

Design of fire resistant concrete using combined fibers

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This study investigates the design of fire resistant concrete using combined fibers. The effect of the combined fiber technique on the level of spalling protection was experimentally confirmed by applying to large columns. Four different size of large columns were prepared for proving the effectiveness of the combined fiber technique. In addition, the authors presented the detailed procedure of the optimum fiber design for spalling protection of concrete in fire. In this design, critical parameters of fiber length, fiber diameter and the total number of fibers per unit volume were quantitatively established, so that the fiber addition can be reduced over 50% for the single type of fibers and can be further reduced for the combined type of fibers.

Key words: Fire resistant concrete, Combined fibers, Spalling, Column

Introduction

In fire, it is known that high strength concrete is at high risk of spalling [1-3]. The spalling is the detachment of pieces of concrete from the concrete surface, thus reducing the load-bearing cross-sectional area and capacity [4-6]. It may be explosive in some cases. In extreme cases, it may result in the loss of entire cross section of a concrete member.

To mitigate the spalling problem of high strength concrete in fire, the addition of polypropylene fibers in the concrete is introduced in the open literature. Since then, the effectiveness of the fibers has been proved by many researchers [7-10]. This mitigation method can reduce the probability of spalling, or prevent it, by reducing the pore pressures that build-up during rapid heating of concrete structures in fire.

Polypropylene fibers initially in a form of solid phase undergo a melt phase at around 160 °C. The spaces occupied by the melted fibers can provide pathways for water vapor within the concrete that can lead to pressure relief and the spalling protection of concrete [11, 12].

Previous research work

In previous research [13-19], the authors have firstly proposed three critical fiber parameters providing effective pathway for water vapor in concrete in fire. They are the total number of fibers per unit volume (N), the length of fibers (L) and the melting point of fibers (k). N determines the level of dispersion of fibers

in concrete; L determines the level of connection of pores and k determine the commencing time of vapor evacuation. These three factors contribute an effective pore network in concrete at elevated temperature and relieve vapor pressure.

Based on the key findings from the investigations, the authors have found that the addition of two types of fibers (nylon and polypropylene fibers) with selected dimensional characteristics could reduce the required fiber content up to three times less than the addition of the single type of polypropylene fibers commonly prescribed for the equal level of spalling protection of concrete in the literature. However, the findings from the previous work were drawn with small cylinders, in which a size effect may adversely affect the results.

Hence, in this current study, to further investigate the true effect of the combined fibers on the level of spalling protection, large column specimens with four different cross-sectional sizes were prepared. Finally, designs of fire resistant concrete using the synthetic fibers were proposed.

Size effect of Combined fiber Technique

Experimental outline

Table 1 shows the experimental outline. The combined fibers of 0.05% by volume and the conventional singled fibers of the same % were added in concrete. The combined fibers were nylon fibers of 0.025 vol.% and polypropylene fibers of 0.025 vol.%, and the singled fibers were polypropylene.

Four different sizes of columns were prepared, i.e. 300 × 300 × 1500, 500 × 500 × 1500, 700 × 700 × 1500 and 900 × 900 × 1500. The list of experimental tests conducted in fresh and hardened concretes are shown in Table 1.

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Table 1. Experimental outline.

Fiber type	Specimen size (mm)	Test conducted
Control (no fiber addition)	500 × 500 × 1500	
PP fibers ^a	300 × 300 × 1500	· Compressive strength
	500 × 500 × 1500	
	700 × 700 × 1500	
Combined fibers ^b	900 × 900 × 1500	· Fire test (3hrs): - Spalling extent - Spalling area - Weight loss
	300 × 300 × 1500	
	500 × 500 × 1500	
	700 × 700 × 1500	
	900 × 900 × 1500	

^aPolypropylene fibers of 0.05 vol.%.
^bPolypropylene fibers of 0.025 vol.% + Nylon fibers of 0.025 vol.%.**Table 2.** Mixture proportion of control concrete.

W/B ^a	Unit water, kg/m ³	S/a ^b , %	Weight mixture, kg/m ³				
			C ^c	FA ^d	SF ^e	S ^f	G ^g
0.25	160	45	448	128	64	660	837

^aWater to binder ratio, ^bSand to coarse aggregate ratio, ^cCement, ^dFly ash, ^eSilica fume, ^fSand, and ^gGravel.

Specimen preparation

The mixture proportion of the control concrete without fiber addition is shown in Table 2. Water to binder ratio of 0.25 was determined to cast high strength concrete. The binders included Fly ash of 20% and silica fume of 10% by cement weight. A forced fan type mixer was used, and combined fibers were added for a dry mix of first 30 sec with cement, binders and aggregates, followed by mixing with water for 60 sec.

