Cement and Concrete Research 40 (2010) 1547–1554

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Synergistic effect of combined fibers for spalling protection of concrete in fire

Young-Sun Heo [a], Jay G. Sanjayan [b,*], Cheon-Goo Han [c], Min-Cheol Han [c]

[a] Department of Civil Engineering, Monash University, Clayton, Victoria 3800, Australia
[b] Engineering and Industrial Sciences, Swinburne University of Technology, POBox 218, Hawthorn, Victoria 3122, Australia
[c] Division of Architectural Engineering, Cheongju University, Cheongju, Chungbuk, Republic of Korea

ARTICLE INFO

Article history:
Received 3 March 2010
Accepted 28 June 2010

Keywords:
Workability (A)
Fiber reinforcement (E)
Concrete (E)
Mechanical properties (C)
Fire

ABSTRACT

This study demonstrates the synergistic effect of some particular combination of fibers that can provide significantly better spalling protection of concrete in a fire than single fiber by themselves at the same fiber content level. Various combinations of polypropylene, polyvinyl alcohol, cellulose and nylon fibers were investigated. Fire tests were conducted in accordance with ISO-834. The combination of nylon (9 mm length) and polypropylene (19 mm length) fibers found to provide the most optimum results. By combining these two fibers, the same level of spalling protection was achieved by three times less fiber content than the single type of 0.10% polypropylene fiber commonly prescribed. A “fiber effectiveness parameter” is proposed which is a function of total number of fibers per unit volume and length of fiber. This parameter is useful in providing quantitative explanations of various fiber additions and their spalling results in fire.

1. Introduction

Spalling in concrete at elevated temperature causes severe damage on the surface of concrete structural elements often exposing reinforcing bars, and it sometimes results in the collapse of building structures [1]. High strength concrete has been particularly susceptible to spalling in fire [2], and a number of studies have been focused on the addition of polypropylene fiber in concrete for spalling protection. With respect to the amounts of fiber, it has been reported that 1 to 3 kg/m^3 of polypropylene fiber can mitigate the spalling [3–6]. However, the higher the fiber content, the worse is workability in fresh concrete [7].

Nylon fiber has been considered as a good performing material with concrete in previous studies. Song [8] has observed that nylon fiber added to concrete improves compressive and tensile strength up to 6 and 7% respectively over those of polypropylene fiber concrete, and the improvement of the properties was due to the favorable distribution of the nylon fiber. In previous research conducted by the authors [9,10], nylon fiber in concrete has improved workability as compared with the addition of other types of fiber. It has been also demonstrated that the fiber has a remarkable effect on spalling protection. This was due not only to the effective distribution of nylon fiber, but most importantly, it has been found that the nylon fiber has significantly higher number of fiber per unit volume in concrete than polypropylene fiber at a given fiber content by volume. The effectiveness of the spalling protection offered by fiber inclusion depends on the ability of the fiber inclusion to create the connectivity of the pores when melted in a fire. Bentz [11] pointed that the connectivity of void spaces in concrete is critical to provide a convenient escape route for vapor generated during fire exposure to reduce spalling risk. For a given fiber content, a higher number of thinner fibers has more chances to connect other pores, compared to a fewer number of thicker fibers. Hence, fiber with small diameter such as nylon is beneficial to provide effective pathways for vapor.

However, it should be noted that high number of fiber is not always helpful for spalling protection of concrete in fire. There is a limitation to the length of fiber, which is also related to the interconnectivity of pores. Since the fiber number and length are inversely proportional to each other for a given fiber content, the length and the diameter of fiber should be chosen at the same time based on the optimum level for spalling protection. Kalifa et al. [12] suggested that 19 mm length of fiber is efficient in connecting pores. However, from the previous work [10], we have found that fine nylon fiber (diameter: 12 μm) has an optimum at 9 mm length whereas coarse polypropylene (diameter: 40 μm) has an optimum at 19 mm. The selected nylon fiber protected concrete from spalling with only half the content of conventional amounts used for polypropylene fiber. However, one drawback of nylon fiber is high melting point. Spalling normally occurs between 200 to 250 °C [2,5,12], so the melting point of the fiber should preferably be at least less than 200 °C. Melting point of nylon fiber is 220 °C, hence it is not optimal with regards to this parameter.

This study demonstrates that the addition of more than one type of fiber in concrete with varying melting points can achieve the optimum level of spalling protection, due to the fact that the fibers with lower melting point can release some vapor pressure at critical

* Corresponding author. Tel.: +61 3 92148034; fax: +61 3 92148364.
E-mail address: jsanjayan@swin.edu.au (J.G. Sanjayan).

0008-8846/$ – see front matter
doi:10.1016/j.cemconres.2010.06.011

temperatures. The objective of this study is to optimize the fiber addition for spalling protection of concrete as well as workability.

2. Experimental work

2.1. Experimental outline

In all the concrete mixes studied, the water to binder ratio was fixed at 0.25. The binder included 20% of fly ash and 10% of silica fume by weight. The experimental program is summarized in Table 1, and consists of three Series. In Series I, polypropylene fiber (PP) was added in concrete with various combinations of different lengths (3, 6, 12 and 19 mm). Since PP fiber has been commonly used for spalling protection of concrete, three other types of fibers (polyvinyl alcohol: PVA; cellulose: CL; and nylon: NY) were combined with PP in Series II. The length of PP was selected based on the results of Series I, and the lengths of other types of fiber were determined by previous research [9]. In Series III, the most effective combination of fiber from Series II was selected for fire tests at a wide range of fiber contents, and several combinations of different lengths of selected hybrid fibers were also compared. The selected hybrid fibers from Series II was the combination of PP and NY. To ensure the effect of the hybrid fibers, concretes containing single type of NY fiber were examined in fire tests in Series IV. The fiber content of the study was varied to investigate the effectiveness of the hybrid fibers as follows: Series I and II was 0.050, 0.100, and 0.150% (by volume); Series III was 0.010, 0.020, 0.030, 0.040 and 0.050% (by volume); and Series IV was 0.010, 0.015, 0.020, 0.025 and 0.030% (by volume).

