INFLUENCE OF FIBRE CONTENT AND AGGREGATE SIZE ON THE BEHAVIOUR OF ULTRA-HIGH PERFORMANCE FIBRE REINFORCED CONCRETE DURING FIRE

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Abstract

The behaviour of ultra-high performance fibre-reinforced concrete (UHPFRC) during fire exposure needs special focus in an analysis of load bearing capacity of structures. On one hand the temperature-induced decrease of compressive strength and Young's Modulus of such concrete seems to be different compared to ordinary concrete due to hard stone aggregates which are predominantly responsible for the mechanical properties during fire. On the other hand the spalling effect increases in UHPFRC because the cement matrix is denser than the cement matrix of ordinary concrete. The research activities presented in this paper aimed at evaluation of 5 different UHPFRC mixes from which 5 meso-scale plate specimens were prepared and tested at standard fire conditions. Only one tested specimen survived the test with only few surface cracks. The rest collapsed completely into a depth up to 10 cm. The results implied that only adding PP-fibres to an UHPFRC mix is not enough to improve its fire resistance up to a level comparable to ordinary and high performance concrete.

Résumé

Le comportement du béton fibré à ultra-hautes performances (BFUP) lors d'une exposition au feu à besoin d'une attention toute particulière dans l'analyse de la capacité portante des structures. D'une part, la baisse de la résistance en compression et du module d'Young induite par la température sur un tel béton semble être différente en comparaison d'un béton ordinaire, en raison des granulats issus de roches dures qui sont principalement responsables des propriétés mécaniques lors de l'incendie. D'autre part, le risque d'instabilité thermique (écaillage) augmente pour le BFUP car la matrice cimentaire est plus dense que la matrice cimentaire du béton ordinaire. Les recherches présentées dans cet article visent à évaluer 5 compositions de BFUP dont 5 échantillons plats de taille intermédiaire ont été préparés et testés dans des conditions standard d'incendie. Seul un échantillon testé a résisté au test avec seulement quelques fissures en surface. Les autres ont été complètement détruits sur une profondeur allant jusqu'à 10 cm. Les résultats montrent qu'ajouter des fibres PP dans un BFUP ne suffit pas à améliorer sa résistance au feu à un niveau comparable au béton ordinaire ou au béton à haute performance.

1. INTRODUCTION

When talking about concrete, we usually talk about a NSC (Normal Strength Concrete) which is a well-known 5 compound system of fine and coarse aggregates, cement, admixtures, water and additives. In the present case, the used concrete is an UHPFRC (Ultra High Performance Fibre Reinforced Concrete) which means a finest compound system with the finest components smaller than 0.5 mm including silica fume, extreme dosage of admixture and steel fibres. Because of the very fine ingredients, the concrete has a very high packing density, which leads to a compressive strength of 150 – 250 MPa. This is in fact 5 times higher than the strength of NSC and because of that it is possible to save concrete volumes (e.g. in cases of columns under compression up to 40% of the cross section can be reduced). The high packing density also leads to some other positive aspects like hardly any capillary porosity, low permeability, almost negligible carbonation depths and lower chloride penetration. All these advantages also lead to a much higher durability (this can be up to 5 times higher than that of NSC) and sustainability [1, 2]. Under fire treatment, the properties of UHPFRC are changing, like those of NSC. The compressive strength decreases from the origin room temperature at 20°C to 80 % at 800°C. At 750°C the tensile strength decreases to 55 % of the origin and the modulus of elasticity decreases by about 50 % to 80 % at 600°C [3, 4].

The negative fact of the high packing density in case of fire is that there are no pores for water to expand and so it comes to spalling. Some former single tests show that the influence of PP fibres leads to a reduction of spalling during fire [3, 5] and that the spalling intensity is much higher than NSC. Fire load without PP fibres leads to a complete collapse and because of that the study does not check mixtures without fibres. Furthermore the test of spalling is current discussed in the RILEM TC SPF. A recommendation of test specimen and test conditions is under construction.

The study, which is presented in this paper, deals with massive plates without restraint during the tests. Two possibilities of mixtures for decreasing spalling of UHPFRC was examined. One solution could be the addition of PP (Polypropylene) fibres and the second one could be the usage of coarse aggregates. The idea behind these two possibilities is that in case of fire the PP fibres melt and so new pores for expanding of water will occur or, if coarse aggregates are used, such pores will occur already during the mixing process. The study is a result of joint efforts of two research groups of CUAS (Austria) and ZAG (Slovenia) which started with a fire test performed in March 2016.

