-Technical paper-

PERMEABILITY OF HEATED FIBER REINFORCED HIGH STRENGTH CONCRETE

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ABSTRACT: Explosive spalling has been observed as a common failure mechanism of high strength concrete under high temperature. This behavior is closely related to the very dense concrete matrix associated with high strength concrete. Recently, addition of polypropylene fibers has been found quite successful in mitigating this kind of failure mechanism. As heating increases, fibers in the matrix will start to melt at 160-170ºC providing more space in which moisture vapor accumulate at lower pressure. This paper presents the correlation between heated fiber reinforced concrete with its water permeability coefficient.
KEYWORDS: explosive spalling, water permeability coefficient, fiber reinforced concrete, fiber volume fraction, steel fiber, and polypropylene fiber

1. INTRODUCTION

By improving the concrete properties, discrete fibers have gained popularity as one reinforcement alternative in concrete technology field. From the viewpoint of mechanical properties, fibers greatly improve concrete “ductility” in addition to improving its impact resistance, fatigue properties and abrasion resistance [1]. From the viewpoint of durability, fiber reinforced concrete (FRC) to some degree also shows better performance comparing to plain concrete since fibers arrest cracks inside the concrete. As widely known that some deterioration mechanisms inside the concrete (i.e. corrosion, chemical attacks, etc) happened as water permeates through cracks, fibers cracks arresting ability would serve as countermeasure preventing water permeation through cracks. As a result, concrete durability will be enhanced permitting longer service life of structure.

Meanwhile, according to some research, high strength concrete (HSC) specimens are prone to explosive spalling due to exposure to elevated temperature in some cases. One particular example can be seen when fire accident happened in the Channel Tunnel connecting England and France in 1996. Explosive spalling failure mechanism is believed to be caused by the dense hardened cement paste (HCP) closely relating to HSC that prevents moisture vapor from escaping hence developing significant pore pressure in the case of HSC subjected to high temperature. Another possibility is related to the large thermal stresses encountered inside the concrete under elevated temperature condition [2].

In recent time, addition of synthetic fibers is considered as one feasible method to alleviate the effect of high temperature on HSC. Usage of polypropylene fibers with approximately 0.2% volume fraction has been reported to be able to reduce spalling and cracking on HSC subjected to high temperature [3]. As heating increases, synthetic fibers in the cement matrix will start melting at 160-170°C and hence increase total pore area. This melting effect

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mitigates the explosive spalling as it provides pore space in which moisture vapor can accumulate at lower vapor pressure. This paper presents the effect of fiber reinforcement on permeability of HSC under high temperature condition.

2. EXPERIMENTS

2.1 SPECIMENS

In this research, total of 11 series of cylindrical concrete specimens were cast using normal portland cement, river aggregate, and river sand. All series had the same concrete mix proportions: w/c of 25%, water content of 175 kg/m^3, and s/a of 50%. Superplasticizer and air entraining agent were used accordingly to achieve desired workability and air content of fresh concrete mix. The main differentiation between each series laid on the fibers. This included fiber material, length, and volume fraction. Specimens were cured 28 days for the first batch and 1 year for the second under water at 20±2°C. Table 1 and table 2 present the properties of fibers and mix proportion respectively.

Table 1. Properties of fibers

Fiber material	Length (mm)	Shape	Denier	Effective diameter (mm)	Aspect ratio (l/d)	Specific gravity
Steel	30	Indent-Straight	-	0.56	54	7.8
Polypropylene	12	Monofilament	350	0.25	48	0.9
	30	Fibrillated	20	0.06	500	
	38				633	

Table 2. Mix proportion

Specimen	Fiber percentage	Curing term	Flow slump	Air (%)
Plain	0	28 days	310	4.9
PFRC-M12-0.25	0.25		490	4.6
PFRC-M12-0.5	0.5		560	4.6
PFRC-M38-0.25	0.25		560	5.2
PFRC-M38-0.5	0.5		375	5.5
PFRC-M30-0.25	0.25	1 year	300～500	5～7
PFRC-M30-0.375	0.375			
PFRC-M30-0.5	0.5			
SFRC-M30-0.25	0.25			
SFRC-M30-0.375	0.375			
SFRC-M30-0.5	0.5			

After designated curing time elapsed, prepared specimens from each series were heated using electric furnace to reach peak temperature of 200°C and 400°C with heating rate of 10°C per minute. Specimens were heated for two hours at peak temperature and then let to cool down naturally in the furnace hence avoiding cracks induced upon cooling. This condition was prolonged until the specimens reached room temperature and ready for testing.