Cylinders of size Ø100 × 200 mm were prepared, and three specimens for each type were conducted for all tests designed in this study. Target slump flow of control concrete was 700 ± 100 mm, and the air content was 3 ± 1.0%. These targets were chosen since they are widely used in construction practice [13]. The tests conducted for concretes in all Series are presented in Table 1. As for the test methods, slump flow was performed in accordance with ASTM C 1611. Air content of control concrete was measured according to ASTM C 138. ASTM C 39 was conducted for compressive strength test of hardened concretes. Fire tests were carried out for one hour according to the standard heating curve of ISO-834. After the test completed, all specimens left in a furnace for 24 hours to be naturally cool off to room temperature. On the following day, the extent of spalling was visually observed, and the weight loss and residual compressive strength of concretes were tested and compared with the values before the test.

Table 1
Experimental outline.

Series	Combination of fibers		Fiber addition (%)	Tests conducted
	Type	Length[a] (mm)		
I	Control	(No fiber addition)		
	PP[b] + PP	19	0.50, 0.010, 0.150	Slump flow
		3 and 12		
		3 and 19		
		6 and 12		Compressive strength
		6 and 19		
				Fire tests (1 h)
II	CL[c] + PP	3 and 19	0.050, 0.010, 0.150	−Spalling extent
	PVA[d] + PP	6 and 19		−Weight loss
	NY[e] + PP	9 and 19		−Residual
III	NY + PP	6 and 12	0.010, 0.020, 0.030, 0.040, 0.050	compressive strength
		6 and 19		
		9 and 12		
		9 and 19		
		9	0.010, 0.015,	spalling extent
IV	NY		0.020, 0.025, 0.030	

[a] Combination rate: 50% to 50%.
[b] Polypropylene fiber: commonly used fiber (length: 19 mm) in a conventional spalling resistant method.
[c] Cellulose fiber.
[d] Polyvinyl alcohol fiber.
[e] Nylon fiber.

2.2. Materials

The cement used is similar to the ASTM Type I cement (Density: 3,150 kg/m^3 and fineness: 330 m^2/kg). Fly ash (Density: 2,210 kg/m^3, fineness: 406 m^2/kg and loss on ignition: 3.5 %) and silica fume (Density: 2,200 kg/m^3, fineness: 20,000 m^2/kg and loss on ignition: 1.5%) were incorporated as mineral admixtures. As 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 are 2600 kg/m^3 and 0.46%; and unit weight is 1518 kg/m^3 and 1684 kg/m^3 respectively. Coarse aggregate (density: 2610 kg/m^3, absorption: 0.58% and unit weight: 1564 kg/m^3) was crushed aggregate type with a 20 mm maximum in size. The mixture proportion and the properties of control concrete are summarized in Table 2, and the physical properties of fiber are presented in Table 3.

3. Test results

3.1. Properties of the concrete

Fig. 1 shows the results of slump flow of fresh concrete made with various combinations of types and lengths of fibers. As shown in Fig. 1a, control concrete without fiber addition indicated 735 mm slump flow, which was in the target range, but the high contents of fiber notably decreased workability. Especially, the concrete containing PP 19 (abbreviation according to Table 2) had the highest loss of workability, while the others with combinations with shorter lengths of fibers showed relatively better performance. It is believed that the combination of short lengths of fiber improves the distribution of the fiber in concrete mixture. For the effect of combination of different types of fibers (Fig. 1b), the addition of CL 3, PVA 6 or NY 9 in conjunction with PP 19 appeared to be beneficial (abbreviations described in Table 2). Although PP 19 showed the worst workability (Fig. 1a), the combination with NY fiber significantly improved the values (Fig. 1b). With smaller content of NY fiber as shown in Fig. 1c, slump flows of all concretes were within the range of 650 to 750 mm.

Fig. 2 shows the compressive strength of hardened concrete containing hybrid fibers at 28 days. Control concrete was 74 MPa. The figure illustrated slight reduction in some specimens with fiber addition: up to 10% in Series I (0.1% of PP 3/PP 12), 13% in Series II (0.15% of PVA 6/PP 19), and 6% in Series III (0.04% of NY 9/PP 12). However, NY 9/PP 19 maintained the strength more than 71 MPa in all fiber content, which is only less than 4% loss of the control strength values.

3.2. Extent of spalling

Figs. 3 to 6 show the extent of spalling in concrete after fire tests. It is commonly reported in literature that high strength concretes without any mitigation method causes severe spalling in fire [14–16]. A similar result of control concrete exposed to fire is also found in this test confirming the literature. As fiber content in concrete increased, it was clear that spalling tendency decreased in all tested specimens.

Regarding the combination of different lengths of the same type of polypropylene fiber, the test results revealed that any combination with small length was not effective for spalling protection of concrete in fire (Fig. 3). This figure indicated that PP 19 without combination fully resisted spalling at 0.10% of fiber content, whereas, with the

Table 2
Mixture proportion and properties of control concrete.

W/B[a]	Unit water (kg/m^3)	S/a[b] (%)	Weight mixture (kg/m^3)					Slump flow (mm)	Air content (%)	Compressive strength (MPa)		
			C[c]	FA[d]	SF[e]	S[f]	G[g]			3 days	7 days	28 days
0.25	160	45	448	128	64	665	816	685	3.4	42.9	56.2	74.0

[a] Water to binder ratio.
[b] Sand to aggregate ratio.
[c] Cement.
[d] Fly ash.
[e] Silica fume.
[f] Sand.
[g] Gravel.

combination with the smallest length of fibers (PP 3/PP 12), severe spalling occurred even at the highest fiber content. It is important to note that, for a given fiber content, PP 3 has more than six times the number of fiber per unit volume than PP 19. For example, at 0.05% by volume of fiber content, PP 3 has 133 fibers/cm^3 while PP 19 has only 21 fibers/cm^3. From the observation of the results, it seems that the length of fiber is a dominant factor over the number of fiber per unit volume for a given fiber content. However, it has been found that, in some cases, the number of fiber can be the dominant parameter [9,10], which is why 9 mm length nylon fiber (instead of 19 mm) was chosen in this test as the optimum length. The underlying relationship of the dimensional properties of fiber is explored in detail later in this paper in the section titled ‘fiber effectiveness parameter’.