2. UHPFRC MIXTURES AND SPECIMENS

2.1 Mix design

Determining the fire resistance of structures starts with the definition of materials and their properties during fire. According to Eurocode 2 concrete mixtures shall include PP-fibres if the targeted compressive strength class is more than C50/60 and if pronounced fire-induced concrete spalling has to be avoided. Because of that different dosages of PP-fibres were used in UHPFRC mixes in the testing programme. Another possibility which could contribute to a reduction of spalling intensity is the usage of coarse aggregates. That is why a variation of coarse aggregates was chosen, containing basalt stone with a very high compressive strength of more than 180 MPa. The bulk density of the basalt stones is 2,970 kg/m³.

To test the influence of different contents of PP fibres and coarse aggregates, the following mixtures were prepared:

Table 1: UHPFRC mixtures

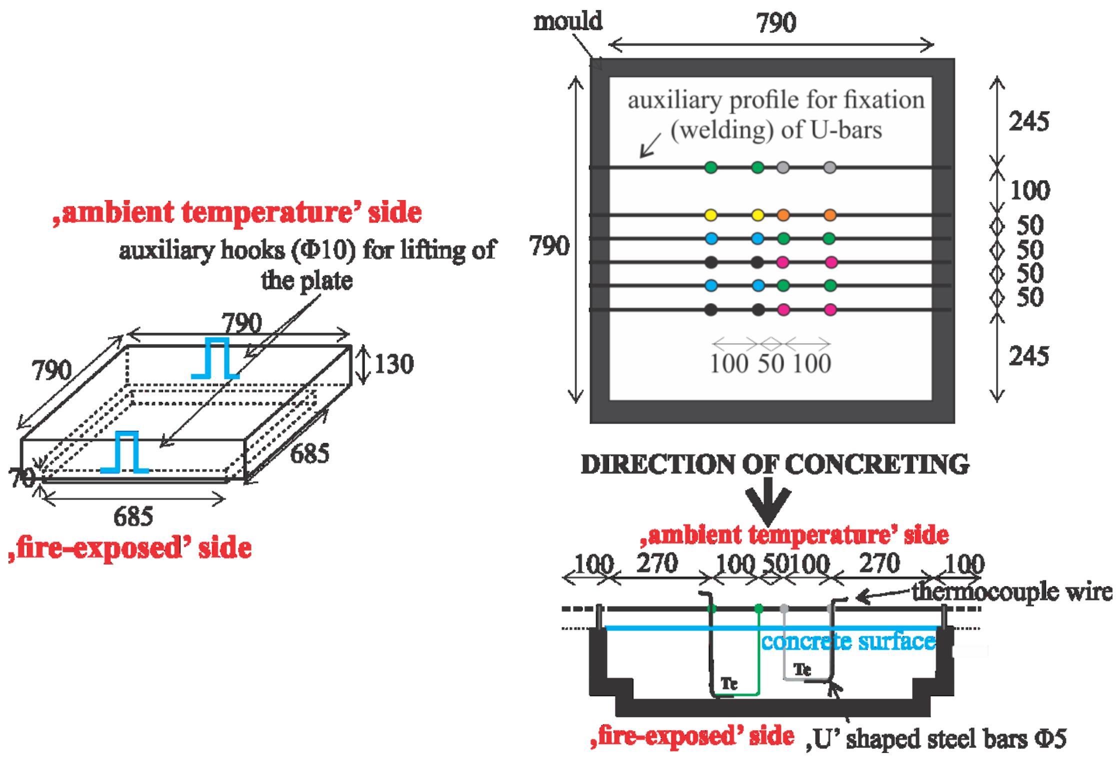
	M1 without basalt 1 kg PP/m³	M2 without basalt 2 kg PP/m³	M3 without basalt 4 kg PP/m³	M4 with basalt 2 kg PP/m³	M5 with basalt 4 kg PP/m³
CEM I 42,5 R	127.5	127.5	127.5	127.5	127.5
Silica fume	21.45	21.45	21.45	21.45	21.45
Quartz flour	36.75	36.75	36.75	36.75	36.75
Basalt 4/8	0	0	0	44.55	44.55
Quartz sand 0.1 – 0.4 mm	129.75	129.75	129.75	89.96	89.96
Water	29,.25	29.25	29.25	29.25	29.25
Super-plasticizer	3.0	3.0	3.0	3.0	3.0
Steel fibers ∅ 0.2 mm / length 15 mm	23.55	23.55	23.55	23.55	23.55
PP fibers ∅ 0.018 mm / length 6 mm	0.15	0.30	0.60	0.30	0.60

The amounts shown in Table 1 are the amounts that were used for preparation of 150 l of fresh mixture which belongs to the needed amount of mixture to fill up the moulds of the 5 plates and the accompanying cubes (see capture 3).

