Experimental contribution to the optimization of the choice of polypropylene fibers in concrete for its thermal stability

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ABSTRACT

Numerous studies conducted by researchers have indicated a positive effect of polypropylene fibers (PP fibers) in terms of the reduction of concrete spalling due to fire. Variation of test parameters such as concrete composition, curing conditions, heating curve, aggregate nature and size, etc. creates a challenge for identification of optimal fiber dosage and geometry. The purpose of this work is to study the influence of the fiber length with respect to aggregate size in order to identify optimal fiber length necessary to prevent spalling of concrete. Prisms of cementitious materials of three aggregate sizes (D_{max} = 1, 10 and 20 mm) and two fiber lengths (6 and 12 mm) at three fiber dosages (0, 0.5 and 1 kg/m^3) resulting in total of 15 different mixes are prepared. These prisms are unixially loaded at 5 MPa and tested in water saturated condition under ISO 834-1 heating curve. The results show that the maximum aggregate size has an influence on the cracking patterns of the cementitious materials exposed to high temperature. The addition of PP fibers at low dosage produces a positive influence on the reduction of concrete spalling due to fire exposure.

KEYWORD: Polypropylene Fibers, Concete Spalling, Fiber Length, Fire Tests.

INTRODUCTION

Polypropylene fibers have become a cost-effective and efficient solution for the reduction of the risk concrete spalling due to fire exposure. Eurocode 2 EN 1992-1-2:2004 on "Design of concrete structures - Part 1-2: General rules - Structural fire design" states that for high performance concretes of class strength ranging from 80/95 to 90/105 the addition of more than 2 kg/m^3 of monofilament polypropylene fibers is necessary. In French annex of the code it is specified that fiber diameter should be less than or equal to 50 µm and fiber length should vary between D_{max} and 4D_{max} where D_{max} is the size of the largest aggregate.

Numerous studies attempting to optimize the polypropylene fiber geometry and dosage choice have been presented in literature. The first work on this subject by Bentz [1] provided a percolation model of ITZ (interfacial transition zones) of high performance concretes by use of PP fibers. He suggested the use of 0.2 % to 0.5 % vol. of PP fibers to achieve percolation. Debicki et al. [2] has stated that 1 kg/m^3 was sufficient for prevention of spalling of high performance concrete. It was found that higher dosage of fibers results in the higher pressure drop during heating [3], [4]. Kalifa et al. [3] has completed fire tests on samples containing fibrillated fibers of a rectangular section of 150 x 50 µm^2. He suggested a dosage of 1 kg/m^3 of 20 mm PP fibers for high performance concretes under ISO 834-1 fire curve. Bilodeau et al. [5] proposed to use 1.5 kg/m^3 for ultra-high performance concretes. Persson [6] concluded that a minimum dosage for conventional use should be around 0.7 kg/m^3 and 1.4 kg/m^3 for tunnels. Arai and Furuichi [7] found necessary to use 1.82 kg/m^3 for tunnels and railroads.

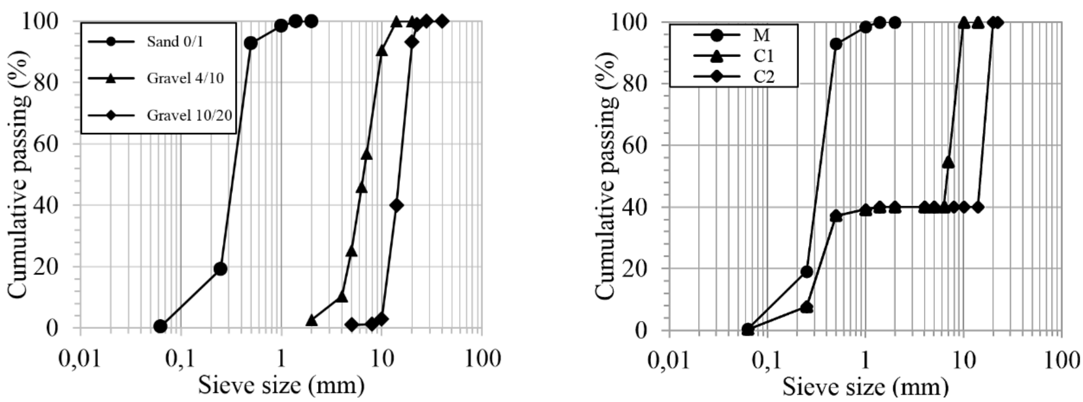
As fibers are used to ensure percolation between pores, air bubbles and cracks in the cementitious matrix, their length should be sufficient for this purpose. Therefore, it appears logical that longer fibers are preferred to shorter ones. In [5] it was shown that longer fibers of 20 mm vs. fibers of 12.5 mm have improved spalling resistance for the samples after hydrocarbon fire (dosage of 1.5 kg/m^3). For the same fiber diameter, Mugume et al. [8] has found that for 12 mm fibers gas pore pressures are lower than for 6 mm fibers. For the same dosage, Heo et al. [9] has found fibers shorter than 12 mm to be less efficient. Sideris and Manita [10] having compared fibers of 6 mm and 12 mm found the longer fibers to decrease the intrinsic permeability while Hager and Tracz [11] have compared fibers of 6, 12 and 19 mm and found that the longest fibers lead to the highest permeability increase. A relation between the size of the largest aggregate and minimal fiber length was described in Heo et al. [12]. In his work it was found that the optimum fiber length increases with the size of the aggregate.