All specimens were demoulded after seven days and then placed in an atmospheric condition: temperature was 8 °C-20 °C; humidity was 32%-43% and wind speed was 1.4 m/s-2.1 m/s. Fire tests were conducted at 91 days after casting the specimens.

Materials

Ordinary Portland cement (Density: 3150 kg/m³ and fineness: 330 m²/kg) was used in this study. Fly ash (Density: 2210 kg/m³, fineness: 406 m²/kg and loss on ignition: 3.5%) and silica fume (Density: 2200 kg/m³, fineness: 20000 m²/kg and loss on ignition: 1.5%) were incorporated as mineral admixtures. For aggregates (granite type), the combination of river sand and crushed rock (4 : 6) was mixed to obtain a 2.6 fineness modulus of fine aggregate. Density and absorption of the both fine aggregates were 2600 kg/m³ and 0.46%. All coarse aggregates used in this study were a crushed aggregate type. Density and absorption of the coarse aggregates were 2610 kg/m³ and 0.58%. The physical properties of nylon and polypropylene fibers are shown in Table 3.

Test methods

ASTM C 39 was conducted for compressive strength

Table 3. Physical properties of synthetic fibers.

Type of fiber	Diameter, mm	Length, mm	Density, kg/m ³	Melting point, °C
Polypropylene	0.040	19	910	160
Nylon	0.012	9	1150	220

test of hardened concretes. Cylinders of size Ø100 × 200 mm were prepared and tested in triplicate for each type for this strength test. Fire tests were carried out for three hours according to the standard heating curve of ISO-834. After the test completed, the extent of spalling was visually observed, and weight loss due to spalling was examined by comparing the values before and after the test. The spalling area was calculated by using the automatic area measurement software after tracing and blacking out the contours of detached parts of heated concrete specimens on a transparent sheet.

Experimental Test Results

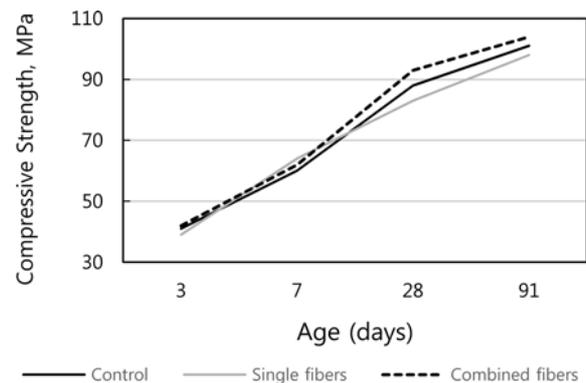
Properties of the concrete

Fig. 1 shows the compressive strength of the control concrete, single fiber-added concrete and combined fiber-added concrete to be placed in column specimens. Strengths of all concretes were properly developed and indicated around 100 MPa at the due date of fire tests, curing age of 91 days.

Extent of spalling

Fig. 2 shows the calculated % of spalling area of concrete column specimens. It was clear that the control column without fiber inclusion had severe damage due to spalling. The spalling area of the control column was 92.4%. Fiber addition in concrete improved the spalling resistance, but a fiber type significantly affected the results.

For the specimens with a cross sectional size of 500 mm that were exactly the same size with control, the spalling area of the column with singled polypropylene

**Fig. 1.** Compressive strength of concrete.

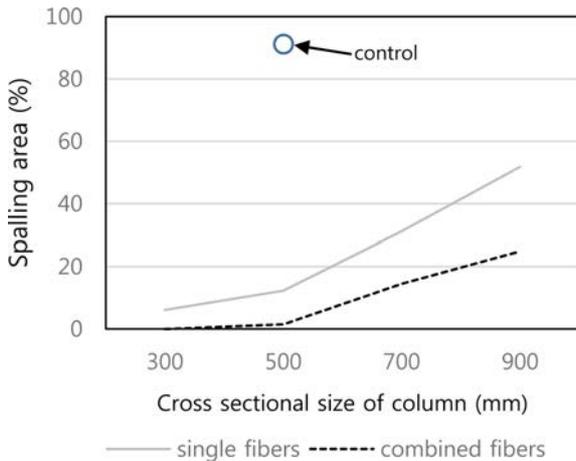


Fig. 2. Spalling area of concrete after fire exposure.