The results presented in Fig. 4 illustrate the most favorable combination of the two types of fiber for spalling protection of concrete at elevated temperature. Since PP 19 had the most efficient results in Series I, this length of PP fiber was chosen for Series II. The remarkable results were found in the combination of NY 9/PP 19. It showed no explosion taking place even at only 0.05% of fiber content. The effectiveness of this combination was confirmed by the results of the fire test in Series III. Most surprisingly, the fiber content of as small as 0.03% was a minimum requirement for the concrete containing the selected hybrid fibers (NY 9/PP 19) to resist the spalling (Fig. 5). This reduction of fiber content is approximately three times less than the content of single type of PP fiber for spalling protection.

The results of Series IV also confirmed the effectiveness of the selected hybrid fibers in concrete exposed to fire. The combination of fiber rate in Series III was 50% to 50%, and the minimum fiber requirement was 0.030%, so that the content of NY in the selected hybrid fibers was 0.015% out of 0.030%. As shown in Fig. 6, severe damage caused by spalling was found in the concrete containing NY fiber with 0.015%. The results of NY fiber with 0.030% also revealed that the resistance of concrete spalling was less favorable than the addition of the selected hybrid fibers. Hence, the hybrid fiber in concrete is more effective for spalling protection than the fibers by individual fibers at the same fiber contents. It is clear that there is a beneficial synergistic effect when fibers are combined.

3.3. Weight loss due to fire exposure

Fig. 7 shows the weight loss of specimens after the fire tests. As expected, all the results were proportional to the extent of spalling observed from the phtographs. It was noted that 20% of weight loss (including 8 to 10% of moisture loss during the fire tests) was nominated as the threshold for severe spalling of concrete, above which level the spalling is said to have occurred. The worst result was found in the control concrete indicating 74% weight loss. In Series I (Fig. 7a), all concretes containing PP 19 fiber had favorable results. The effectiveness of PP 19 was clear when compared with concretes containing 0.05% of fiber content: PP 19 recorded 33% weight loss, PP 3/PP 19 recorded 28% loss and PP 6/PP 19 recorded 55% loss, whereas rest of concretes had more than 75% weight loss. Interestingly, PP 3/PP 19 had the lowest loss at this level of fiber content whereas PP 19 indicated the lowest loss at 0.1% of fiber content followed by PP 6/PP 19. These results may be counter-intuitive. The possible reason for this behavior is that the high number of fibers even as short as 3 mm length partially contributes to spalling resistance, but it can be only shown when combined with long length of fibers. Overall, the combination of short length of PP fiber in concrete lost more weight after fire than the combination of long length.

The results of weight loss were dramatically improved by adding different types of fiber (Fig. 7b and c). Especially, NY 9/PP 19 indicated 8% of weight loss at 0.03% of fiber content, followed by 10% in NY 6/PP 19 (Fig. 7c). Both concretes appeared to mitigate spalling at a fiber content of as small as 0.02% (Fig. 7c).

3.4. Residual compressive strength after fire

Fig. 8 shows the residual compressive strength of specimens after the fire tests. Similar to the observations for spalling, the addition of NY fiber in all concretes is found to be beneficial in retaining residual strength. Among the concretes, NY 9/PP 19 was the most effective in retaining residual strength. The residual compressive strength of this specimen was 59% at 0.05% of fiber content, whereas the specimens containing other types of fibers had no strength at all left at 0.05% fiber

Table 3
Physical properties of fiber.

Type	Length (mm)	Abbreviation	Total number of fiber/cm^3 (e.g.,: content 0.05%)	Diameter (mm)	Density (kg/m^3)	Tensile strength (MPa)	Melting point (°C)
Polypropylene	3	PP 3	133	0.040	0.91	560	160
	6	PP 6	66				
	12	PP 12	33				
	19	PP 19	21				
Polyvinyl alcohol	6	PVA 6	414	0.016	1.26	1073	220
Cellulose	3	CL 3	943	0.015	1.50	488	260
Nylon	6	NY 6	737	0.012	1.15	918	220
	9	NY 9	491				

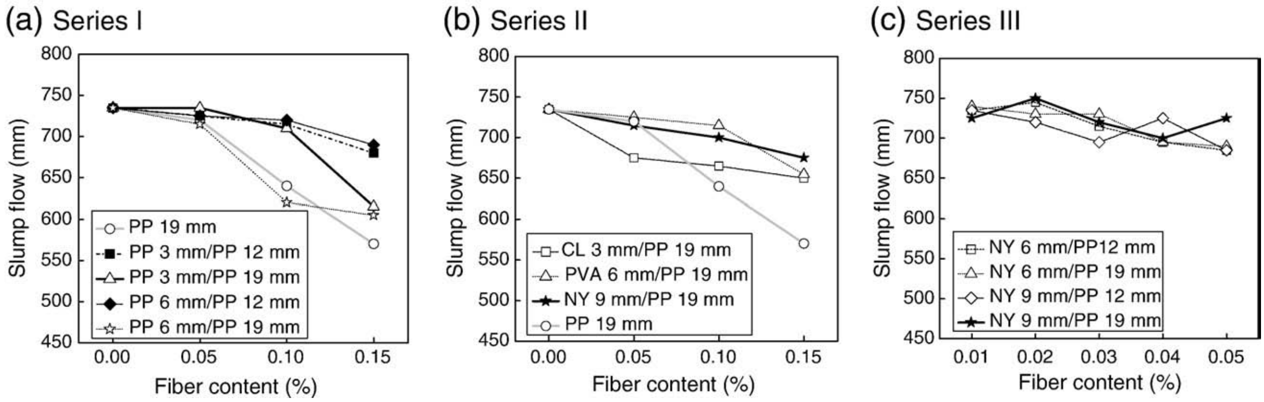

Fig. 1. Slump flow.