The purpose of this work is to study the effect of fiber length and dosage on the behaviour at high temperature of different cementitious materials. A mortar and two concretes with different aggregate skeleton are studied to evaluate the efficiency of two fiber geometries with regard to spalling.

PRESENTATION OF THE STUDY

Cementitious mixes

The cement used is CEM III/A 52.5 L CE from Heming (Eqiom). Silica filler from Sibelco (99.1 % SiO_2) was used as filler. The aggregates are siliceous sand 0/1 from Messanges and two types of calcareous gravel 4/10 and 10/20 from Sare. Their particle size distribution curve are given in Figure 1A. Two types of PP fibers were used in this work; the corresponding information is given in Table 1. For flowability, superplasticizer Krono 26 from SIKA was used.



A. B.

Figure 1 Particle size distribution for (A): aggregates, (B): granular mixes.

Three types of the cementitious materials are produced, their mix proportions are given in Table 2. The first is mortar (M) prepared using a sand 0/1. The second one is concrete (Concrete 1 or C1) made with a granular mix of 40 % of the sand 0/1 and 60% of the gravel 6.3/10. The third one (Concrete 2 or C2) contains a mix of 40 % of the sand 0/1 and 60% of the gravel 14/20. The particle size distribution for granular mixes of each of the cementitious materials is given in Figure 1B. Discontinuous aggregate skeletons were chosen in order to obtain different cracking patterns. A requested size of the aggregate for concretes C1 and C2 namely sizes 6.3/10 and 14/20 were obtained by screening, passing through the sieves the aggregates 4/10 and 10/20 respectively. Before mixing, all of the aggregates were dried in the oven at 80 °C for 24 hours and then cooled down.

Table 1 Tested polypropylene fibers.

Fiber		Length (mm)	Diameter (µm)	Total number (10^6)		Total length (km)	
				0.5 kg/m³	1 kg/m³	0.5 kg/m³	1 kg/m³
1	EUROFIBER PRO-MIX 6/32	6	31.7	114	228	683	1366
2	EUROFIBER PRO-MIX 12/32	12	31.7	57	114	683	1366

Two types of PP fibers from Baumhüeter were used (see Table 1). In addition to fiber-free case, two fiber dosages of 0.5 and 1 kg/m³ were used. Table 2 presents all the tested mixes. Example of explanation of mix name: C2-12/32-1 stands for concrete 2 containing PP fibers with a length of 12 mm and a diameter of 32 µm with a dosage of 1 kg/m³.

Table 2 Mix proportions of the materials in kg/m³.

Mix	Cement CEM III/A	Water	Filler	Sand 0/1	Gravel 6.3/10	Gravel 14/20	PP fibers 6/32	PP fibers 12/32	SP
M-0							-	-	
M-6/32-0.5							0.5	-	
M-6/32-1				1557	-	-	1	-	10
M-12/32-0.5							-	0.5	
M-12/32-1							-	1	
C1-0							-	-	
C1-6/32-0.5							0.5	-	
C1-6/32-1	500	200	120		945	-	1	-	3.75
C1-12/32-0.5							-	0.5	
C1-12/32-1							-	1	
C2-0				623			-	-	2.5
C2-6/32-0.5							0.5	-	
C2-6/32-1					-	952	1	-	2
C2-12/32-0.5							-	-	
C2-12/32-1							-	-	

Cylindrical samples of 11 x 22 cm² for compressive strength test at 28 days and prismatic samples of 20 x 20 x 10 cm³ for fire tests were cast and demolded after 24 hours and placed in water for 60 days. The properties of fresh and hardened materials such as compressive strength at 28 days and water content of mixes are given in Table 3.