2.2 PERMEABILITY TEST (OUTPUT METHOD)

The heated specimen was then set inside the permeability test apparatus as shown in figure 1 and filled with de-aired water. Next day, pressure was applied to let water permeate through the specimen followed with some intervallic readings of water outflow. The reading was continued until water outflow had reached its steady state flow.

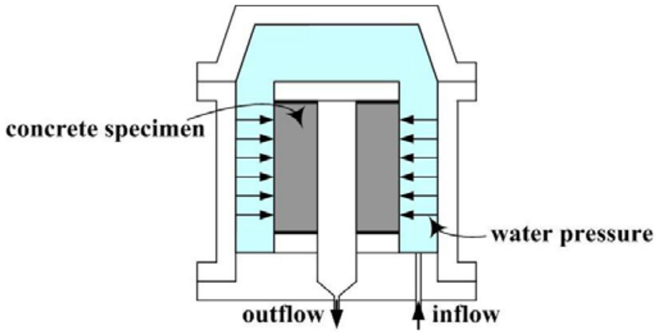


Figure 1. Permeability test apparatus

3. RESULTS AND DISCUSSION

Explosive spalling was observed within the temperature range of 350-400°C for plain HSC with the occurrence percentage of 30%. On the other hand, no explosive spalling was observed in the specimen containing fiber.

Water permeability coefficient of specimens was calculated based on the well-known Darcy's formula assuming water flow to be continuous and laminar through the concrete.

$$\frac{dq}{dt} = kA\frac{\Delta h}{L} \quad (1)$$

where: *dq/dt*: rate of water flow (m^3/s), *k*: water permeability coefficient (m/s), *A*: specimen cross section (m^2), Δh: drop in hydraulic head (m), and *L*: specimen thickness (m)
as for this particular output method, the equation becomes:

$$k = \frac{\rho \; ln\left(\frac{r_o}{r_i}\right)}{2\,\pi\,h}\,\frac{Q}{P} \quad (2)$$

where, ρ: water density (kgf/m^3), r_o: specimen radius (m), r_i: central hole radius (m), *Q*: water outflow (m^3/s), *h*: specimen height (m), and *P*: water pressure (kgf/m^3).

The water permeability coefficient of each series and its difference to plain concrete as control specimen is shown in table 3. For comparison, water permeability test result of unheated specimen is also given [4].

As can be seen in this table, water permeability of heated concrete increases tremendously compared to the non-heated concrete (20°C). Considering having the same cracks due to initial hydration, significant difference of water permeability between heated and non-heated concrete might be caused by the increase in capillary pore size (as the result of water removal from porous network) [5] and cracks occurred to heated concrete. Further studies using Mercury Intrusion Porosimetry (MIP) is considered to be a good way to confirm this phenomenon.

Furthermore, for heated specimen, steel fiber reinforced concrete (SFRC) gives lower value on water permeability coefficient compared to polypropylene fiber reinforced concrete (PFRC) since polypropylene fibers, having fusion point of 160-170°C, melt under high temperature leaving more space for water to permeate through the concrete. Water permeability of PFRC could increase up to the order of 4 and 6 (compared to non-heated concrete) after being heated at peak temperature of 200°C and 400°C respectively.

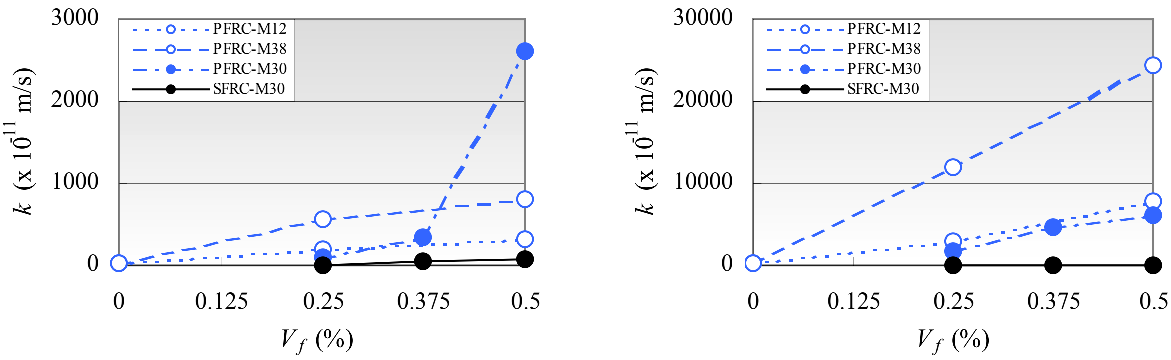
Hence, although the insertion of polypropylene fibers can mitigate the explosive spalling failure mechanism for HSC subjected to high temperature, there are some drawbacks concerning its permeability after exposure to heat.