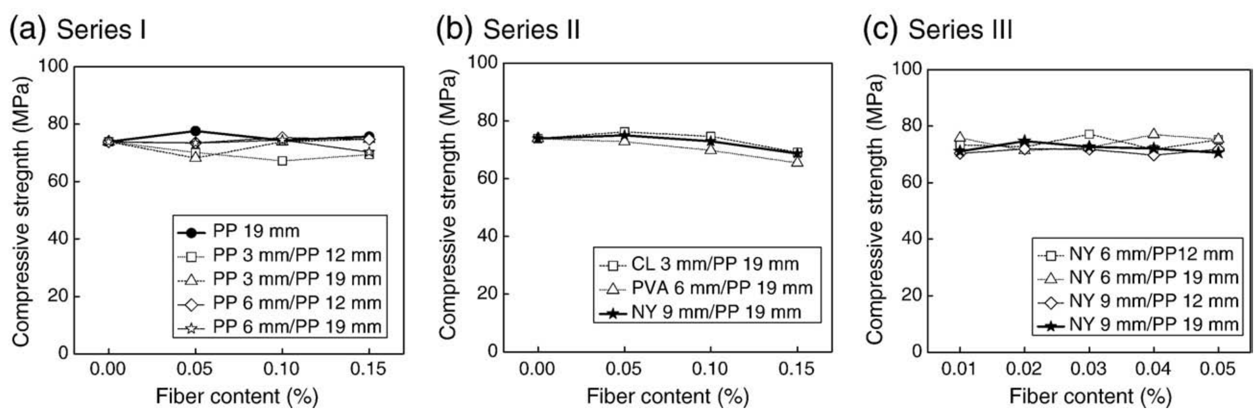

Fig. 2. Compressive strength.

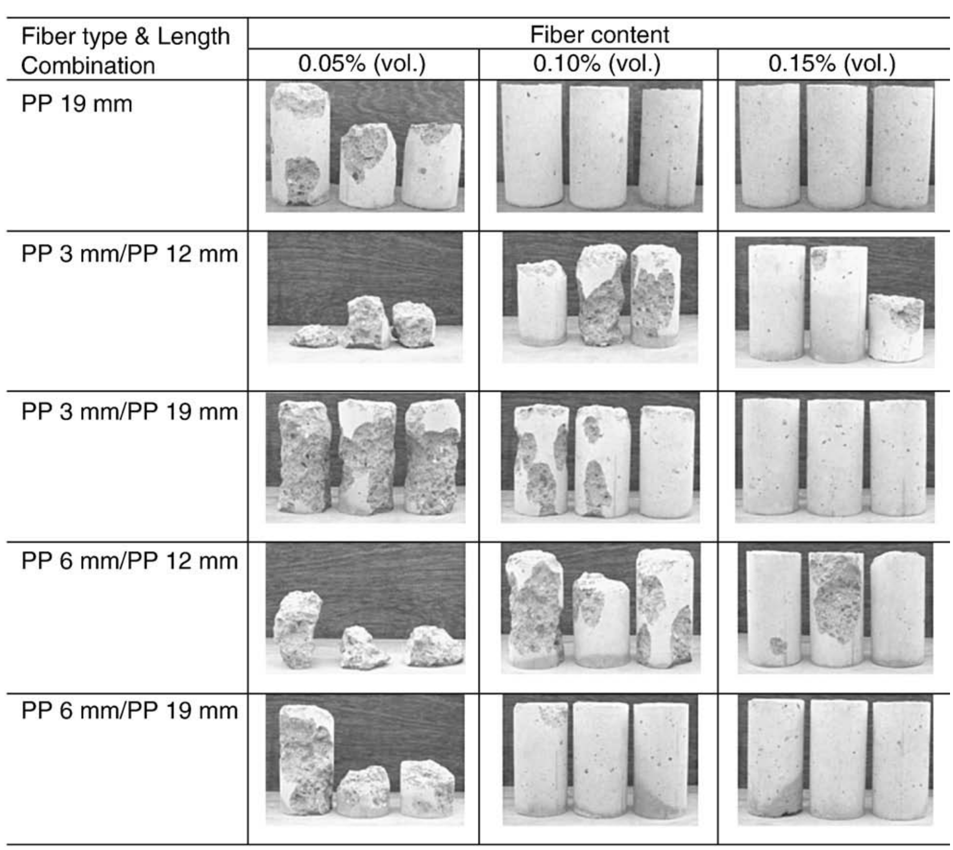

Fig. 3. Extent of spalling (Series I).