2.2. Preparation of meso-scale plates and accompanying cube specimens

Five plates were prepared from the designed 5 UHPFRC mixtures to be tested in a meso-scale fire experiment (Fig. 1-3). First, suitable moulds were designed in the way that each plate would fit exactly into a corresponding opening of the front cover of the fire-testing furnace (Fig. 3a). Before concreting, a special steel frame was also prepared for each mould using steel U-bars and auxiliary profiles which served for attachment and routing of thermocouples (Fig. 2-3). The frame was designed in a very high stiffness so that the sensors could remain in place during concreting despite high pressures of the low viscosity fresh concrete. K type Ni-Cr-Ni (2×0.5 mm) thermocouples with ceramic braided insulation were attached to U-bars.

In addition to the 5 meso-scale plates, several cubes were also prepared from the same UHPFRC mixtures for the determination of two of the most important material parameters as nowadays known for influencing spalling-related phenomena [6, 7], i.e. compressive strength (the latter was tested at regular time intervals during curing and conditioning of the plates) and moisture content (measured on the day of fire testing). For measurements of compressive strength, 100 mm × 100 mm × 100 mm cubes were used. For measurements of moisture, one 200 mm × 200 mm × 200 mm cube was used per UHPFRC mixture. Four sides of the 200 mm cubes were coated with paraffin to simulate the unidirectional drying of the plates.



(a) (b)

Figure 1: (a) Sketch of one plate (in mm). (b) Sketch of preparation of the plates. Coloured circles represent stiff fixations of the U-bars onto auxiliary profiles. The U-bars are represented by different colours which denote different depths of the bars, i.e. different positions of the hot junctions of the thermocouples with respect to the fire-exposed concrete surface: −25 mm (green), −40 mm (black), −55 mm (yellow), −60 mm (grey), −70 mm (blue), −85 mm (pink), −100 mm (orange).

(a) (b)

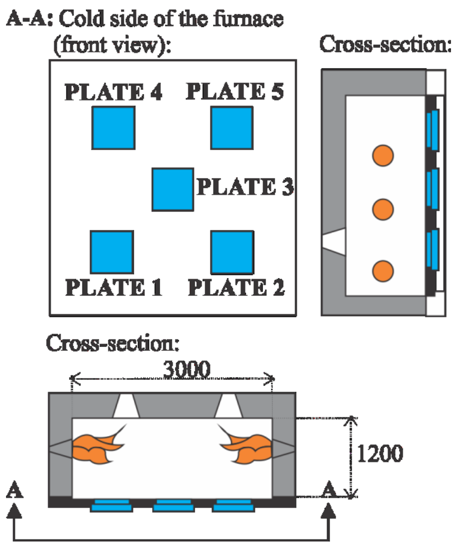
Figure 2: (a) The mould for preparation of one of the plates with attached auxiliary steel frame. (b) Concreting of the plate.

Moreover, after 163 days of curing, the prepared specimens were put into a climate chamber 23°C/50% RH and conditioned for 95 days. According to EN 1363-1:2012 such conditioning is necessary to ensure that the equilibrium moisture content is established in the concrete specimens at the time of fire loading. This should correspond to the value expected under normal service. Just before the fire test the moisture content of the concrete was measured using the cubes by the oven drying technique described in EN 1363-1 (Annex F, Part F.3.2).

