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Article

Effects of Mixing Sequence of Polypropylene Fibers on Spalling Resistance of Normal Strength Concrete

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Abstract. This paper presents an experimental study on the spalling resistance of normal strength concrete with different mixing sequences of polypropylene (PP) fibers subjected to fire. The mixing sequences of PP fibers in concrete mixture investigated are: (1) mixing PP fibers with fresh concrete; (2) mixing PP fibers with coarse aggregates; and (3) mixing PP fibers with fine aggregates. According to the test results, the degree of concrete spalling is reduced for specimens containing PP fibers at 0.2% by volume in the concrete mixture. The beneficial effect on spalling resistance is maximized when the PP fibers are mixed with fresh concrete and when the PP fibers are mixed with fine aggregates. The results are confirmed using scanning electron microscope (SEM) to investigate the dispersion of PP fibers in hardened concrete. In the case of mixing PP fibers with fine aggregates, smaller amount of superplasticizer is needed to obtain the target slump, and it is therefore recommended for practical use.

Keywords: Concrete spalling, fire, mixing sequence, polypropylene fibers.

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1. Introduction

A critical function of structures in the event of fire is to maintain their stability and strength for a suitable time to ensure life safety and property protection. Concrete has been considered a leading structural material in terms of fire resistance. However, at high temperatures concrete material tends to have micro-structural changes and internal stresses that alter its mechanical properties which lead to a decrease in load-bearing capacity and an increase in deformation of concrete members.

At elevated temperatures, a number of complex phenomena in concrete elements can occur simultaneously. These include heat conduction and convection, transport of liquid water and gases, dehydration of cement paste, evaporation of liquid water in pores and thermal expansion of the solid skeleton. These processes will lead to the build-up of pore pressures and of thermally induced stresses inside the concrete elements resulting in fracturing and loss of material from the surface of the concrete elements known as spalling [1]. Two factors that contribute to the occurrence of concrete spalling exposed to fire are pressure build-up and restrained thermal dilatation [2-3]. The build-up of pore pressure gradient in concrete is close to the heating surface, causing tensile loading of the microstructure of the heated concrete. The restrained thermal dilatation results in compressive stresses parallel to the heated surface causing tensile stresses in the perpendicular direction.

Spalling is not only defined as damage and fall-off of concrete from the surface but also as explosion that occurs when the concrete structures are subjected to high temperatures [4-6]. The occurrence of explosive spalling is due to high pore pressure build-up in dense concrete, creating effective tensile stresses in excess of the tensile strength of the concrete [7].

Concrete spalling is influenced by many factors including concrete strength, age and permeability, heating rate and profile, section size and shape, type and size of aggregate, moisture content, the presence of cracks, reinforcement and imposed loading [8].

Previous studies have shown that polypropylene (PP) fibers can increase spalling resistance of concrete. This is because PP fibers melt at a relatively low temperature of 170°C, creating more porosity by leaving cavities through which the vapor pressure can escape [9]. The amount of PP fibers needed to minimize spalling in concrete under fire condition ranges between 0.05-0.2% (by volume) [10-15].

The dispersion of PP fibers in hardened concrete is considered crucial for effective release of the internal vapor pressure at high temperature. Thus far, investigation on the mixing sequence to ensure a thorough distribution of PP fibers in the concrete mixture is scarce. This study is aimed to examine the effects of mixing sequence of PP fibers in the concrete mixture on spalling resistance of normal strength concrete subjected to fire. The mixing sequences investigated are: (1) mixing PP fibers with fresh concrete; (2) mixing PP fibers with coarse aggregates; and (3) mixing PP fibers with fine aggregates. The dispersion of PP fibers in hardened concrete specimens is also investigated using scanning electron microscope (SEM).

2. Experimental Investigation

2.1. Design of Experiment

The experimental details of this study are shown in Table 1. The mixture proportion of concrete was determined to satisfy compressive strength of 20 MPa (cubes) at 10 hours and target slump of 15±2.5 cm for precast structures. The water/cement ratio used was 0.4 while varying PP fiber mixing ratios of 0% and 0.2% by volume were used. The mixing sequence varied from mixing PP fibers with fresh concrete, coarse aggregates and fine aggregates through incorporating each material into the concrete mixture in different orders as shown in Table 1. The properties of fresh concrete and hardened concrete measured, mixing sequences and mixture proportions of concrete are shown in Tables 1 and 2, respectively. Note that the superplasticizer/cement ratios used were in incremental trial of 0.5% until the target slump was reached.

