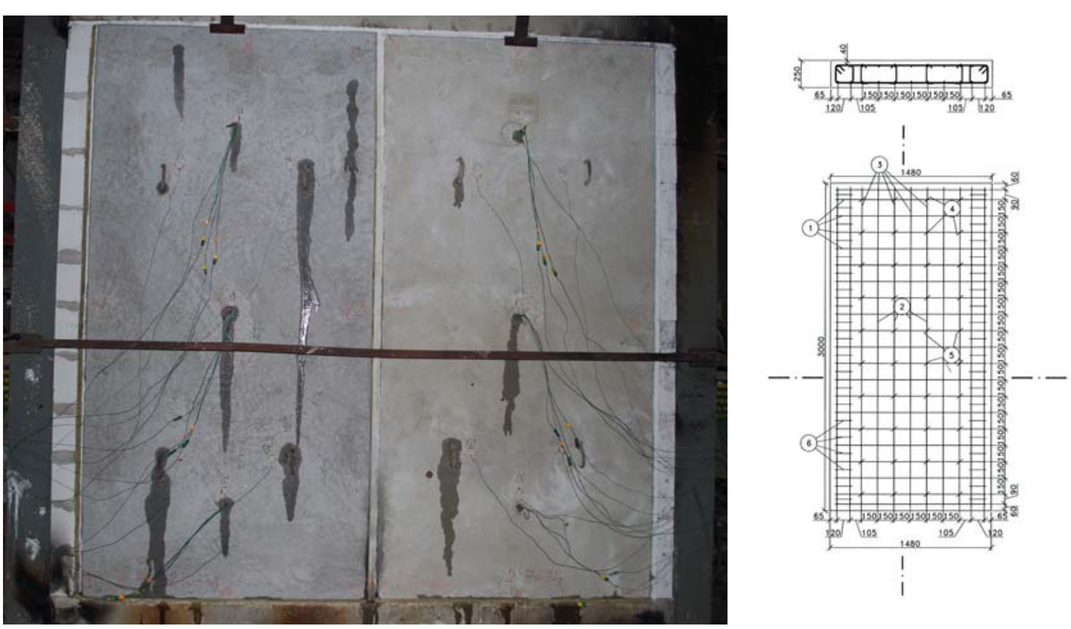
2. Full scale physical experiments

In order to fairly describe the impact of the heavy fire load on tunnel linings full scale experiments have been set up. Two specimens having dimensions and other properties, e.g. reinforcement, very similar to the linings used in tunnels (except for the shape) have been installed in the fire chamber. In fact they present one of the sides of fire chamber as shown in Fig. 1 (a). The fire chamber is cube shaped with a side length 3.4 m. Four computer controlled gas burners 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 inside the specimen is measured in 3 points (upper third, middle, lower third) located on the middle vertical line. Each point contains again 3 thermocouples positioned 50 mm, 125 mm (centre) and 200 mm from the inner surface. Another seven thermocouples are measuring the temperature of the outer surface of each specimen.



(a) (b)

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

The deflection of the specimen is measured in nine points located by three in three horizontal lines (top, middle and bottom) against parallel vertical plane created by rotational laser beam. All measured values are plotted against time, counting from the start of the experiment.

2.1. Specimen description

The specimens intended for large scale experiments are panels with dimensions 3000x1500x250 mm. Major reinforcement present steel bars 10 mm in diameter at 150 mm distance in both directions and surfaces. The cover thickness is 40 mm. Shear reinforcement bars are 6 or 8 mm in diameter. Position of the reinforcement is evident from Fig. 1 (b). Both the specimen geometry and reinforcement were selected as close to the ones used in tunnels as possible. Thus only the concrete mixtures were alternated.

Four different mixtures were tested in order to describe the effect of increased amount of fly ash in the mixture and the possible enhancement by plastic fibres. 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