Table 3. Water permeability coefficient of heated fiber reinforced concrete

Specimen	Water permeability coefficient					
	(x 10^{-13} m/s)		(x 10^{-11} m/s)			
	20°C	$(k_i-k_o)/k_o$	200°C	$(k_i-k_o)/k_o$	400°C	$(k_i-k_o)/k_o$
Plain OPC	5.3	0	27.6	0	142.8	0
PFRC-M12-0.25	4.6	-0.13	184.8	5.7	3026.7	20.2
PFRC-M12-0.5	4.2	-0.22	305.4	10.1	7720.8	53.1
PFRC-M38-0.25	4.6	-0.14	569.0	19.6	11890.6	82.3
PFRC-M38-0.5	4.1	-0.24	805.7	28.2	24408.3	169.9
PFRC-M30-0.25	2.4	-0.54	88.7	2.2	1605.4	10.2
PFRC-M30-0.375	2.1	-0.60	350.7	11.7	4576.7	31.0
PFRC-M30-0.5	11.4	1.15	2621.7	94.0	6201.2	42.4
SFRC-M30-0.25	2.1	-0.60	6.6	-0.8	56.7	-0.6
SFRC-M30-0.375	1.4	-0.73	47.9	0.7	79.8	-0.4
SFRC-M30-0.5	1.1	-0.79	75.4	1.7	97.0	-0.3

k_o= k of plain concrete at one particular temperature condition

The relationship connecting fiber volume fraction (V_f), fiber length (L_f), and fiber material with the water permeability coefficient of heated concrete specimens will be shown in these following figures.

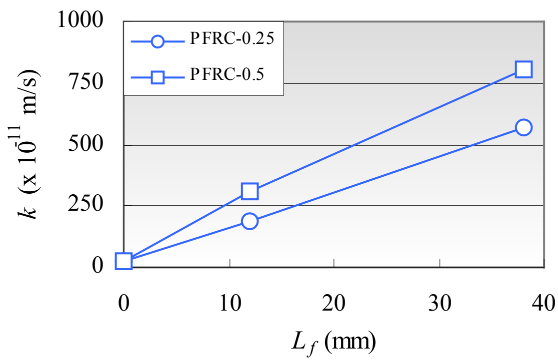


(a) 200°C **(b) 400°C**

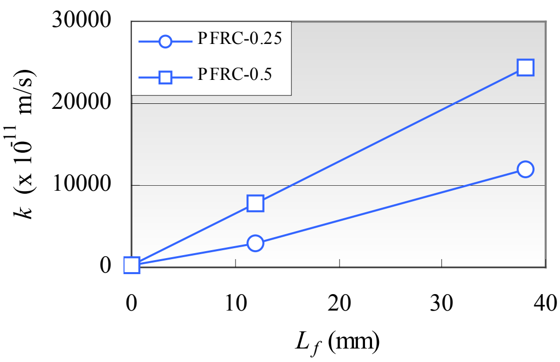
Figure 2. Fiber volume fraction vs water permeability coefficient

From figure 2, we can see that water permeability coefficient tends to increase with the increasing of fiber volume fraction. For PFRC, this can be explained as the more fibers volume inside the concrete specimen the more space will be left as they melt providing more voids for water to permeate. In case of SFRC, series that was heated at 400°C showed reduction in its water permeability coefficient compared to the plain concrete. Although the difference was insignificant, this phenomenon might explain the cracks arresting action of the steel fiber inside the cement matrix against cracks induced by heating.

From figure 3, the water permeability coefficient shows the tendency to increase with the increasing of polypropylene fiber length, as longer fibers will leave more interconnected voids upon melting.