Table 3 Fresh and hardened properties of cementitious materials.

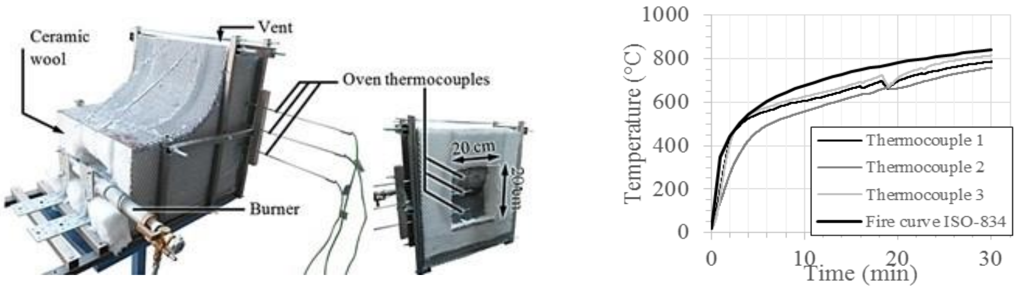
Mix	Fresh properties		Hardened properties	
	Slump (mm)	Slump flow (mm)	Average $f_{c28,\ cyl}$ (MPa)	Water content (%)
M	354 ± 15	-	41.3 ± 2.5	6.10 ± 0.62
C1	-	790 ± 21	90.1 ± 5.3	4.90 ± 0.47
C2		626 ± 41	79.7 ± 0.3	4.54 ± 0.39

Compressive strength was measured on three samples and water content - on two samples. In order to determine water content, samples were dried at 80 °C until mass stabilization. The sample is considered dry when the difference between the two consecutive daily mass loss measurements is less than or equal to 0.02% of the mass of the dry sample.

Experimental procedure

The fire tests were conducted using a furnace with a gas burner as seen on Figure 2A. The opening of the furnace is 20 x 20 cm^2. Butane is supplied to the burner and temperature is followed by three K-type thermocouples placed at 4, 10 and 16 cm from the bottom of the furnace opening and 1 cm from the heated face of the concrete specimen. Gas pressure is adjusted during the test so that the temperature measured close to the heated surface follows the ISO 834-1 fire curve (see Figure 2B).

Before conducting the test, an aluminum foil was glued on the lateral sides of the sample with a high temperature resistant glue in order to block moisture escape as seen from Figure 3A. The fire tests are performed on uniaxially loaded prismatic samples of 20 x 20 x 10 cm^3 during 30 minutes. The loading is fixed to 5 MPa before beginning of the test. All of the tests were conducted on water saturated samples. The tested specimen was placed between two concrete blocks to distribute uniformly mechanical loading. The lateral sides of the tested specimen and support blocks were insulated by 12 cm of rock wool. The insulated and loaded setup before the start of the fire test is presented in Figure 3B. The furnace is placed in front of the setup and the gas in the burner is ignited (see Figure 3C). One face of the concrete sample was heated (20 x 20 cm^2). During the test, each of the spalling events has been recorded. At the end of the test (see Figure 3D), after 30 minutes, the gas supply from the bottles is shut down, the burner is closed and sample is discharged.



A. B.

Figure 2 Experimental setup (A): Furnace [13] (B): ISO 834-1 fire curve and thermocouples' readings.