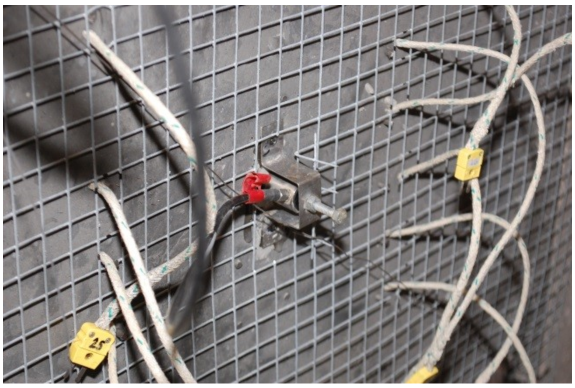
3. SET-UP OF THE FIRE TEST

While the 200 mm cubes were measured for moisture content, the installation of the plates onto the furnace began. The plates were placed in a frame which forms one side (i.e. the front wall) of an oil-burned vertical furnace of dimensions 3000 × 3000 × 1200 mm (Fig. 3a) and mounted in the way that during the test only one of the larger sides of the plate would be exposed to fire while the other would face normal ambient conditions. After being mounted firmly, air-permeability of concrete was measured acc. SIA 262/1:2003, Annex E [8] on each of the plates. In addition, each plate was equipped with one Physical Acoustic PK6I acoustic emission (AE) sensor [9]. As the plates tested were isolated from the furnace frame by isolating material no environmental noise was detected by the AE system before starting of the fire test. Prior testing the AE system was tested both by using pencil-lead break and Automatic Sensor Test application of AEwin Physical Acoustic software.

The fire test commenced right after installation and testing of AE sensors and followed standard ISO 834 testing conditions. During the test fire test, the AE technics were used for monitoring the spalling, similar to Ozawa et al. [10] and following the RILEM TC 212-ACD Recommendations [11]. Thermocouples installed during concreting of the plates were used for monitoring heat penetration and for monitoring the acceleration of the latter due to spalling.



(a)



(b)

Figure 3: (a) Scheme of the furnace with two cross-sections and a front view. (b) Unexposed side of one of the plates with visible AE sensor and thermocouple wires extended out from the UHPFRC plate.

4. RESULTS OF THE TESTING

4.1 Basic material data measured prior to fire testing

This section presents results of measurements of basic material characteristics of the prepared UHPFRC specimens, i.e. compressive strength measured during different storage conditions and ages of the concrete (Table 2), concrete moisture content measured on the day of fire testing (Table 3), and air-permeability (Table 4).

Table 2: Results of compressive strength of the UHPFRC mixtures

Testing age	M1	M2	M3	M4	M5
	[MPa]				
7 days	132.3*	117.0*	114.3*	119.9*	111.2*
28 days	176.0* 163.9**	155.6* 148.2**	153.6* 144.1**	167.8* 154.3**	153.6* 128.8**
163 days***	201.1* 174.3**	161.9**	-	180.4**	151.9**

* water stored / ** component support / *** day of testing

The influence of storage condition leads to a higher difference of the results of compressive strength. It seems that the influence of surface (cracks, shrinking, drying, pore structure etc.) during component support leads to a decrease of compressive strength. It was not a target of the project to explain this influence but it is important that the compressive strength of the plates at the age of testing is more than 150 MPa, this is shown in Table 2.

Table 3: Moisture content on the day of fire testing

	M1	M2	M3	M4	M5
mass as delivered [kg]	19.290	19.039	18.584	20.114	19.783
dry mass [kg]	19.070	18.812	18.169	19.845	19.510
Moisture content [% by mass]	1.2%	1.2%	2.3%	1.4%	1.4%
Density of dry UHPFRC [kg/m³]	2,384	2,352	2,271	2,481	2,439

Table 4: Measured air-permeability

Mix	M1	M2	M3	M4	M5
Air-Permeability [10^{-16} m^2]	0.52	0.01	0.46	0.06	0.01

4.2 Results of fire testing

Fig. 4 shows the exposed side of the front cover of the furnace with 5 tested plates mounted. The photograph was taken after the termination of the test and 24-hours cool-down (note that no additional spalling was obtained during cool-down; the front cover of the furnace with the plates still embedded was cooled-down naturally, in the air). The extent of the spalled areas is clearly visible in Fig. 4a (see the grey areas visible on each plate except on the plate 5). In addition, there is some information regarding spalling depth in Table 5.

Figure 4: Exposed side of the front cover of the furnace after the fire test with visible spalling damage of the 5 plates.

Table 5: Maximal spalling depth

Plate (Mix)	M1	M2	M3	M4	M5
Max spalling depth [mm]	51	99	42	56	7

In Table 6 the damage is estimated by grades from 1 to 5 with respect to detected spalling intensity (the intensity of spalling was evaluated considering the time of the start and the end of the detected AE signal and its time-averaged strength).