2.2. Materials

The physical properties of each material are presented in Tables 3-6. The cement used in this study is a Portland cement (type 3) produced in Thailand. Chao Phraya river sand produced in Central region of Thailand is used as fine aggregates. The crushed limestone with a maximum size of 20 mm is used as coarse aggregates. The main composition of the superplasticizer used is melamine sulfonate and PP fibers were provided by Siam Gabions Co., Ltd.

Table 1. Design of experiment.

Parameters			Properties Measured	
w/c	**PP fiber (% by volume)**	**Mixing sequence**	**Fresh concrete**	**Hardened concrete**
0.4	0	• Plain concrete (CT1: ca→fa→c→w→sp)	• Slump	• Compressive strength • Fire resistance test • Weight reduction ratio • SEM
	0.2	• Mixing PP fibers with fresh concrete (CT2: ca→fa→c→w→PP→sp) • Mixing PP fibers with coarse aggregates (CT3: ca→PP→fa→c→w→sp) • Mixing PP fibers with fine aggregates (CT4: fa→PP→ca→c→w→sp)		

Note: ca: coarse aggregates, fa: fine aggregates, c: cement, w: water, sp: superplasticizer, PP: polypropylene fibers.

Table 2. Mixture of concrete.

w/c (%)	Water Content (kg/m³)	PP fiber (% by volume)	sp/c (%)	Absolute Volume Mix (l/m³)				Weight Mix (kg/m³)			
				c	fa	ca	PP	C	fa	ca	PP
40	155	0/0.2	1.5/2.5	119	362	345	0/2.0	375	941	959	0/1.8

sp/c: superplasticizer/cement ratio.

Table 3. Physical properties of cement.

Specific Gravity	Setting Time (min)	
	Initial setting	Final setting
3.15	90	130

Table 4. Physical properties of aggregates.

Type	Specific Gravity	Fineness Modulus	Absorption Ratio (%)	Unit Weight (kg/m³)	Passing 4.75 mm Sieve (%)
Fine aggregate	2.60	3.18	0.65	1792	94.0
Coarse aggregate	2.78	2.28	0.37	1640	5.4

Table 5. Physical properties of admixture.

Type	Main Composition	Form	Color	Specific Gravity at 25°C
Superplasticizer	Melamine sulfonate	Liquid	Dark brown	1.185-1.200

Table 6. Physical properties of PP fibers.

Type	Specific Gravity	Length (mm)	Diameter (μm)	Tensile Strength (MPa)	Melting Point (°C)
Mono-filamentary polypropylene	0.91	12	34	554	160-170

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2.3. Test Method

Concrete was mixed in a forced circulating pan mixer (MATEST C165, 1 HP motor power). In order to investigate dispersion of fibers, different mixing sequences were carried out as shown in Table 1. CT1 represents plain concrete, while for CT2 PP fibers were added after preparing fresh concrete. Note that the superplasticizer was used at the last step in order to achieve the target slump. For CT3 and CT4, dry mixing was carried out with PP fibers introduced after coarse aggregates and fine aggregates, respectively. For all of the mixing sequences investigated, PP fibers were gradually added to the concrete mixture and the mixing time of each step was set at a minimum of 180 seconds to ensure thorough mixing of materials. Based on preliminary tests, PP fibers show high water absorption rates (up to 80%) depending on the apparent saturation level. Therefore, PP fibers were prepared in saturated surface dry (SSD) condition to avoid altering the designated water content for the concrete mixture. The coarse aggregates and fine aggregates for each concrete mixture were also prepared in SSD condition.

Slump test was conducted according to ASTM C143 [16]. Hardened concrete specimens were fabricated in 150x150x150 cm cubes in accordance with BS EN 12390-1 [17]. The specimens used for compressive strength test were cured in air, covered with dampened cloth for 10 hours. The specimens used for the fire resistance test were cured by the same method for 28 days. The compressive strength test was carried out according to BS EN 12390-3 [18]. After the compressive strength test, small samples of concrete specimens (approximately 20 mm in diameter) were also randomly taken for SEM inspection. The SEM was used to observe dispersion of PP fibers in hardened concrete with magnification in the range of 15x, 50x and 75x and scale in the range of 100 μm, 500 μm and 1 mm.