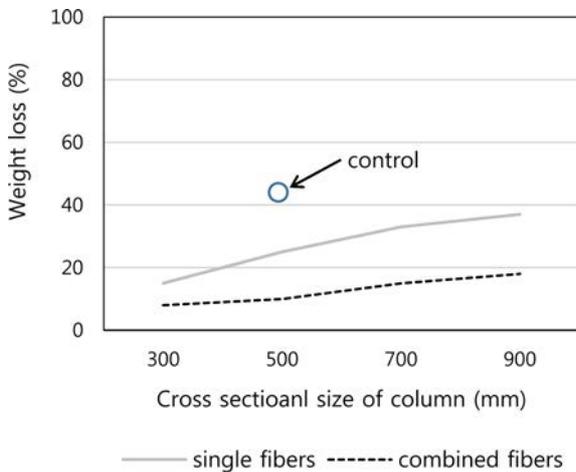


Fig. 3. Weight loss of concrete after fire exposure.

fibers was 12.0%, whereas that with combined fibers was only 1.5%. The good result of the column with the combined fibers was equally observed in other larger specimens tested in this study, which provides evidence that the combined fiber technique is effective in large specimens. It is noted that the larger the size of specimens, the higher was the results of spalling area.

Fig. 3 shows the weight loss of the column specimens after fire exposure. As expected, control concrete without fiber addition lost over 40% of its original weight before fire exposure. However, the combined fiber technique was much more effective on minimizing the weight loss of the concrete in fire, compared to the addition of single type of polypropylene fibers.

Design of fire Resistant Concrete using combined Fibers

In the literature, it was observed that the addition of polypropylene fiber of 1.8 kg/m^3 and 3.0 kg/m^3 had a similar effect on pressure relief in heated concrete exposed to fire. In other words, this mean that as soon as fibers constitute a connected network, the latter is

large enough to evacuate gases and vapor, thus to reduce pore pressure, in which the level of reduced pore pressure is similar to former dosage. Hence, it is very important that the amount of fiber inclusion should be just to resist the spalling of concrete to avoid any side effects that might occur when the fiber content unnecessarily increases. In fact, it should be noted that the capability of evacuating the vapor from the concrete in fire is dependent on the level of connected pores. Since the main role of fibers is to provide the connection between un-connected pores, the length of fibers and the total number of fibers are the essential parameters for spalling protection as characterized in previous work, by which the fiber content can be minimized.

By taking these essential parameters of fibers into the design of fire resistant concrete, the optimum level of fire resistant concrete can be achieved. The detailed procedure is presented as follows.

Inter-aggregate spacing

It is important to note that for a given fiber content, the essential parameters, fiber length and total fiber number, are in inverse proportion to each other. The relationship is given by

$$N = \frac{4V_f}{\pi d_f^2 L_f} \quad (1)$$

where N is the total number of fibers per unit volume, V_f is the volume of fiber content, d_f is the diameter of fibers, and L_f is the length of fibers. For a given fiber content, increasing N by decreasing d_f or L_f (Eq. 1) is beneficial to obtain a well distributed pore network in concrete at elevated temperature, but unlike limited effect of d_f on spalling protection, L_f has an effect to intersect un-connected pores in concrete, so that L_f should be long enough to provide effective pathways for water vapor, which in turn should decrease N accordingly for a given fiber content.

Percolation of concrete is one of the critical factors that can determine the level of spalling. According to a percolation theory, ITZ regions are normally percolated in normal strength concrete, but not definitely in high strength concrete. To achieve the high strength concrete to be percolated, it is believed that neighboring ITZs which is not connected due to the use of high strength concrete should be re-connected by the addition of fibers with a proper length. For a given fiber content, the addition of fibers shorter than the required length will result in the lack of interconnectivity between the ITZs and the fibers, and that of fibers longer than the required length will result in a decrease of N . In both cases, the concretes would not be percolated in the optimum level. Hence, to optimize the effectiveness of fiber addition, it is the first step to determine the least length of fibers required for percolating concrete.

Since ITZ thickness in high strength concrete is very

small, the distance between neighboring ITZs is referred to as inter-aggregate spacing, which is a function of the size, grading and volume of aggregates as well as other mixture proportions of concrete. It should be noted that the inter-aggregate spacing of fine aggregate is not an important parameter for spalling protection. It is the inter-aggregate spacing of coarse aggregate, i , that is important, so that the least length of fibers should be longer than i for effective spalling protection.

Briefly, in previous study, a C_{shell} model has been developed based on the assumption that all coarse aggregates are spherical, and they are uniformly distributed and covered by uniform thickness of mortar shells. Based on these assumptions, it can be said that i is twice the mortar shell thickness. The procedure for calculating i (equal to the least fiber length for percolated concrete) is summarized in Table 4.

