FIRE RESISTANCE OF CONCRETE WITH FLY ASH CONTENT – EXPERIMENTAL ANALYSIS

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The paper presents results from three large scale experiments on seven reinforced concrete panels obtained during an extensive experimental program. This was aimed at possible application of cement reduced (fly ash replaced) concrete in the production of precast segmental linings for tunnels created by a tunnel boring machine (TBM). In particular, this paper is focused on the comparison of fire resistance of enhanced mixtures loaded by the Rijkswaterstaat (RWS) fire curve, which assumes 50 m^3 fuel tanker fire lasting for 120 minutes. The presented results include spalling, overall damage of the surface and temperature distribution of the tested panels. The paper also presents description of the proposed method for the evaluation of the extent of spalling during the experiments since, due to the extreme temperatures, the direct observation of the exposed surface is not possible.

Keywords: *fire resistance, concrete, spalling, fly ash, PP fibres, heat transfer, RWS fire curve*

1. Introduction

Although fly ash is a waste product of power plants, for several decades it has been also considered as a second grade resource. Since cement producing facilities are responsible for a significant portion of CO2 emissions and prices of cement are rising, fly ash offers one of the possibilities in search for an 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. [5]) for massive concrete structures with low requirements on strength or strength increase rate. However, it is only in the past few decades, that an increased effort in the reuse of waste material driven by international agreements, increased taxation and subsidy from national and international agencies, new challenges and improved standards on structural safety enabled incorporation of materials which, so far, have only been used under specific circumstances.

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. 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

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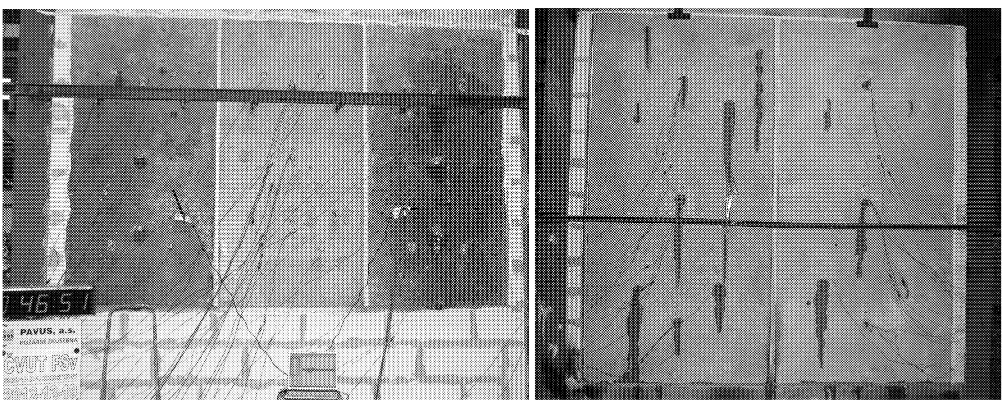
survival of any living creature. Therefore, unlike in case of fires in buildings, the resistance of segmental tunnel lining is assessed in view of repair or replacement costs rather than by setting duration of the resistance. In recent years a great deal of research has taken place internationally to 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 modelled.

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 an irreplaceable role in the assessment of the impact of fire. In addition, the 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.

Two or three specimens, which had very similar thickness and other properties such as reinforcement used in tunnel linings, were built in the fire chamber. In fact they presented 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 to 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.



(a) (b)

Fig.1: Specimens built-in the fire chamber: (a) three specimens, (b) two larger specimens

Specimens are held in place by either steel beam welded to specimens' handling reinforcements in case of three specimens in a chamber, see Fig. 1(a), or by steel T profile attached to the top of each specimen in case of two specimens, see Fig. 1(b). 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 from the start of the experiment.

3. Specimens and mixtures

A uniform distribution of temperatures in the fire chamber allows for simplification of the problem by straightening the tunnel lining into panels with dimensions 2000×1000×250 mm and 3000×1500×250 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. 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.

Seven 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.

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

Tab.1: Grain distribution in mixtures

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 on small samples five mixtures with replacement of 30 % and two mixtures with replacement of 70 % of the cement were suggested. 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 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. [3] or [2]). Three 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.

Mixture:	FAC1	FiFAC1	FAC1+PRO	FAC2	FiFAC2	FAC3	FiFAC3
Material	Amount (kg/m^3 of mixture)						
CEM I 52.5 R	322	322	322	322	322	138	138
Fly ash (Melnik I)	138	138	138	276	276	322	322
Water	150	150	150	187	187	170	170
Limestone powder	40	40	40	40	40	40	40
Gleanium ACE 40	4.2	4.2	4.2	4.2	4.2	4.2	4.2
FORTA-FERRO fibres	0	4.5	0	0	4.5	0	4.5