Table 6: Spalling intensity of the plates

Plate (Mix)	M1	M2	M3	M4	M5
Spalling intensity	4	5	1	2	0*

*no spalling observed

Fig. 5 further shows the temperatures measured at different depths of two selected specimens, i.e. plate 1 and 5, and demonstrates that due to the effects of intense spalling plate 1 suffered from up to 300°C higher temperatures. For plate 2, for which even more intense spalling was detected, this increase was up to 400°C. Nevertheless, although some spalling was detected also on plates 3 and 4, temperatures measured within these two specimens were not significantly different compared to the temperatures measured on the non-spalled plate 5. Furthermore, it should be stressed specifically that initially the heat penetration into the plates coincided very well for all of the 5 mixes; in Fig. 5 the graphs of the presented plates coincide almost identically up to certain times, i.e. up to times equal or higher to the time when spalling started. This leads to conclusion that thermal characteristics (thermal conductivity, specific heat capacity) of the developed UHPFRC concretes were similar to one another and enables us to assess them numerically (a classic Fourier heat transfer simulation of the non-spalled plate 5 could be applied for these purposes).

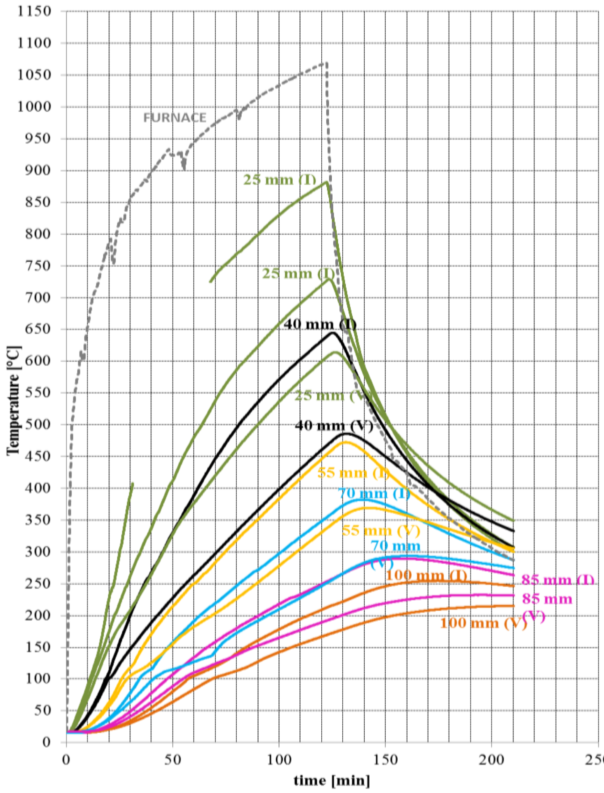


Figure 5: Temperatures of plates 1(I) and 5(V) as measured at different depths from the exposed concrete surface and the average temperature of the furnace.

More thermocouples were installed for measuring temperature at some concrete depths as demonstrated in Fig. 1 (e.g. for 25 mm depth three thermocouples were used at three different locations) but the corresponding time-temperature curves followed very closely to one another in most cases, thus, only one curve is shown for each depth. The exception is the curves for plate I measured at 25 mm depths where larger discrepancies were obtained due to intense spalling in this region. More temperature measurement stations were active for each depth of the plate but only one curve is shown as only small differences were observed between them. Otherwise, more curves with the same denotations are shown. Enclosed in brackets is the denotation of the plate.

4.3 Compressive strength after fire exposure

During the fire test 10 cm cubes, one of each concrete, were put into the furnace. Although heavily damaged they were tested in compression. The results are presented in Table 7. The masses of the “cubes” were also measured, where possible. One cube was so heavily damaged that it was not possible to perform the test.

Table 7: Compressive strengths of oven stored “cubes”

	Mix 5	Mix 4	Mix 3	Mix 2	Mix 1
Mass [kg]	2.14	2.15	1.98	1.96	-
Load [kN]	431	377	297	179	-
Strength [MPa]	43.1	37.7	29.7	17.9	-

4.4 Acoustic emission test results

The acoustic emission test results in the form of number of hits vs. time are presented in Figure 6. The Channel 1 was used to measure the AE activity of the mix 1 plate, the Channel 2 for the mix 2 plate, the Channel 6 for the mix 3 plate, the Channel 7 for the mix 4 plate and the Channel 8 for the mix 5 plate.