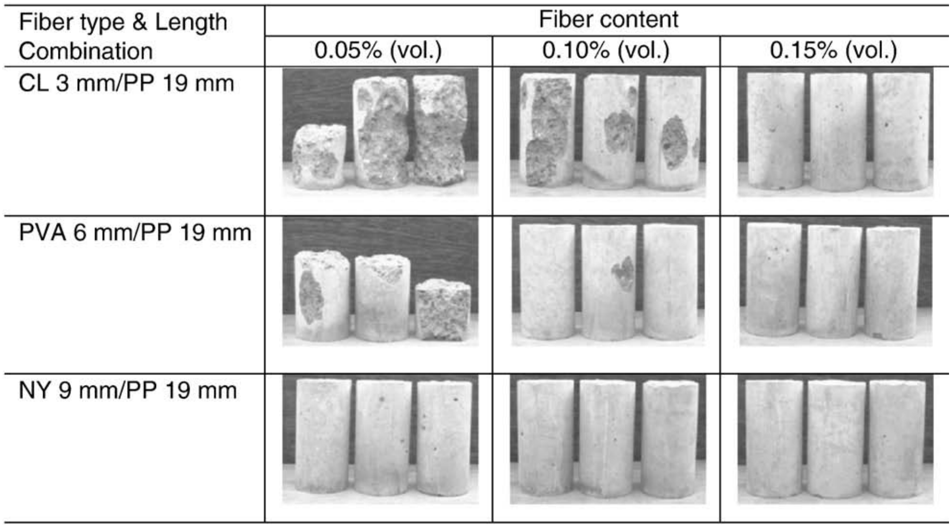

Fig. 4. Extent of spalling (Series II).

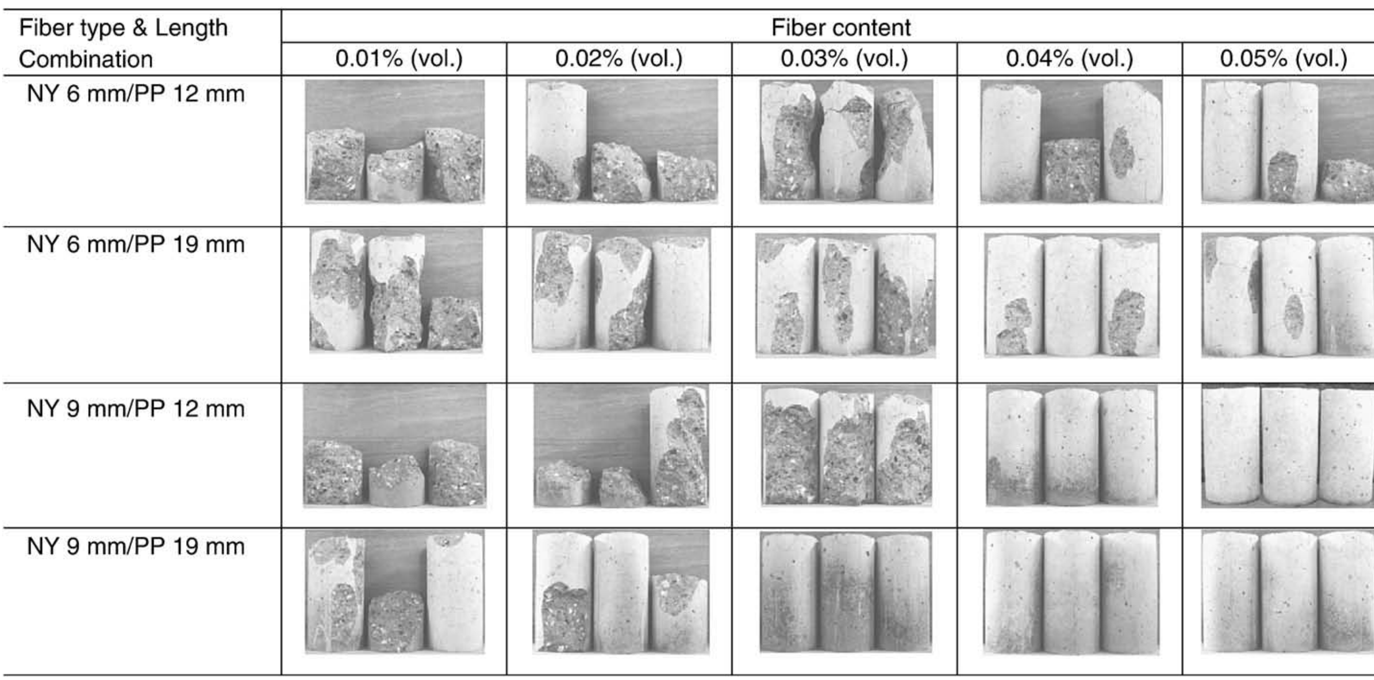

Fig. 5. Extent of spalling (Series III).

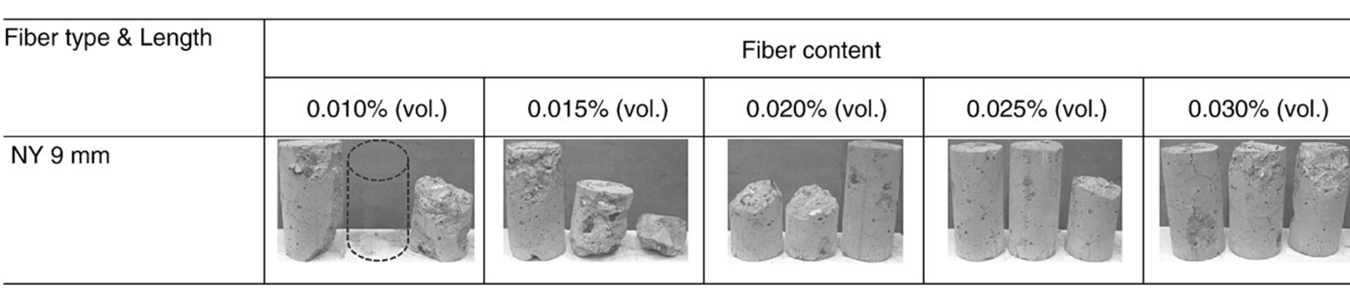

Fig. 6. Extent of spalling (Series IV).