A. B. C. D.

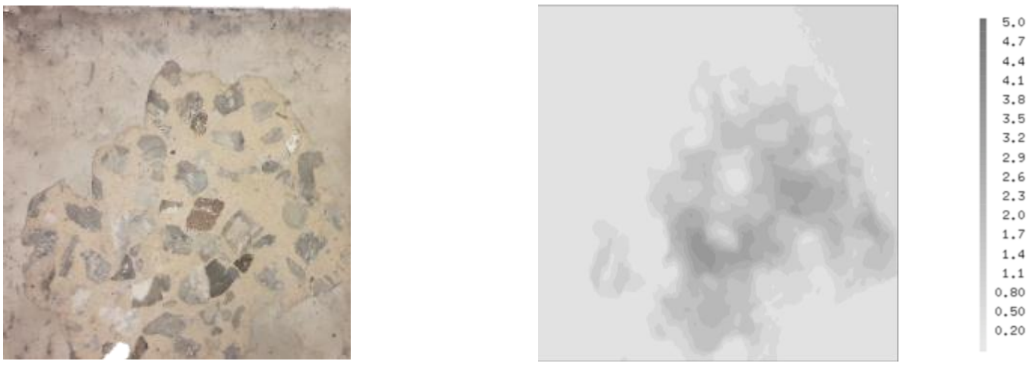
Figure 3 Testing procedure (A): insulation of lateral sides with aluminium foil, (B): before fire test, (C): during fire test and (D): after fire test.

EXPERIMENTAL RESULTS AND DISCUSSION

The average values of the results for the fire tests including time of the 1st spalling event, number of spalling events, mean and maximum spalling depth are presented in Table 4. Mean and maximum spalling depth were determined by means of photogrammetry. An image of spalled surface and spalling depth cartography for sample C2-6/32-0.5 are provided in Figure 4. The error from photogrammetry is 4.2%.

Table 4 Average values of test results.

Mix	1st spalling event (min)	Number of spalling events	Mean spalling depth (cm)	Maximum spalling depth (cm)
M-0	15	1.5	0.95	3.75
M-6/32-0.5	12	1.67	0.62	2.18
M-6/32-1	-	0.33	0.27	1.3
M-12/32-0.5	14.5	0.67	0.49	1.9
M-12/32-1	-	0	0	0
C1-0	9.3	3.33	1.04	2.78
C1-6/32-0.5	8	3.5	0.35	1.17
C1-6/32-1	9	2.5	0.39	1.68
C1-12/32-0.5	13	1	0.25	0.84
C1-12/32-1	9	1.67	0.3	0.84
C2-0	5.7	6.5	0.54	1.36
C2-6/32-0.5	6	4	0.04	0.58
C2-6/32-1	5	3	0.03	0.53
C2-12/32-0.5	6	4.67	0.1	0.79
C2-12/32-1	6.3	3.33	0.18	1.22



A. B.

Figure 4 An image of the spalled surface for C2-6/32-0.5 (A) and cartography of the spalling depth (B). All the measurements are in cm.

Relationship between mean and maximum spalling depth and spalled volume

Mean spalling depth is calculated as a spalled volume over the exposed surface of the sample; therefore, a linear relationship between these variables is expected. We then plot an average value of maximum spalling depth as a function of an average value of mean spalling depth in Figure 5. It is observed that the relationship between these two quantities is linear. Therefore, in this study we will present spalling results in terms of mean spalling depth.

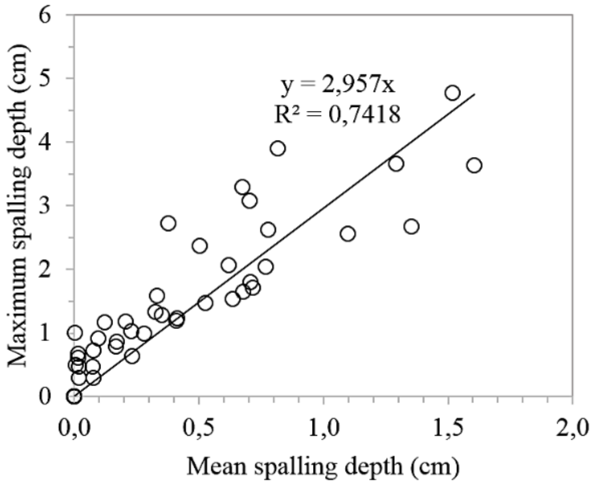
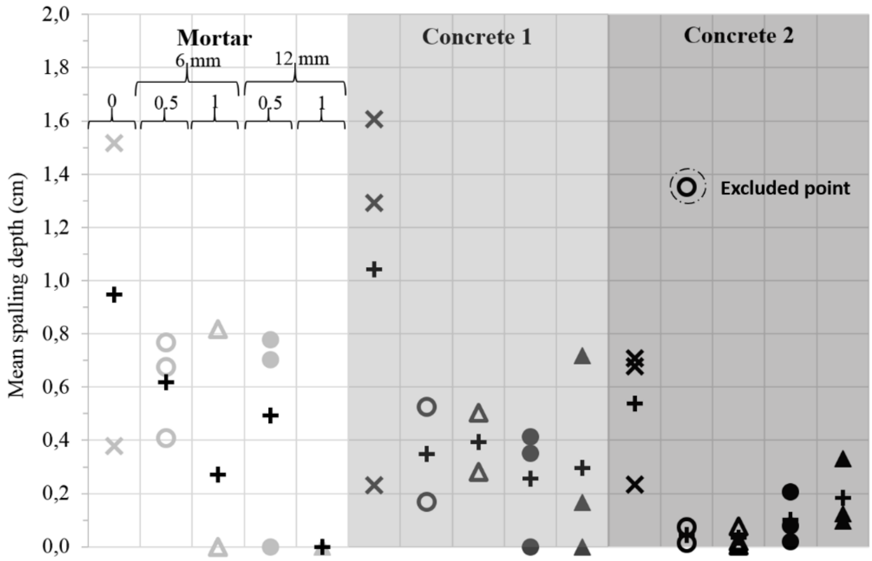