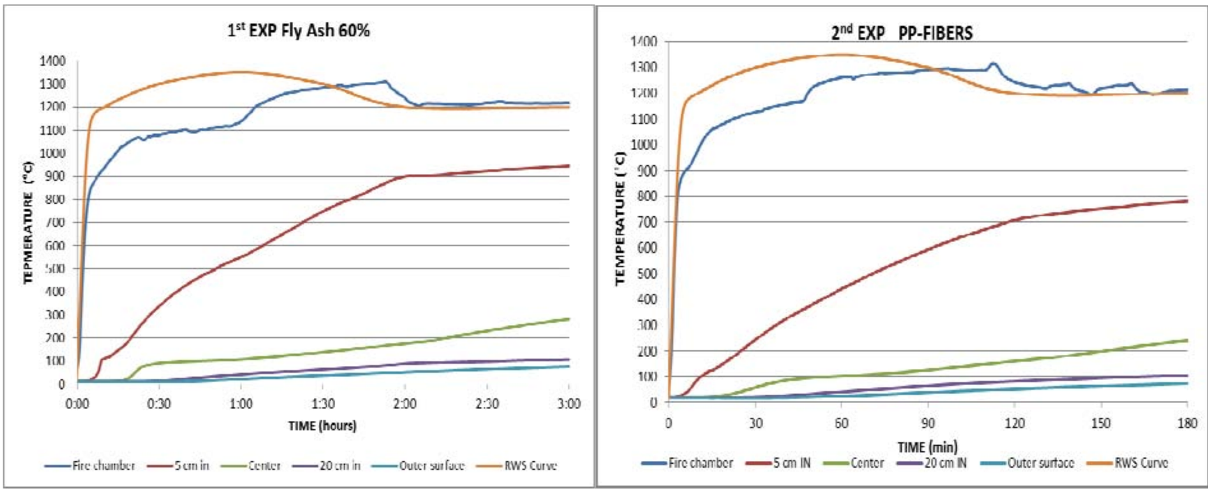
The principal aim of the experimental program was to substitute cement by brown coal fly ash. Therefore, all the mixtures were based on the replacement of 30% of the cement. In order to improve the long term behaviour more fly ash (30% of the original cement weight) was added into two of the mixtures increasing the total amount of binding material. The improvement is expected due to Pozzolanic reaction of the fly ash that runs more slowly but for longer time than in the case of pure clinker cement as described by (e.g. Helmuth, 1987 or Fraay, Bijen and de Haan, 1989). Half the mixtures were 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 except for grains.

Tab. 2: Mixtures for full scale experiments

Mixture	**FAC1**	**FiFAC1**	**FAC2**	**FiFAC2**
Material	Amount (kg/m^3 of mixture)			
CEM I 52.5 R	322	322	322	322
Fly ash (Melnik I)	138	138	276	276
Water	150	150	187	187
Limestone powder	40	40	40	40
Gleanium ACE	4.2	4.2	4.2	4.2
FORTA-FERRO fibres	0	4.5	0	4.5

2.2. Results

The obtained results include temperatrure distribution along the specimens as is shown in Figure 2 (a) and (b), surface spalling of the specimens as discribed in Figure 3 and Figure 4 and Table 4. Measured deflection of the specimens is plotted in Figure 8 together with the results obtained from numericall analyses.



(a) (b)

Fig. 2: Measured temperatures: (a) FAC2 specimen, (b) FiFAC2 specimen (PP fibres included)

Mixtures enhanced by plastic fibres experienced significantly lower temperatures in the surface areas during the entire experiment and also during cooling. This fact also influences the spalling of the surface areas. Differences in the amount of fly ash content did not prove any significant influence on the results.

Tab. 3: Temperatures in °C inside specimens

Mixture	**FAC1**	**FiFAC1**	**FAC2**	**FiFAC2**
Location	End of fire loading (T = 180 min)			
50 mm from inner surface	929	781	945	862
Centre of the specimen	312	241	282	242
Location	Peak temperature (time differs)			
50 mm from inner surface	930	789	946	869
Centre of the specimen	348*	297	322*	277

* The logging was stopped after 210 minutes although the peak temperature in the centre of the specimen is reached after app. 250 minutes.

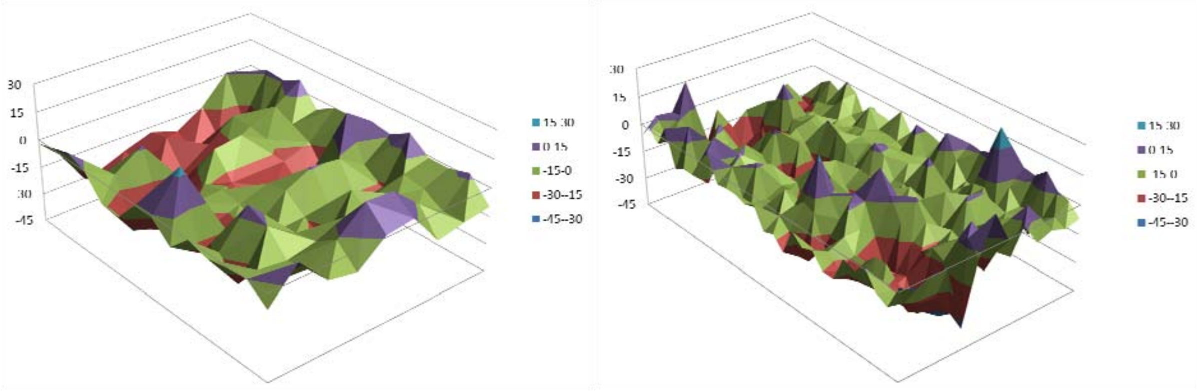
The fast increase of pore pressure due to evaporation is typically indentified as the main cause of spalling of concrete mixtures during the fire load. It seems, however, that is mainly influenced by the temperature rate increase and by the peak temperature in the exposed zones. Positive effect of the 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 mixtures with added fibres shown better behaviour during fire loading indeed but as the fibres also influence other mechanical parameters of the specimens it was necessary to include these mixtures in the program.