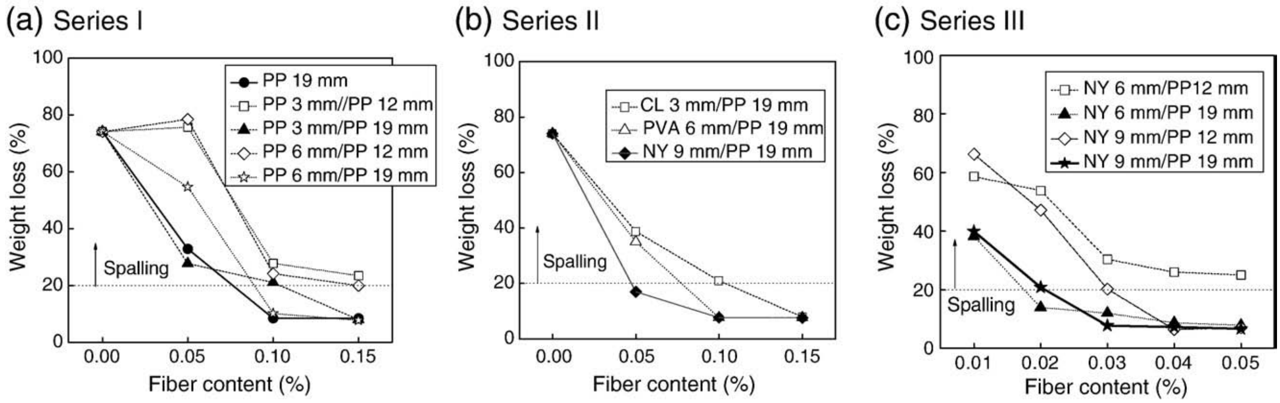

Fig. 7. Weight loss after fire exposure.

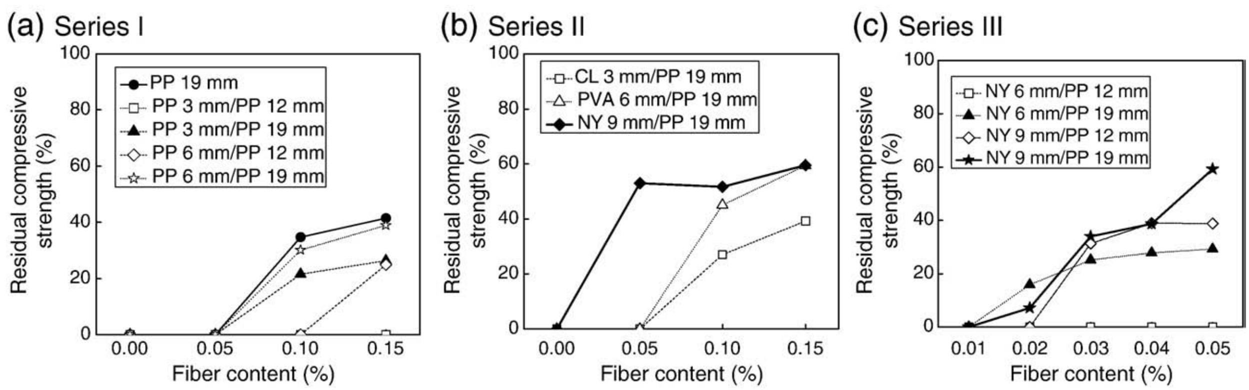

Fig. 8. Residual compressive strength.

content level. While the values of most specimens started to have some residual strength (more than zero strength) at 0.10%, that of specimens containing NY started to have non-zero strength at 0.02%.

4. Fiber effectiveness parameter

In order to understand the spalling mechanism with fiber addition, the fiber length (L) and total number of fiber per unit volume (N) should be considered at the same time for the connectivity of pores in concrete. N.L is the total length of fiber network per unit volume. While the total length (NL) is an important parameter, the individual length of fiber is also an important parameter. It can be imagined that if the individual length (L) is extremely small, the fiber would not be effective, even if the total length remains the same. Hence, the fiber length (L) should have a higher representation in a fiber effectiveness parameter than what is represented in total length (N.L). Hence, a fiber effectiveness parameter in the form of NL^x was trialled. The x values based on best-fit was found to be in the range of 2.7 to 3, regardless of the type of fibers. Since $N.L^3$ is a unit-less parameter, it is proposed that this parameter can be used as the fiber effectiveness parameter.

Fig. 9 shows the summary of the weight loss versus NL^3 for all the different fibers tested. The best-fit curves for PP, NY and hybrid (NY + PP) based on power function are shown. The degree of spalling is numerically represented by weight loss, with higher the weight loss, the higher the degree of spalling. This correlation is confirmed by visual observation of degree of spalling shown in Figs. 3 to 6 and the weight loss values. It is also confirmed that when the weight loss is less than about 20%, minor or no spalling was observed. This is due to the fact that up to about 10% moisture loss occurred in most specimens.

As can be seen in Fig. 9, for the same NL^3, the PP fiber is more effective than NY fiber. This is because the PP fiber melting point is 160 °C as compared to NY fiber has a melting point of 220 °C. Only three fiber combinations of CL + PP and three of PVA + PP were tested, hence trend lines were not drawn for these data. However, it can be seen that they fit within the general trend, despite being different type of fibres. The combined NY + PP trend curve do not lie between the NY and PP results, as would be expected. For the same NL^3, the combined NY + PP fibers provide better results than NY or PP.

Nylon (NY) fiber is available in smaller diameters than PP fibers, hence can make up large N for the same fiber content by volume. This leads to a better performance at a lower dosage making nylon more economical for spalling protection of concrete in fire. However, one disadvantage of nylon fiber is high melting point. Although it was reported that the melting point of fibers below 200 °C does not improve the spalling protection of concrete in fire [17], the melting

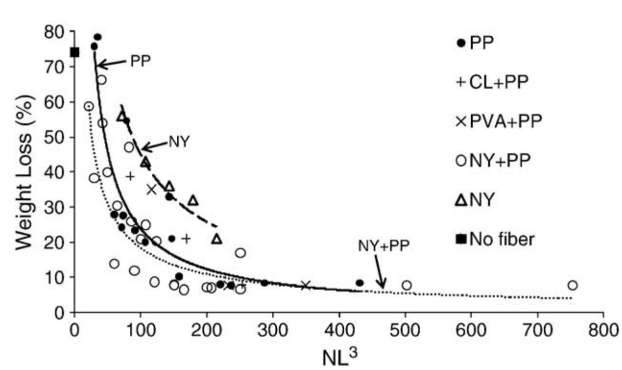

Fig. 9. Weight loss as a function of NL^3.