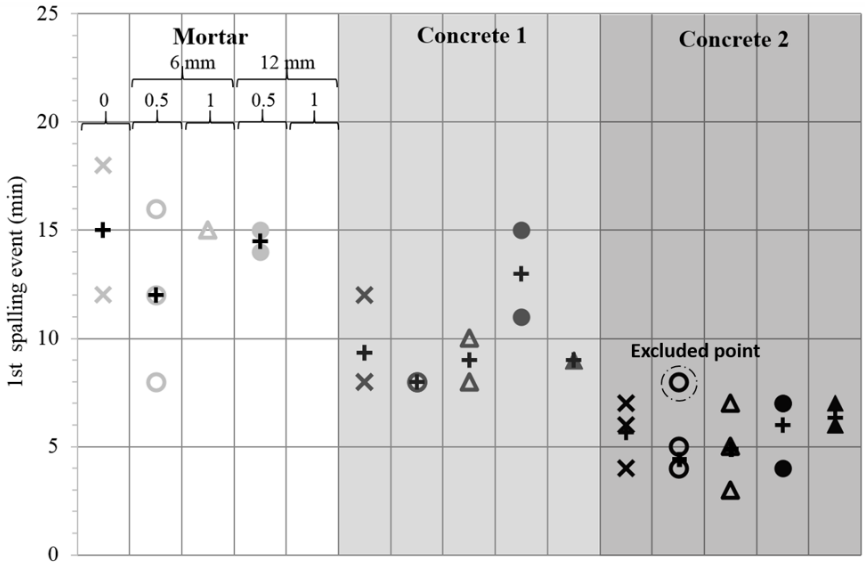
Figure 5 Linearity between average values of maximum and mean spalling depth.

Influence of aggregate size on spalling

Next we study the influence of the aggregate size on spalling of cementitious materials. As observed from Figure 6A, mortar samples (M) have the highest values of mean spalling depth for spalled samples compared to concrete 1 (C1) and concrete 2 (C2). The increase of the aggregate size decreased the spalling as well as in [14, 15]. It is noted that spalling of C2 samples was less severe than of C1 in terms of spalling depth even if the compressive strength is just 12 % lower for C2 than for C1. It is interesting to notice that in [16], on contrary, the increase of the aggregate size from 18 mm to 25 mm has increased the extent of spalling. Concerning spalling pattern, spalling for mortar samples is more profound on the sides than in the center which is the opposite of what is observed on concrete samples C1 and C2.



A.



B.

Figure 6 Spalling tests results: (A): Mean spalling depth, (B): 1st spalling event time.

The results of the literature show an increased risk of spalling with an increase of mechanical strength [17, 18]. The mortar (M) without fibers, despite its relatively low strength, exhibits spalling as important as C1 and more important than C2, whose compressive strengths are almost 2.5 times and twice higher than that of M. Two phenomena occur during heating that have contradictory effects. The increased strength of a cementitious material leads to a decrease in its permeability, an increase in pore pressures and an increase in the risk of spalling. At the same time, heating induces strains that are different for cement paste and aggregates: from about 150 °C, the cement paste shrinks while the aggregates have a positive coefficient of thermal expansion at any temperature [19-21].This difference in behaviour, named as a thermal mismatch, induces cracks developing at the interface between the paste and the aggregates. The larger are the aggregates, the more developed the cracking network is.