As for the fire resistance test, concrete specimens were heated in a gas-fuelled furnace (see Fig. 1) at Fire Safety Research Center (FSRC), Chulalongkorn University, in accordance with standard heating curve of ISO 834-1 [19] for 45 minutes as shown in Fig. 2. Each specimen was exposed to heat on four sides, with top and bottom surfaces protected by 20 mm thick insulating ceramic fiber blankets (see Fig. 3). After the fire resistance test, spalling was visually inspected, and the weight reduction ratio was calculated by comparing the weight of specimens before and after the fire resistance test.

Fig. 1. Gas-fuelled furnace at Fire Safety Research Center (FSRC).

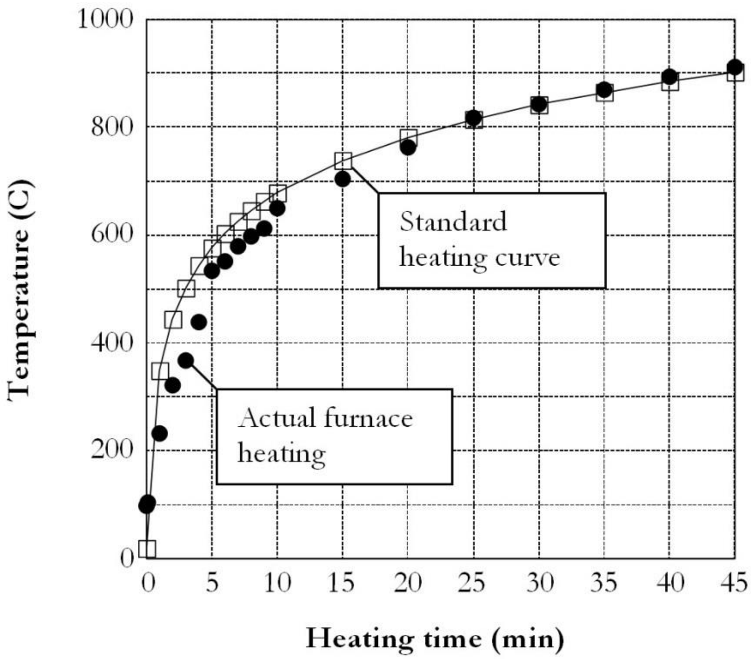

Fig. 2. Standard heating curve and actual temperature curve of testing furnace.

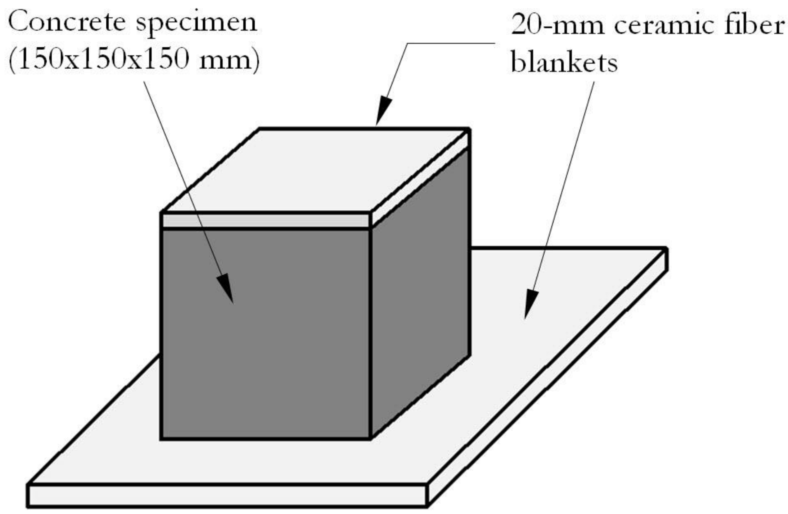

Fig. 3. Specimen protection for fire resistance test.

3. Results and Discussions

3.1. Properties of Fresh and Hardened Concrete

Table 7 shows slump with the variation of PP fiber mixing sequence. With PP fibers of 0.2% by volume in the concrete mixture, fluidity slightly decreased. The amount of superplasticizer used to obtain the target slump of 15±2.5 cm increased when compared to the mixture without any PP fibers except when PP fibers were mixed with fine aggregates (CT4).

Table 7 also shows compressive strength of concrete with different mixing sequences, considering compressive strength of plain concrete as the reference. With the presence of PP fibers, compressive strength of concrete is not significantly improved. Variation of compressive strength is marginal for different mixing sequences.

Table 7. Physical properties of concrete.