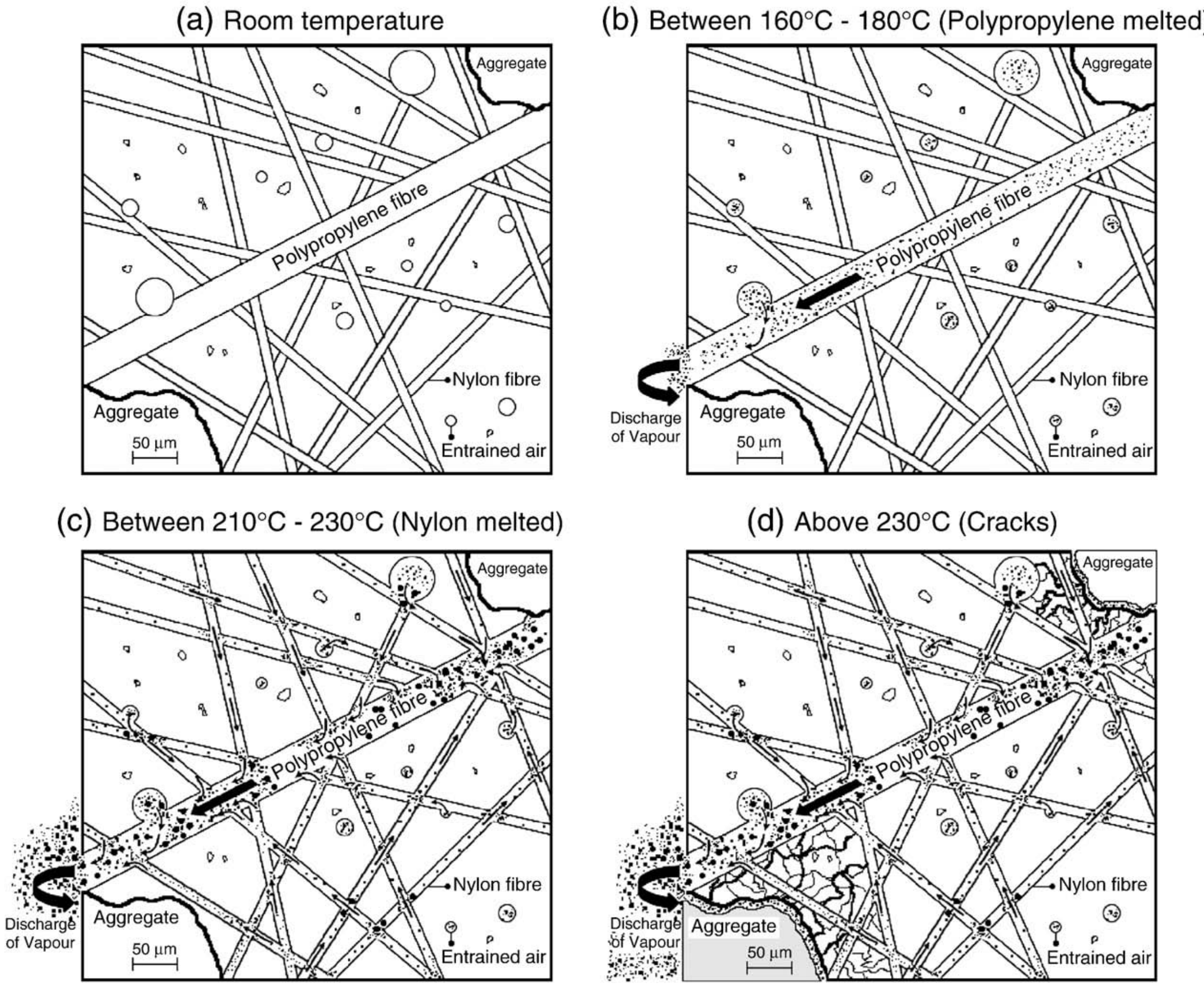

Fig. 10. Pathways for vapor discharge by hybrid fibers melting at different temperatures.

points above 200 °C significantly reduces the effectiveness of the fibers. This is because spalling occurs in temperatures between 200 and 250 °C [2,5], and the melting point of fiber determines the temperature at which the pressure relief of vapor would occur. This disadvantage of nylon fiber can be offset by the combination of polypropylene fiber which has lower melting point, and can release some vapor pressure prior to the melting of nylon fiber.

Fig. 10 shows the overall idea of how a synergistic effect of the combination (nylon + polypropylene) plays a crucial role in providing effective connections of pores in concrete at different thermal conditions. When the concrete is exposed to fire, firstly polypropylene fiber melts at 160 °C and provides wide and long channels (Fig. 10b). These channels connect to some of pre-existing pores, such as air and capillary, and allow vapor to escape, which helps concrete to reduce vapor pressure at early stages. Secondly, when temperature inside the concrete reaches 220 °C, nylon fiber melts and creates large number of small size pores (Fig. 10c). It should be noted, at the same fiber content by volume with the optimum length of each fiber (nylon: 9 mm and polypropylene: 19 mm), nylon fiber would make 23 times higher number of channels than that of polypropylene fiber, which is critical to improve spalling protection with low content of fiber. Further, there are cracks induced by thermal incompatibility of aggregates and cement paste. This also helps vapor released at the last stages, so the rest of vapor remained in other pores can be discharged (Fig. 10d). The addition of 0.03% of hybrid fibers of NY with 9 mm and PP with 19 mm demonstrates the synergistic effect explained above for spalling protection of concrete in fire. The synergy is evident when the comparison is made with individual additions of 0.03% of 19 mm PP or 0.03% of 9 mm NY, the results showed that the spalling protection was not achieved.