In our study, at the end of the fire tests, mortar samples present less cracks, highly spaced between each other. For most of the mortar samples one big crack with a possible orthogonal crack was observed. A network of microcracks is very limited and dispersed with a distance between the cracks of about 50 mm. For the concrete samples, the cracking is more pronounced and visible. The distance between cracks increases with the size of the aggregate (approximately 15 mm and 30 mm for concrete 1 and concrete 2 respectively).

Evolution of spalling with a time

During the fire test the information about the 1st spalling event, number and time of each spalling event has been recorded. The 1st spalling event time for each mix is presented in Figure 6A. The graph of the cumulative number of spalling events as a function of the fire test duration for all the tests performed on each material can be observed in Figure 7. It can be seen that as the size of the aggregate increases, the 1st spalling event occurs earlier and number of spalling events increases. As we increase the size of the aggregates, we observe the increase in the frequency of the spalling events.

Concretes have significant cracking and high pore pressures due to their high compacity and water saturation [17]. Spalling can thus occur early after the start of heating, affecting a thinner layer which has been weakened by the formed crack network. The low-cracked mortar also has a relatively low pore pressure development. Due to its high permeability, delay in development of pore pressures and maximum of pore pressures appears leading to delay of spalling.

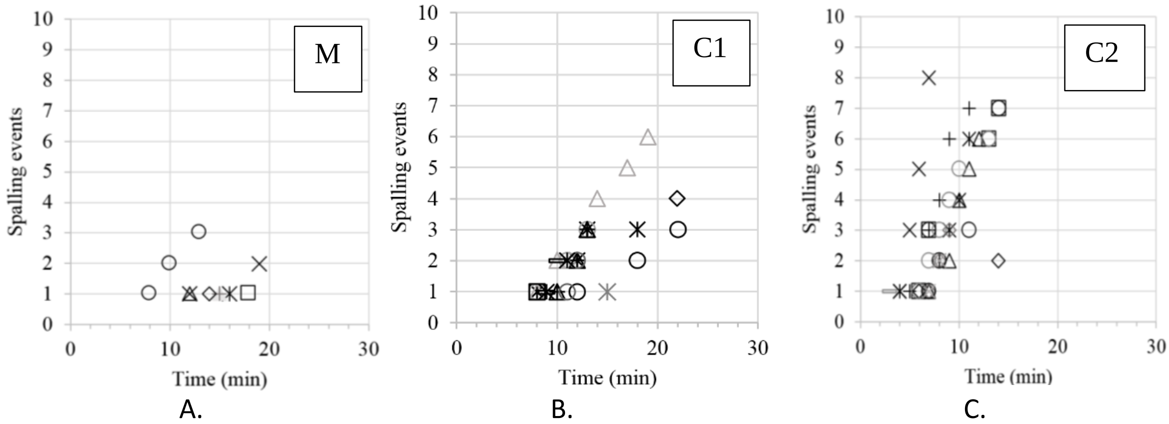


Figure 7 Cumulative number of spalling events as a function of test duration for (A): mortar, (B): concrete 1 and (C): concrete 2.

Influence of PP fibers on spalling

In order to evaluate the influence PP fibers on the spalling behaviour of cementitious materials, we plot Figure 8. Three differents tracing lines were produced in order to observe the influence of the dosage for the same length of fibers, the influence of length for the same total length and for the same total number.