Specimen Series	sp/c (%)	Slump (cm)	Compressive Strength at 10 hours (MPa)
CT1	1.5	12.5	25.5
CT2	2.5	12.5	26.6
CT3	2.5	12.5	25.1
CT4	1.5	17.5	25.5

3.2. Properties of Spalling and Dispersion of PP Fibers

Figure 4 shows spalling of specimens and the weight reduction ratio after fire resistance test in which the variation of the weight reduction ratio (WRR) for each concrete mixture is also provided. Moderate spalling occurs in the case of plain concrete. When the concrete mixture contained PP fibers, degree of spalling was reduced as evident from smaller weight reduction ratios. The weight reduction is below 10% when PP fiber is mixed in quantities of 0.2% by volume. This result is in line with previous studies [11, 20] which explained that vapor pressure is relieved as PP fiber in concrete melts at the high temperature (at about 160-170°C).

As for the spalling resistance with mixing sequences, smallest weight loss occurs when PP fiber is mixed with fresh concrete (CT2) and when PP fiber is mixed with fine aggregates (CT4). Figures 5-7 show images of dispersion of PP fiber in concrete using SEM. Local concentration of PP fibers is observed for the mixture which PP fiber is mixed with coarse aggregates (CT3), while thorough distribution of fiber is observed for other mixtures. The SEM results confirm dispersion of PP fibers in the concrete mixture with high spalling resistance.

4. Conclusions

An experimental study was conducted to examine the spalling resistance of normal strength concrete with different mixing sequences of PP fibers subjected to fire. Based on the test results, moderate spalling (with weight reduction above 10%) occurs in the case of plain concrete which does not contain PP fiber. Spalling resistance increases when PP fiber (in SSD condition) is mixed in quantities of 0.2% by volume in the concrete mixture.

The most effective spalling resistance occurs when PP fiber is mixed with fresh concrete and when PP fiber is mixed with fine aggregates as observed from smallest weight reduction. The result is confirmed by using SEM to investigate dispersion of PP fiber in hardened concrete. Local concentration of PP fibers is observed for the mixture which PP fiber is mixed with coarse aggregates. Variation of compressive strength is marginal for different mixing sequences. However, smaller amount of superplasticizer is needed to obtain the target slump of 15±2.5 cm in the case of mixing PP fibers with fine aggregates. Therefore, the mixing sequence recommended for practical use is to mix PP fibers in SSD condition with fine aggregates. However, since dry mixing of PP fibers with aggregates may occasionally cause fiber breakage, care should be taken by gradually mixing PP fibers into the concrete mixture.

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Specimen Series	Weight Reduction Ratio (%)	Spalling		
		A	B	C
CT1	13.2	 WRR =14.0%	 WRR =14.4%	 WRR =11.2%
CT2	6.9	 WRR =7.3%	 WRR =6.2%	 WRR =7.2%
CT3	8.2	 WRR =9.2%	 WRR =7.3%	 WRR =8.1%
CT4	6.9	 WRR =6.3%	 WRR =7.3%	 WRR =7.1%

Fig. 4. Spalling and weight reduction of specimens after fire resistance test.

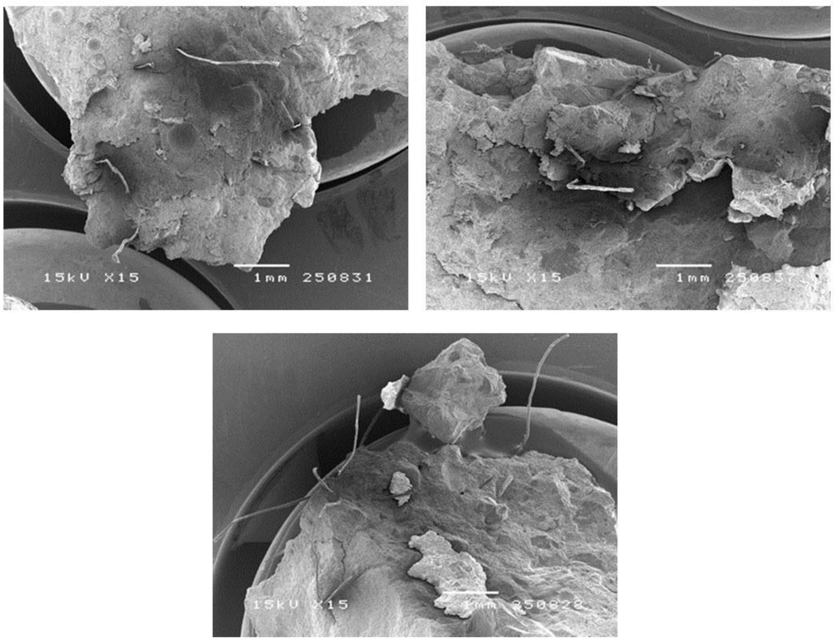

Fig. 5. SEM images of dispersion of PP fiber in CT2 specimens.