Tab.2: Tested mixtures

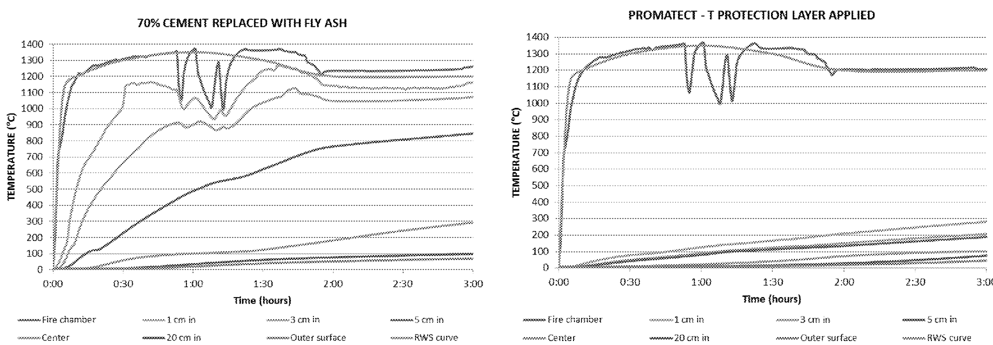
4. Results

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, during the experiment with three smaller specimens 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. 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 example of 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 3 summarizes the peak temperatures along the specimens, i.e. 30, 50 and 125 mm from the inner surface) which are sometimes higher than temperatures at the end of the fire loading.

The specimen equipped with protection layer experienced by far the 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.



(a) (b)

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

Mixture:	FAC1	FiFAC1	FAC1+PRO	FAC2	FiFAC2	FAC3	FiFAC3
Location	End of fire loading ($T = 180$ min)						
30 mm	—*	—*	208	—*	—*	1073	—*
50 mm	929	781	189	945	862	847	703
centre of the specimen	312	241	102	282	242	293	197
Location	Peak temperature (time differs)						
30 mm	—*	—*	222	—*	—*	1125	—*
50 mm	930	789	208	946	869	852	710
centre of the specimen	348*	297	122	322*	277	352	273

* The sensor in this location was either not implemented or malfunctioned.

Tab.3: Temperatures in °C inside specimens

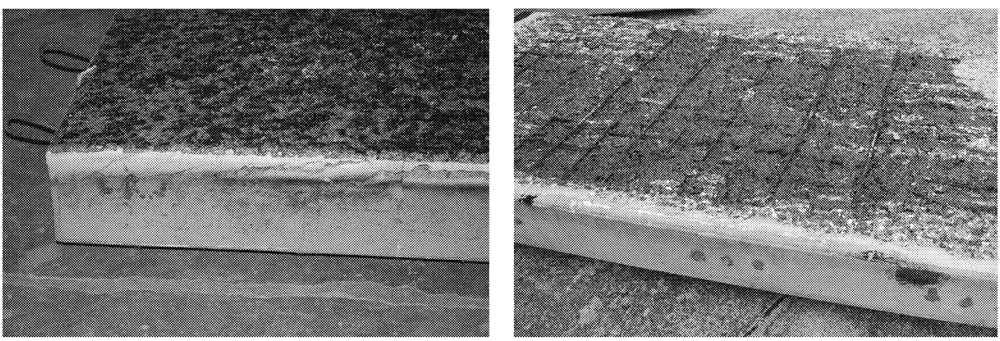
Even though the mixtures enhanced by plastic fibres (FiFAC) did not fulfil the temperature requirements they generally experienced significantly lower temperatures in the surface areas than the mixture without (FAC) during the entire experiment and also during cooling. This fact also influences the damage 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 [9], [10], significant decrease in temperatures can be observed for mixtures having large portion of cement replaced.

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 influenced mainly by the temperature increase rate and the peak temperature and initial moisture content near the exposed zones. Observed positive effect of the polypropylene fibres that burn out causing spalling to be of smaller magnitude was experimentally proved several times in the past (e.g. [6]). The specimen with added fibres has indeed shown better behaviour during fire loading. However, 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. Nevertheless, it was not spared from the impact of heat to the compressive strength.

Specimens with increased amount of fly ash FAC3 and FiFAC3 did not experience heavy spalling resulting in large areas of exposed and deformed reinforcement which is typical of non protected concrete surface [9], see Fig. 3. The high temperatures, however, caused the entire cover layer of concrete above the reinforcement to delaminate. The strength of the top 100 mm must be 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) FAC2 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.

Mixture: Value	FAC1	FiFAC1	FAC1+PRO	FAC2	FiFAC2	FAC3	FiFAC3
Scrap in % of weight	6.4	3.6	0	5.8	4.6	2.6	0.5
Vaporised water per m^3	142	139	104	144	143	138	130
Exposed reinforcement	large zones	not directly	no visible damage	large zones	locally	not directly; delaminated	not directly; delaminated

Tab.4: Spalling

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 [4].

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 the description of spalling phenomenon. The obtained experimental data are further used to enhance the current constitutive relations for concrete at very high temperatures [7], [8] or [1].

5. Conclusions

The paper summarizes the results obtained from large scale fire resistance experiment with seven 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 the specimen covered with protection layer made of 25 mm of calcium-silicate material (PROMATEC-T plate) did not exceed a generally accepted limit values and no visible damage was observed on the specimen, the residual mean compressive strength measured on columns drilled from the specimen was less than 60 % of the mean compressive strength after 28 days.

Specimens with added plastic fibres showed better behaviour in terms of spalling and temperature distribution but the compressive strengths were smaller by more than 10 % when compared to the specimens without fibres.

The 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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