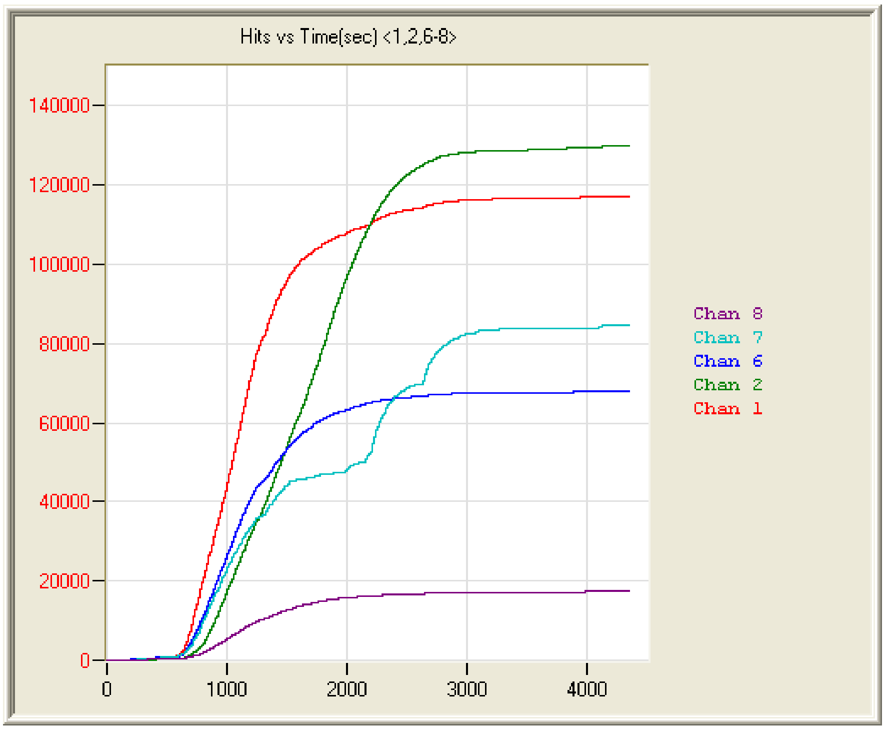


Figure 6: Acoustic emission activity; cumulative number of hits vs. time

From Graph 6 clear difference in AE activity can be observed. If the cumulative number of hits can be considered as a measure for damage, mix 2 is the most damaged and the mix 5 the least. Plates made of Mixes 3 and 4 exceed similar number of AE hits. The AE results are in good correlation with visual observations of plates' damage after the test. From the graph also the rate of spalling can be seen; the fastest spalling rate was recorded on Mix 1, the slowest on Mix 5. Some irregularity in the graph of Mix 4 can be explained by inhomogeneity of the concrete in plate, probably having more or fewer fibres in some areas. For all mixes the spalling starts at app. 700 s and dies out at 3,000 s to 3,100 s.

5. CONCLUSION

The influence of the test conditions is important. This study was made with plates without restraint; that means the storage in the oven did not lead to restraint in the plate due to thermal elongation. The amount of 2 kg PP fibres was not enough to prevent the spalling effect. Other publications have shown that a PP fibre ratio of 2 to 3 kg was sufficient to avoid spalling [12]. The importance of tests is shown in the project because the behaviour of the material is different according to the information of the literature. Mixtures of UHPFRC are very specific and the behaviour during tests is very sensitive. Another aspect is the validation of spalling. In this study the authors confine the spalling value on maximum spalling depth and spalling intensity, measured by acoustic emission activity. From the 5 fire-tested UHPFRC plates only the one with basalt aggregates and 4 kg/m^3 of PP fibres survived the test with only some surface cracks. The mixes 1 to 3 increase the amount of PP fibres from 1 kg to 4 kg without adding some coarse aggregates of basalt stones. The spalling was not completely avoided with adding PP-fibres during the chosen test condition. The mixtures 4 and 5 contain coarse aggregates and PP-fibres. It is observed that the amount of 2 kg PP fibres leads to spalling during the chosen test condition. The results of this study clearly imply that adding PP-fibres to the examined UHPFRC mixes was not enough to substantially reduce the spalling intensity.

However, a big improvement can be expected if in addition appropriate aggregate size is selected.

6. OUTLOOK

This work is an ongoing research on the field of fire resistance of UHPFRC. Important influences of the spalling behaviour of UHPFRC were detected. In the next step the influence of the test procedure is more in focus according to RILEM TC SPF.

In the study basalt stones were used as coarse aggregate. The mineral composition of the stone has an influence certainly. This variation is also included in the ongoing research.

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