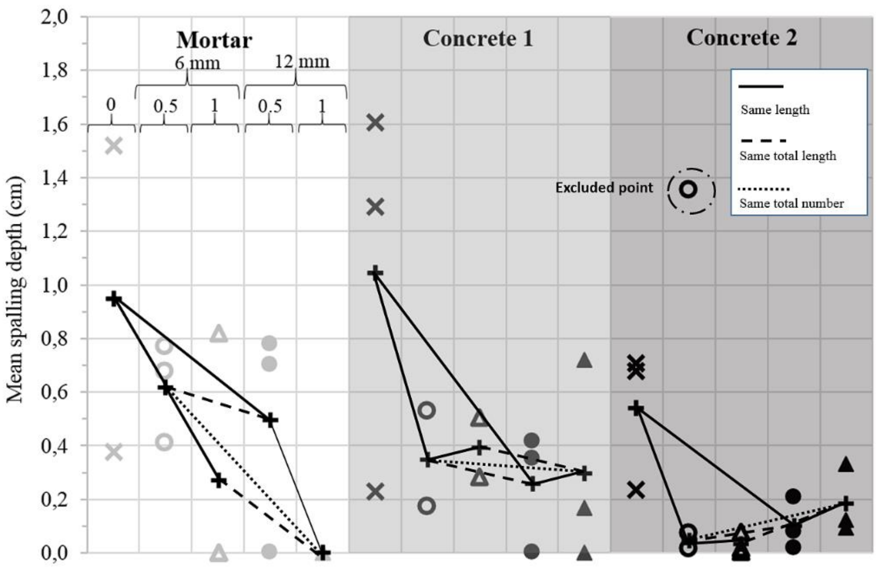


Figure 8 Mean spalling depth for all tested cementititious mixes. Full line shows PP fibers of the same length with a different dosage, dotted line- different length for the same total length and dot line – different length for the same total number.

Figure 8 shows the efficiency of fibers in reducing the risk of spalling even at relatively low dosages: 0.5 and 1 kg/m^3. The addition of 0.5 kg/m^3 of 6 mm fiber reduces the average spalling depth by 1.5, 3 and 13 times respectively for M, C1 and C2. The addition of 0.5 kg/m^3 of 12 mm fiber is slightly more effective than 6 mm fibre in mortar and C1 but slightly less effective for C2.

The fibre network coupled with the crack network induces an increase in permeability if the fibre dosage and the fibre dimensions are sufficient to ensure percolation and decrease pore pressures. In the case of mortar, 1 kg/m^3 of 12 mm fibre is required to avoid spalling. In the case of C2, only 0.5 kg/m^3 of 6 mm fibre is required to nearly prevent spalling (less than 0.1 mm average spalling depth). For C1 and C2, the addition of fibers above 0.5 kg/m^3 has no efficiency in reducing spalling. It seems to be explained by the appearance of spalling very soon after the start of heating, which the fibers do not seem to help to avoid. This is due to the water saturation of samples as explained above. Indeed, the fiber-free C1 specimens showed instabilities between the 8th and the 22nd minutes. But 70% of the C1 fiber containing specimens showed instabilities between the 8th and 13th minutes. This highlights the ability of fibers to avoid the instabilities that occur later in the test and not the ones that occur early.

CONCLUSIONS

This paper presents an experimental study aimed at contributing towards the optimization of fiber geometry and dosage choice according to the granular skeleton of cementitious materials. First, a linear relationship between mean spalling depth, maximum spalling depth and spalled volume was established. Then, the influence of the aggregate size on the spalling depth and 1st spalling event occurrence was examined. We explain the high spalling depth of the mortar by its low cracking that leads to low increase of permeability during heating and high pore pressure development which results in delayed spalling. As concrete is cracked very early due to thermal mismatch of aggregate and cement paste, the pore pressures are released and less instabilities occur. As aggregate size increases, the number of events increases as well; whereas, mean spalling depth decreases. Lastly, we have investigated the influence of the PP fiber addition. The positive influence of fibers was observed for all the samples as the dosage of fibers increased to 0.5 kg/m^3. It was noted that 1 kg/ m^3 of 12 mm fibers was efficient for spalling prevention of mortar and 0.5 kg/m^3 is sufficient to decrease significantly spalling in particular for C2. The increase of fiber dosage between 0.5 and 1 kg/m^3 has no significant effect on spalling for C1 as well as for C2. A saturated state of samples presents a difficulty for PP fiber to prevent instabilities occuring early during the fire tests.

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REFERENCES

1. Bentz, D.P., “Fibers, Percolation, and Spalling of High-Performance Concrete”, *ACI Materials Journal*, **97**, 351-359, 2000.
2. Debicki, G., Haniche, R., and Delhomme, F., “An experimental method to investigate concrete spalling in temperature”, Proceedings of the 2nd International Workshop on Concrete Spalling due to Fire Exposure, 189-195, Delft, Netherlands, 5-7 October, 2011.
3. Kalifa, P., Chéné, G., Gallé, C., “High- temperature behaviour of HPC with polypropylene fibres: From spalling to microstructure”, *Cement and Concrete Research*, **31**, 1487-1499, 2001.
4. Bei, S., Zhixiang, L., “Investigation on spalling resistance of ultra-high strength concrete under rapid heating and rapid cooling”, *Case Studies in Construction Materials,* **4**, 146-153, 2016.
5. Bilodeau, A., Kodur, V.K.R., and Hoff, G.C., “Optimization of the type and amount of polypropylene fibres for preventing the spalling of lightweight concrete subjected to hydrocarbon fire”, *Cement and Concrete Composites,* **26**, 163-174, 2004.
6. Persson, B., “Fire resistance of self-compacting concrete-SCC”, *Materials and Structures,* **37**, 575-584, 2005.