Total number of fibers per unit volume

For the next stage, it is important to estimate the least N required for spalling protection. With the pre-calculated i , the estimated N has an effect on the determination of the optimum fiber length. This is because, for a given fiber content, dramatically increased N can overtake the effect of fiber length, thus

decreasing the optimum fiber length. Prior to determine the least N , the effect of the influential factors into the design of the fire resistant concrete at the material level should be carefully considered. A way of measuring fiber content as N is due to the fact that essential parameters of fibers for spalling protection is N and L_f , and N is independent of d_f .

The optimum length of fibers

The optimum fiber length can be calculated based on the calculated i and pre-determined N . To finalize the optimum fiber length, another contributing factor, an aggregate size in concrete, should be introduced. Because the aggregate size in concrete affects an external tangent length of adjacent aggregates, which directly affect the required length of fibers for the interconnectivity of adjacent aggregates. An average aggregate size parameter, d , can be used to represent the aggregate sizes in the concrete. This is given by

$$d = \frac{6}{S_{\text{tm}} \rho_s} \quad (8)$$

It is important to note that there is a threshold of the critical number of fibers per unit volume, N_c , that can determine a dominant fiber parameter (L_f or N) for spalling protection. This is because L_f and N have an effect to compensate each other in terms of the pressure relief of vapor in concrete in fire. By taking this into account, the equation for the optimum length of fibers for spalling protection is given by

$$\zeta = (i + d) \left(\frac{N_c}{N} \right)^{\frac{1}{3}} \quad (9)$$

where ζ is the optimum length of fibers, N_c is a constant, empirically determined to be 250, which is believed to be the critical boundary of a dominant factor for fiber effectiveness parameters (L_f and N), which can be said that if N is started to be higher than N_c , the dominant factor of the fiber parameters for spalling protection is likely to be N , so that the optimum fiber length decreases to achieve increased N ; and if N is lower than N_c , the dominant factor is likely to be L_f , so that the optimum fiber length increases.

New measurement for fiber content

At this stage, the quantity of calculated N and α is finally examined to see whether these values are sufficient for spalling protection. In the literature, the addition of polypropylene fibers has been used for spalling protection of concrete for over a decade, and its excellent performance has been verified by many researchers. For the concretes having up to 100 MPa of compressive strength, it has generally been observed that the addition of polypropylene fibers with 0.1% to 0.3% is necessary for the spalling protection of the concretes. However, it has been demonstrated that these amounts of fibers being used in the past can be

Table 4. Procedure for the calculation i , calculated for 1 m³ concrete.

Parameter description	Equation
Void volume between the dry rodded aggregate occupied by the total amounts of the coarse aggregates used, η	$\eta = \gamma - \left(\frac{\omega}{\rho_s} \right)$ (2)
Specific surface area of spheres uniformly distributed in the size between the mesh size (mm), d_x and d_y of adjacent sieves, S	$S = \frac{6}{(1-\eta)\rho_s\sqrt{d_x d_y}}$ (3)
Specific surface area of actual used coarse aggregate having fractions of the total mass retained on different sieves, S_{tm}	$S_{\text{tm}} = \sum_{x=1}^n S_x x_x$ (4)
Excess volume of mortar after filling ' η ', ε	$\varepsilon = V_{\text{conc}} - (\gamma + a)$ (5)
Mortar shell thickness covering each coarse aggregates by ' ε ', T_m	$T_m = \frac{\varepsilon}{S_{\text{tm}} \omega}$ (6)
Inter-aggregate spacing of coarse aggregates, i	$i = 2T_m$ (7)

γ is the total volume of dry rodded aggregate occupied by the amounts of the coarse aggregates used.

a is the volume of air content measured.

ω is the weight of coarse aggregate.

ρ_s is the density of coarse aggregate.

$S_1 S_2 \dots$ and S_n is the specific surfaces of uniform spheres distributed in the different sieves [Eq. 3], and $x_1 x_2 \dots$ and x_n is the fractions of the total mass of the actual used aggregate retained on the corresponding sieves.

V_{conc} is the volume of concrete used, which is equal to 1 m³.

reduced to over 50%.

As discussed in Section 2, there is a method to quantify the required fiber content for spalling protection with dimensional characteristics of synthetic fibers. The new measure for fiber content to determine the critical threshold for fiber addition for spalling protection has been established. This is given by

$$N\zeta^3k \geq 190 \quad (10)$$

where k is a factor introducing the effect of fiber melting point which is empirically determined as $160/t_m$, where t_m is the melting point of fibers in degrees Celsius. It can be said if $N\zeta^3k$ is greater than 190 where the fiber addition is optimized, there is no or minor spalling occurred in concrete in fire.