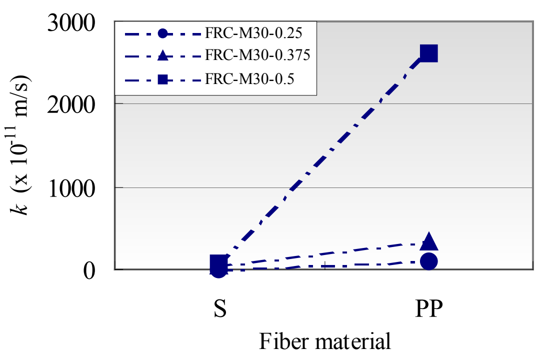
(a) 200°C



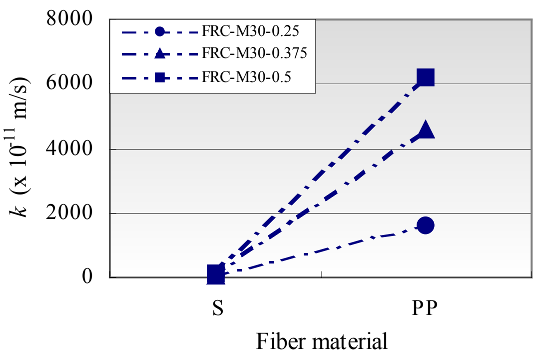
(b) 400°C

Figure 3. Fiber length vs water permeability coefficient

Like mentioned earlier, SFRC give less water permeability coefficient compared to PFRC hence showing better performance for heated concrete as can be seen in figure 4 and 5 (b). This implies to the vulnerability of PFRC to heat compared with SFRC. However, the usage of steel fibers to alleviate explosive spalling failure mechanism on HSC subjected to high temperature does not give the same effect as the polypropylene fibers do. To combine this two type of fibers cooperating together alleviating the negative effect caused by heat on HSC exposed to fire, hybrid fiber reinforced concrete should be considered.

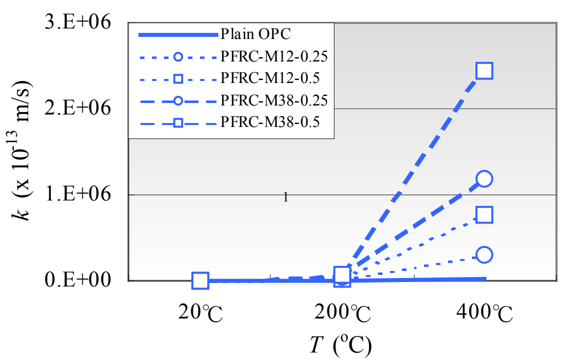


(a) 200°C

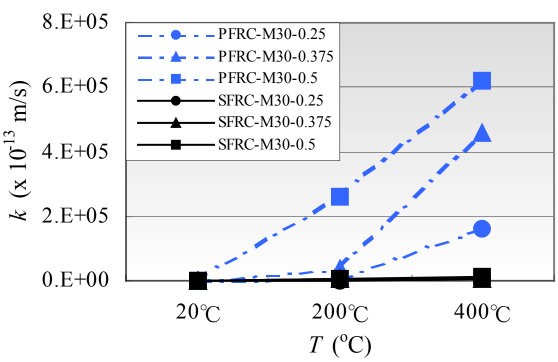


(b) 400°C

Figure 4. Fiber material vs water permeability coefficient



(a) 28 days



(b) 1 year

Figure 5. Heating temperature vs water permeability coefficient

From figure 5, the effect of curing time can also be observed as the water permeability for concrete specimens cured for 28 days showed higher value compared to the specimens cured for 1 year. This result can be explained as the more the curing time the more degree of hydration took place inside the concrete.

4. CONCLUSION

1. Significant difference of water permeability coefficient was observed between 200 and 400°C heated concrete.
2. Polypropylene fiber reinforced concrete (PFRC) gives higher water permeability coefficient compared to steel fiber reinforced concrete (SFRC) under elevated temperature.
3. Water permeability coefficient has the tendency to increase with the increasing of fiber volume fraction in terms of heated FRC.
4. For PFRC, increasing in fiber's aspect ratio (*l*/*d*) will lead to the increasing of its water permeability coefficient in terms of heated PFRC.
5. The water permeability of concrete after 28 days curing was about ten times higher than concrete after 1 year curing.
6. The ability of PFRC to mitigate explosive spalling failure mechanism followed by its vulnerability to water permeation compared to SFRC in the case of concrete subjected to high temperature have become another reason of researching hybrid fiber reinforced concrete (HFRC).

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