The effect of fibres can be observed in the temperatures measured during the experiment (Tab. 3) and is also visible in the following figure which clearly states the extent of damage. Figure 3 (a) shows a specimen without fibres. Although the surface is not scoured by 40 mm, which is the cover thickness, and only on average by 10.5 mm as shown in Figure 4 and Table 4, the reinforcement bars are exposed. On the other hand, Figure 3 (b) shows a specimen with added fibres, which surface was also scoured on average by 10.5 mm and yet the reinforcement bars were not exposed.


(a) (b)

Fig. 3: Specimens after an experiment: (a) FAC2 mixture, (b) FiFAC2 mixture (PP fibres included)

The following figure shows surfaces of the same specimens created by plotting measured points. For the measuring purpose rectangular mesh was created and measurement was done at each node against selected parallel plane on specimens without any further treatment. That is important mainly due to the presence of large “bubbles” with very thin shell cover on the surfaces. Even though in average the surface is scoured by 10.5 mm some areas are actually higher than the original surface due to these bubbles.



(a) (b)

Fig. 4: Measured surface after an experiment: (a) FAC2 mixture, (b) FiFAC2 mixture

Tab. 4: Spalling

Mixture **Value**	**FAC1**	**FiFAC1**	**FAC2**	**FiFAC2**
Weight before experiment (kg)	2775	2763	9633	2637
Weight after experiment (kg)	2443	2511	2325	2360
Weight of the scrap (kg)	172	96	146	116
Scrap in % of weight	6.4	3.6	5.8	4.6
Average scour depth (mm)	10.5	4.4	9.5	10.5
Exposed reinforcement	large zones	not at all	large zones	locally

Missing weight i.e. the difference between weight before the experiment and weight after the experiment plus the weight of the scrap is vapored water. From the measured values it is clear that the amount of evaporated water is in overall the same for all tested specimens and nearly equals the total amount of water included in the mixture. Therefore, it can be stated that even chemically bonded water vaporize during the fire loading with RWS curve.