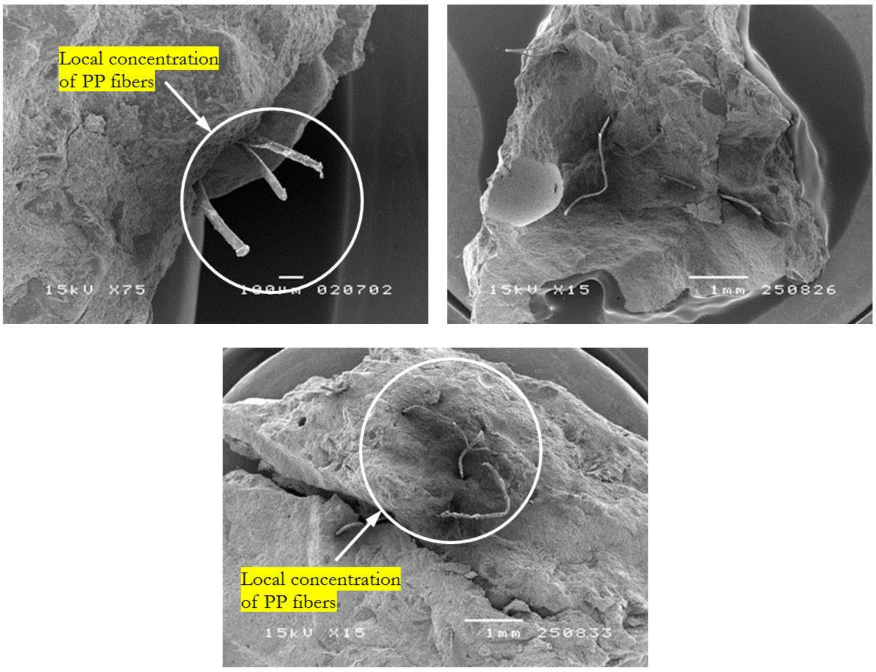

Fig. 6.   SEM images of dispersion of PP fiber in CT3 specimens.

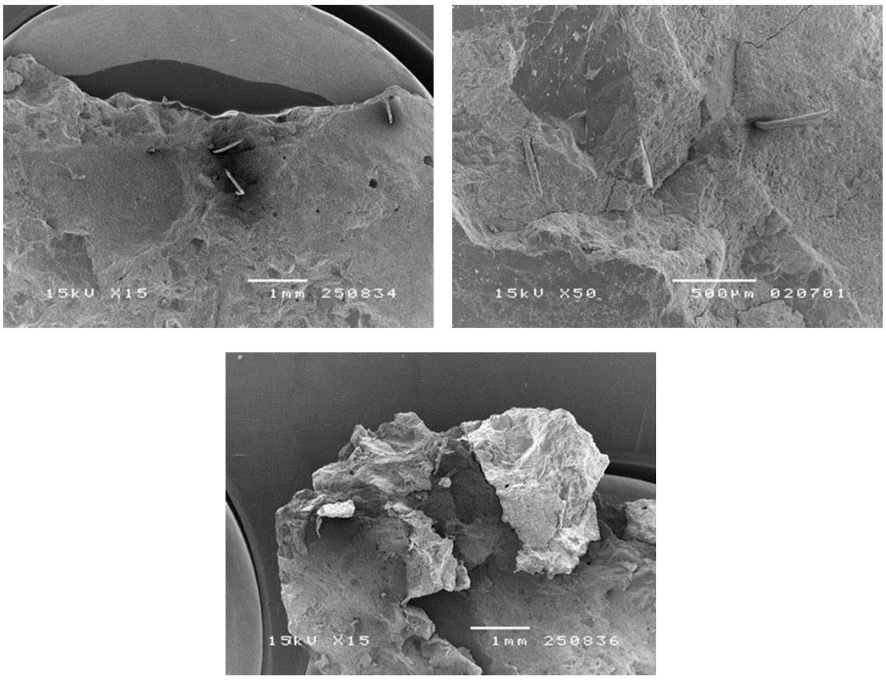

Fig. 7.   SEM images of dispersion of PP fiber in CT4 specimens.

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