Combined fibers

As discussed in 3rd section, there is a synergistic effect of combined fibers showing outstanding performance of spalling protection. By combining nylon and polypropylene fibers, concrete spalling has started to be resisted (no or minor spalling) when N^3k is more than 52, which is over 3 times less than the critical threshold, 190, mentioned above.

This is because although polypropylene fibers have low melting point, this fiber can only provide limited number of fibers per unit volume due to their large diameter. Combining other types of fibers which are small in diameter such as nylon fibers can improve the deficiency of polypropylene fibers by providing larger number of fibers per unit volume. In addition, since nylon fibers have higher melting point, the concrete containing both fibers can timely provide pathways for water vapor throughout fire exposure (in early and latter stages), which also improve the effectiveness of combined fibers as compared with the addition of a single type of fiber.

Conclusions

This study has investigated the effect of the combined fiber technique on the level of spalling protection by applying to large column specimens and proposed the design of fire resistant concrete using synthetic fibers. The conclusions are drawn as follows.

- 1) It is proved that the proposed combined fiber technique with significantly reduced fiber content is applicable to large concrete columns.
- 2) The size of a column has an effect on the level of spalling. The larger the size of specimen, the lower is the effectiveness of the combined fiber technique.
- 3) To design the fire resistant concrete by using synthetic fibers, the melting point of fibers, the length of fibers and the total number of fibers per unit volume

are the important parameters. In addition, it was found that the optimum length of fibers is mainly determined by the inter-aggregate spacing and the critical fiber number per unit volume parameters.

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References

1. J.G. Sanjayan and L.J. Stocks, *ACI Materials Journal* 90 (1993) 170-173.
2. C.G. Han, *Magazine of Korea Concrete Institute* 10 (1998) 5-10.
3. G.A. Houry, C.E. Majorana, F. Pesavento, and B.A. Schrefler, *Magazine of Concrete Research* 54 (2002) 77-101.
4. G.R. Consolazio, M.C. McVay, and III J.W. Rish, *ACI Materials Journal* 95 (1998) 525-536.
5. X.T. Chen, T. Rougelot, C.A. Davy, W. Chen, F. Agostini, F. Skoczylas, and X. Bourbon, *Cement and Concrete Research* 39 (2009) 1139-1148.
6. V.K.R. Kodur and L. Phan, *Fire Safety Journal* 42 (2007) 482-488.
7. R. Britenbucker, "High strength concrete C105 with increased fire resistance due to polypropylene fibers", *Proceedings of 4th International Symposium on Utilization of High Strength/High performance Concrete*, Paris, France (1996) 571-578.
8. K. Pierre, C. Gregoire, and G. Christophe, *Cement and Concrete Research* 31 (2001) 1487-1499.
9. P. Kalifa, G. Chene, and C. Galle, *Cement and Concrete Research* 31 (2001) 1487-1499.
10. L. T. Phan, and N.J. Carino, *ACI Materials Journal* 99 (2002) 54-66.
11. F. Papworth, "Effect of synthetic fibers and silica fume on explosive spalling of high performance concrete exposed to fire", *South East Asia Construction, Trade Link Media Singapore* (2000) 1-6.
12. R. Jansson, "Fire spalling of concrete", PhD thesis, KTH, Sweden (2013).
13. Y.S. Heo, "Identification of fibre parameters from spalling protection of concrete in fire", PhD thesis, Monash University, Australia (2011)
14. Y.S. Heo, J.G. Sanjayan, C.G. Han, and M.C. Han, *Construction and Building Materials* 25 (2011) 2928-2938.
15. Y.S. Heo, J.G. Sanjayan, C.G. Han, and M.C. Han, *Materials and Structures* 44 (2011) 599-610.
16. Y.S. Heo, J.G. Sanjayan, C.G. Han, and M.C. Han, *Materials and Structures* 45 (2012) 325-335.
17. Y.S. Heo, J.G. Sanjayan, C.G. Han, and M.C. Han, *Cement and Concrete Research* 42 (2012) 549-557.
18. Y.S. Heo, J.G. Sanjayan, C.G. Han, and M.C. Han, *Cement and Concrete Research* 40 (2010) 1547-1554.
19. Y.S. Heo, C.G. Han, and K.M. Kim, *Materials and Structures* 48 (2014) 3377-3390.