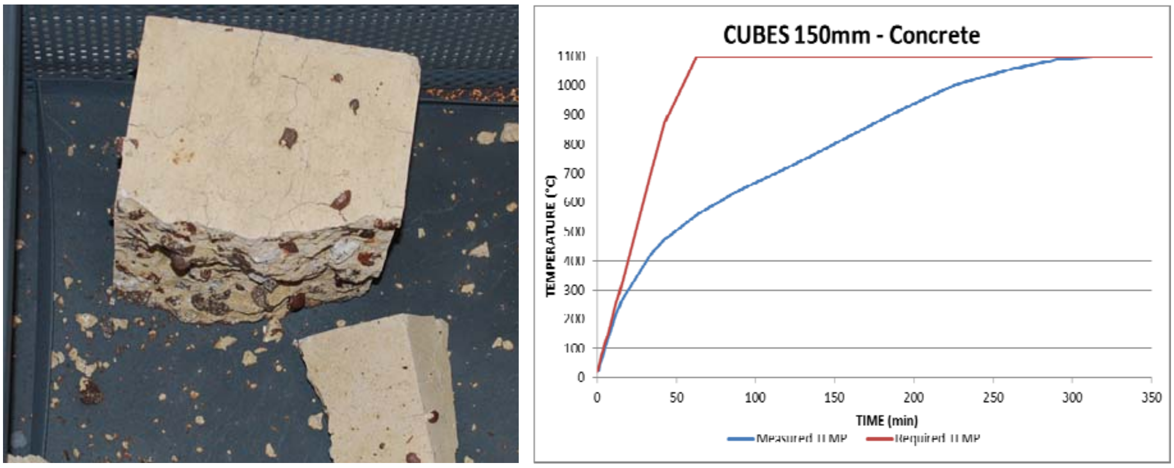
3. Small scale physical experiment

The original governing idea of small scale experiments was to provide faster and cheaper way to experimentally compare the fire resistance of different mixtures. For this purpose cubes with 150 mm side length were prepared from the same mixtures. The limits of available equipment i.e. fire or electric heated chambers respectively which would be large enough to accommodate cubes of this size did not, however, allow for precisely copying the required loading curve. Nevertheless after comparing several small scale experiments with full scale results it would be possible to find correlation sufficient to further utilize the small scale experiments for original purpose. The size of the cubes was originally influenced by the expected range of spalling and should prevent the entire specimen to collapse.

The limits of the used chamber are as follows. Maximum temperature the specimen can be exposed to is lowered to 1100°C and the temperature increase rate is limited to 20°C per minute.

3.1. Results

Despite the claimed parameters of the chamber which were actually tested on smaller samples, the temperature increase was even smaller, see Fig. 5 (b). Although the small temperature increase rate in fact prevent the surface spalling to occur, the concrete specimens could not sustained temperature above 750°C and burst as shown in Fig. 5 (a). The above thus moved the small scale experiments to the reassessment stage.



(a) (b)

Fig. 5: Small scale experiment: (a) Concrete specimen after experiment, (b) Temperature inside the chamber during the experiment

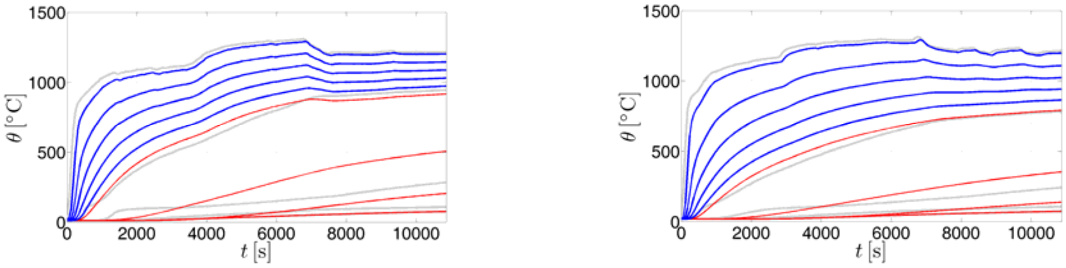
4. Numerical modelling

The possibility of using fully coupled modelling in order to faithfully represent the entire experiment was refused due to the rapid temperature increase in surface areas of the specimen and other difficulties. Instead we concentrate on staggered approach using the heat transport modelling in order to gain appropriate loading conditions for static analysis at different times.

4.1. Heat transfer

Due to lack of the measured data on the side of specimen exposed to fire, we utilize the numerical model for thermal behaviour of concrete at high temperatures. The heat transport is governed by energy conservation law proposed by (Beneš and Mayer, 2007). Two heat sinks representing the energy exchange of vaporation process and hydration / dehydration process are added to the balance equation.

To address this issue we consider two-dimensional rectangular domain discretized by FE mesh. One side of the domain was submitted to the convection and radiation boundary conditions while the opposite side was subjected to the prescribed boundary temperature. The evolutions of λ (thermal conductivity) and *c* (specific heat capacity) as functions of temperature were found also in (Beneš and Mayer, 2007). The resulting temperatures are plotted in Fig. 6 (a) for FAC2 mixture and (b) for FiFAC2 mixture.



(a) (b)

Fig. 6: Calculated temperature distribution – blue lines 0,1,2,3,4 cm from inner surface; calibration lines in red: (a) FAC2 mixture, (b) FiFAC2 mixture