7. Arai, T. and Furuichi, K., Persson, B., “Experimental study on reinforced concrete segement using fireproof concrete for shield tunnel in highway or railway”, Proceedings of the 2nd International Workshop on Concrete Spalling due to Fire Exposure, 255-262, Delft, Netherlands, 5-7 October, 2011.
8. Mugume, R.B. and Horiguchi, T., “Effect of fiber type and geometry on maximum pore pressures in fibre-reinforced high strength concrete at elevated temperatures”, Cement and Concrete Research, 42, 459-466, 2012.
9. Heo, Y.-S., Sanjayan, J.G., Han C.-G. and Han M.-C.,“Effect of fiber type, length and numbers of fibers per unit volume on spalling protection of high-strength concrete”, Proceedings of the 4th International Workshop on Concrete Spalling due to Fire Exposure, 211-220, Leipzig, Germany, 8-9 October, 2015.
10. Sideris, K. K. and Manita, P.,“ Influence of length and dosage of polypropylene fibres on the spalling tendency and the residual properties of self-compacting concrete after heated at elevated temperatures”, Proceedings of the 3rd International Workshop on Concrete Spalling due to Fire Exposure, 02004, Paris, France, 25-27 September, 2013.
11. Hager, I. and Tracz, T., “The impact of the amount and length of fibrillated polypropylene fibres on the properties of HPC exposed to high temperature”, *Archives of Civil Engineering*, **56**, 57-68, 2010.
12. Heo, Y.-S., Sanjayan, J.G. and Han M.-C., “Relationship between interaggregate spacing and the optimum fiber length for spalling protection of concrete in fire”, *Cement and Concrete Research*, **42**, 549-557, 2012.
13. Miah, Md. J., Carré, H., Pimienta, P., Pinoteau, N. and La Borderie, C., “Effect of uniaxial mechanical loading on fire spalling of concrete”, Proceedings of the 4th International Workshop on Concrete Spalling due to Fire Exposure, 124-131, Leipzig, Germany, 8-9 October, 2015.
14. Pan, Z., Sanjayan, J.G., and Kong, D.L.Y., “Effect of aggregate size on spalling of geopolymer and Portland cement concretes subjected to elevated temperatures”, *Construction and Building Materials*, **36**, 365-372, 2012.
15. Nince, A. and Figueiredo A.D., “The influence of aggregate size in the risk of spalling in normal and high-strength concrete subjected to hydrocarbon fire”, Proceedings of the 5th International Conference on Concrete for Structures, 9-20, Coimbra, Portugal, 7-8 July, 2005.
16. Robert, J., “Material properties related to fire spalling of concrete”, Division of Building Materials, LTH, Lund University, Report TVBM-3143, Lund, Sweden, 2008.
17. Mindeguia, J.-C., “Contribution expérimentale à la comprehension des risques d’instabilité thermique des bétons” (in French), PhD Thesis, Université de Pau et des Pays de l’Adour, Anglet, France, 2009.
18. Mindeguia, J.-C., Carré, H., Pimienta, P. and La Borderie, C., “Experimental discussion on the mechanisms behind the fire spalling of concrete”, *Fire and Materials,* **39**, 619-635, 2014.
19. Hager, I.G., “Comportement à haute température des bétons à haute performabce-évolution des principales propriétés mécaniques” (in French), PhD Thesis, l’Ecole Nationale des Ponts et Chaussées et l’Ecole Polytechnique de Cracovie, Krakow, Poland, 2004.
20. Lankard, D.R., Birkimer, D.L., Fondriest, F.F. and Snyder, M.J. “Effects of moisture content on the structural properties of Portland cement concrete exposed to temperatures up to 500 F”, Proceedings of the 21st ACI Fall Meeting, 59-102, Memphis,Tenessee, USA, 1 January, 1971.
21. Schneider, U., “Verhalten von Beton bei hohen Temperaturen Deutscher Ausschuss für Stahlbeton”, Ernst & Sohn, Berlin, 1982.