5. Conclusions

This study investigated the effect of hybrid fibers on workability and spalling protection of high strength concrete. The following conclusions are drawn:

1. The study found that there is the optimum level of fiber properties for spalling protection of concrete in fire, which can be expressed by critical parameters such as total number of fiber, length of fiber, and melting point of fiber. This study suggests that the combination of different types, lengths and diameters of fibers can be best accessed to the optimum level of fiber properties. For a given fiber content, the combination of 9 mm length nylon and 19 mm length polypropylene fibers achieved the highest level of given criteria (= fiber effectiveness parameter), which in turn require the smallest fiber content for spalling protection.
2. The combination of nylon and polypropylene fibers takes a synergistic effect on spalling protection, which is evidenced by the fact that spalling is resisted even with lower values than the minimum threshold of given criteria.
3. In terms of providing connections between pores, total number of fibers per unit volume is critical. The higher the number of fiber, the more is the chance for the connections between pores. Smaller diameter fibers are better since they can achieve higher number of

fibers per unit volume with the same fiber contents of fiber by volume.

4. As for the properties of workability for a given fiber content (by volume), the results are independent of total number of fiber per unit volume. It is the type of fiber and length of fiber that are important. Hence, either addition of polypropylene fiber or combination of long length of fibers caused dramatic loss of workability. However, the deteriorative results of polypropylene fiber addition can be offset when combined with nylon fiber. This combination showed no loss of workability with increasing fiber content until the fiber content reaches 0.05%.
5. Although the combination of short length of fibers in concrete is beneficial for workability, it is not efficient for spalling protection in fire. Only sufficiently long length of fiber (individual fiber length: at least 9 mm) can play a role in providing connections for vapor release.

Acknowledgement

The work presented in this paper was funded by Center for Concrete Corea (05-CCT-D11), supported by Korea Institute of Construction and Transportation Technology Evaluation and Planning (KICTTEP) under the Ministry of Construction and Transportation (MOCT) and also funded by Monash Graduate Scholarship (MGS) from Monash University.

References

[1] C.G. Han, Fire Resistant Performance of High Strength Concrete, 1st International Workshop on Improvement of Fire Resistance on High Strength Concrete, Center for Concrete Corea, Seoul South Korea(March 2009) 35–74.
[2] J.G. Sanjayan, L.J. Stocks, Spalling of high-strength silica fume concrete in fire, ACI Mater. J. 90 (March–April 1993) 170–173.
[3] P. Kalifa, F.D. Menneteau, D. Quenard, Spalling and pore pressure in HPC at high temperatures, Cem. Concr. Res. 30 (2000) 1915–1927.
[4] V.K.R. Kodur, F.P. Cheng, T.C. Wang, Effect of strength and fiber reinforcement on the fire resistance of high strength concrete columns, ASCE J. Struct. Eng. 129 (2003) 253–259.
[5] L.T. Phan, N.J. Carino, Effects of test conditions and mixture proportions on behavior of high-strength concrete expose to high temperature, ACI Mater. J. 99 (January–February 2002) 54–66.
[6] A. Noumowe, Mechanical properties and microstructure of high strength concrete containing polypropylene fibers exposed to temperature up to 200 °C, Cem. Concr. Res. 35 (2005) 2192–2198.
[7] C.G. Han, S.H. Yang, M.C. Han, C.C. Pei, Spalling prevention of high strength concrete with 60–100 MPa of the compressive strength corresponding to addition of polypropylene fiber, Archit. Inst. Korea 24 (2008) 91–98.
[8] P.S. Song, S. Hwang, B.C. Sheu, Stregnth properties of nylon- and polypropylene-fiber-reinforced concretes, Cem. Concr. Res. 35 (2005) 1546–1550.
[9] Y.S. Heo, Influential factors on fire resistance performance of ultra high strength concrete and mechanism models of spalling phenomenon. Master thesis, Cheongju University Korea 2006.
[10] Y.S. Heo, J.G. Sanjayan, C.G. Han, M.C. Han, Effect of Fiber Type, Length and Numbers of Fibers per Unit Volume on Spalling Protection of High Strength Concrete, 1st International Workshop on Concrete Spalling Due to Fire Exposure, MFPA Institute Leipzig, Leipzig Germany (September 2009) 211–220.
[11] D.P. Bentz, Fibres, percolation, and spalling of high-performance concrete, ACI Mater. J. 97 (2000) 351–359.
[12] P. Kalifa, G. Chene, C. Galle, High-temperature behaviour of HPC with polypropylene fibers from spalling to microstructure, Cem. Concr. Res. 31 (2001) 1487–1499.
[13] Ministry of Land, Transport & Maritime Affairs, Concrete standard specification chapter 8 high fluidity concrete, South Korea (2009) 111–118.
[14] L. Phan, Spalling and Mechanical Properties of High Strength Concrete at High Temperature, Proceedings Concrete under Severe Conditions, Consec'07, Paris France (June 2007) 1595–1608.
[15] C.G. Han, Y.S. Hwang, S.H. Yang, N. Gowripalan, Performance of spalling resistance of high performance concrete with polypropylene fiber contents and lateral confinement, Cem. Concr. Res. 35 (2005) 1747–1753.
[16] C.G. Han, M.C. Han, Y.S. Heo, Improvement of residual compressive strength and spalling resistance of high-strength RC columns subjected to fire, Constr. Build. Mater. 23 (2009) 107–116.
[17] I. Knack, New PP-fiber with Exceptional Melting Characteristics for Improved Fiber Protection in Concrete Building, 1st International Workshop on Concrete Spalling Due to Fire Exposure, MFPA Institute Leipzig, Leipzig Germany (September 2009) 238–247.