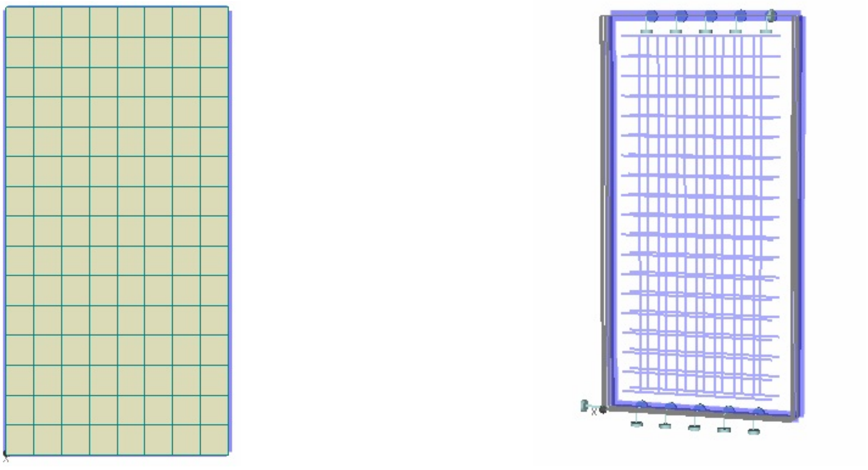
4.2. Static simulation of thermal load

For the static simulations we begun with ATENA code and simple elastic isotropic material for both concrete (3D brick elements – 0.2 m side length) and steel, using parameters provided by other laboratory experiments of tested mixtures. Table 5 summarizes all the material characteristic that have been used.

Tab. 5: Material characteristic for numerical simulations

Characteristic	Concrete	Steel
Elastic modulus (GPa)	40	210
Poisson`s ratio (-)	0.2	0.3
Specific weight (kN.m^{-3})	23	78.5
Coefficient of thermal expansion (K^{-1})	1.2e^{-5}	1.2e^{-5}

The load was applied on vertical layers with different thickness. As the inner surface areas are affected most the layers there were only 10 mm thick while the thicknesses of other five layers were increasing from 37.5 to 50 mm. The finite element mesh used is clear from Fig. 7 (a) while constrains and reinforcement bars incorporated into model can be seen in Fig. 7 (b).



(a) (b)

Fig. 7: Finite element model: (a) mesh – front view, (b) constrains and reinforcements

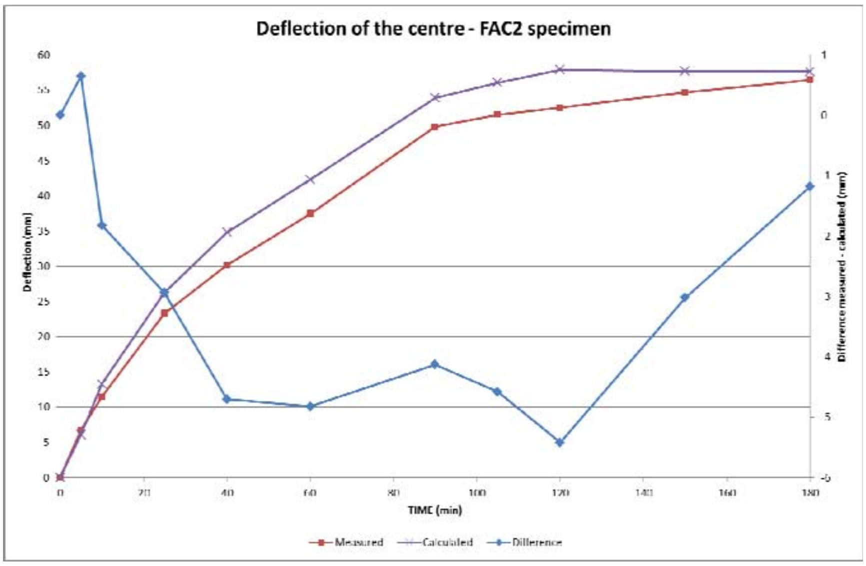


Fig. 8: Measured and calculated deflection of specimen FAC2 – centre of the outer surface

It can be observed in Fig. 8 that the calculated data acquire about 10% difference in the total deflection for most of the time, however, at the end of the experiment the difference is less than 2.5%. These results were obtained by careful estimation of the temperature distribution in the most exposed 50 mm. The effect of heat transfer between the surface and first thermometer plays crucial role as it is heavily time dependent. Using the values gained by numerical model described in section 4.1. larger values of deflection can be observed at the beginning of the experiment.

5. Conclusions

The paper summarizes the results obtained from experiments and numerical simulations of fire loading applied on TBM segment linings made of enhanced concrete mixtures. However, the full scale experiments proved to be irreplaceable when it comes to proper evaluation of the fire resistance of reinforced concrete panels, simple static simulations with appropriate loading distribution can give good results when it comes to total deflection of the panels. Valuable experience obtained due to the issues with small scale specimens will allow for improvement of the method for testing the enhanced mixtures.

Mixtures with increased amount of fly ash did not show significantly different behaviour unlike the mixtures with added plastic fibres. Even though the temperature in the 50 mm distance from the inner surface in all specimens have risen above 500°C, the specimen with the plastic fibres experienced smaller spalling and their reinforcement was not exposed after the experiment.

Numerical approximation of the impact of fire loading will be subjected to further research activities concentrating specifically on the heat transfer problem and spalling.

Acknowledgement

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