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Effect of fibre type and geometry on maximum pore pressures in fibre-reinforced high strength concrete at elevated temperatures

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ABSTRACT

This paper presents results of an experimental and statistical study which investigates the effect of fibre type and geometry on the amount of maximum pore pressures measured at different depths in fibre-reinforced high strength concrete (HSC) exposed to elevated temperatures. Polypropylene, polyvinyl alcohol and steel fibres of varying lengths and diameters were used. Pore pressure measurements showed that addition of organic fibres regardless of the type significantly contributes to pore pressure reduction in heated HSC. Polypropylene fibres were more effective in mitigating maximum pore pressure development compared to polyvinyl alcohol fibres while steel fibres had a slightly low effect. Longer organic fibres of length 12 mm with smaller diameters of 18 μm showed better performance than shorter ones of length 6 mm with larger diameters of 28 and 40 μm. Based on experimental observations and using statistical analysis, a relationship to predict maximum pore pressures in heated concrete was developed.

1. Introduction

Fire still remains one of the most serious risks for tunnels, buildings and other concrete structures especially those made of high strength concrete (HSC). Therefore, there is need for engineers to greatly take into consideration the risks associated with elevated temperatures when designing concrete structures, such as explosive spalling which has been observed by many researchers often resulting in serious deterioration of the concrete [1–4].

It has been widely shown that polypropylene (PP) fibres are very effective in mitigating spalling in HSC exposed to elevated temperatures [5–8]. Other researches have also shown that some other organic fibres such as polyvinyl alcohol (PVA) and nylon are also effective in mitigating spalling while others like cellulose [9] and polyethylene fibres [8] are not so effective. Also some natural fibres such as jute have been observed to be effective in preventing spalling [10].

The effect of fibre geometry on pressure rise and spalling mitigation in concrete exposed to elevated temperatures is also not clearly understood. It has been observed that for a given fibre content, finer PP fibres of length 12.5 mm were more effective in spalling protection during a fire compared thicker PP fibres of length 20 mm [7]. However, Young-Sun Heo et al. [9] observed that for a given fibre content, longer PP fibres of lengths 12, 19 and 30 mm were more effective in preventing spalling compared to shorter PP fibres of lengths 3 and 6 mm. A similar behavior was observed in PVA fibres where by 12 mm length fibres performed better than 6 mm length fibres in spalling prevention. Therefore, the relationship between spalling and fibre type and geometry is complex and not clearly understood. Different lengths and diameters of PP fibres have been used for spalling prevention in HSC, with the lengths ranging between 3 mm to 38 mm while the diameter ranges between 12 and 300 μm. The most common length and diameter of pp fibres used are 12 mm and 18 μm respectively [9,11–14]. In this study, 12 mm length PP fibres were used and compared with the shorter 6 mm lengths PP and PVA fibres. Also 18 μm diameter PP fibres and 16 μm diameter PVA fibres were used and compared with thicker diameter PP and PVA fibres.

The purpose of this study is to investigate the role played by fibre geometry i.e. length and diameter as well as fibre type in mitigating pressure rise in fibre-reinforced high strength concrete exposed to elevated temperatures. Also a relationship to predict relative maximum pressures in heated concrete has been developed. Pore pressures in different series of concretes containing different types and geometries of fibres have been measured at depths of 10, 30 and 50 mm from the heated surface. All fibre-reinforced concretes contained the same amount of organic fibre content of 0.9 kg/m^3 (0.1% by volume) and a heating rate of 10 °C/min was applied to all specimens.

2. Experimental procedure

2.1. Materials and mix proportions

Nine series of concretes were prepared using OPC (Ordinary Portland Cement) and crushed stone with the maximum nominal size of 13 mm. W/C of 0.5 was used for Normal Strength Concrete (NSC) while W/C of 0.3 was used for the remaining High Strength Concrete (HSC) series.

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Some parameters of the mix proportion were kept constant for all series: water content of 170 kg/m^3 and sand to aggregate ratio (s/a) of 50%. Addition of polypropylene (PP) monofilament fibres, polyvinyl alcohol (PVA) fibres, and a combination of PP or PVA with steel fibres i.e. hybrid fibres was the main differentiation of the series. Two types of steel fibres were used in this experimental study and the fibre properties are as shown in Table 1. A polycarboxylate ether superplasticiser was used at a dosage of 0.9% of cement content to achieve the desired workability. Concrete mix proportions of all series cast are shown in Table 2. The convention for naming different series according to fibre type, fibre length and fibre diameter was used. For example HY PP 6–18 is explained as follows: HY means its hybrid concrete containing steel and organic fibres, PP 6–18 mean the organic fibre added is polypropylene (PP) with length of 6 mm and diameter of 18 μm (0.018 mm).

Cast specimens were 100 mm in diameter by 200 mm in height for strength tests and 175 mm in diameter by 100 mm in height for pore pressure tests. After casting, the specimens were covered with wet burlap under polyvinyl sheet. After 24 h, the specimens were demolded and cured under lime-saturated water at temperature of 20 ± 2 °C for 28 days for strength tests. Pore pressure specimens were also cured under the same conditions for about 3 months in order to achieve a homogenous moisture state. The initial moisture content of the pore pressure specimens was between 5% and 7% by mass.

2.2. Experimental set-up

All specimens tested during the pore pressure measurement experiment were 175 mm in diameter and 100 mm in height. Thermal load was applied on one face of the concrete specimen by means of a computer-controlled radiant heater placed 10 mm above it. The heater of power 500 watts exposes the whole surface of the specimen and generates maximum temperature of up to 600 °C. Ceramic fibre was used to heat-insulate the lateral faces of the specimens to ensure quasi-unidirectional thermal load upon it. For each series, two specimens were tested and if the results were different and inconsistent, then more specimens were tested in order to obtain consistent results.

A heating rate of 10 °C/min was applied in the experiment whereby the specimen was set under the heating device and temperature increased gradually at a rate of 10 °C/min until it reaches the maximum temperature of 600 °C. Then this maximum temperature was maintained for 3 h. Then the heated specimens were left to cool down naturally.

All specimens were instrumented with pressure gauges that allow pore pressure measurements. The gauges were made of a disk of porous sintered metal (Ø 12 mm × 4 mm) with evenly distributed pores of diameter 2 μm which was encapsulated into a metal cup that was brazed to a metal tube with inner diameter of 1.5 mm. The free end of the tube then stuck out at the rear face of the specimen. Three gauges were placed with in the central zone of the specimen at 10, 30 and 50 mm respectively, from the heated face. A porous sintered metal is used because it would be able to collect moisture vapour in an evenly manner due to its evenly distributed pores which lead to stable pressure measurements. K-type of thermocouples of diameter 0.65 mm having a covering material of glass fibre was attached on the sides of the gauges which were used to measure the temperature inside the heated specimens. An additional thermocouple was placed on the heated surface of the specimen to measure and monitor the build up of temperature. The set-up of the experimental test is shown in Fig. 1.

After casting, specimens were cured inside a lime-saturated curing tank for about 3 months in order for a homogenous moisture state to be achieved. Prior to heating, all gauges were filled with silicon oil having a flash point of 315 °C and a thermal expansion of 0.00095 cc/cc/°C. A syringe was used to fill the gauges with oil from the top of the gauge and then a very thin wire is used to continuously insert oil into the gauge until it is filled to ensure that no air bubbles were trapped inside the gauge. Then the filled gauges are carefully connected to the pressure transducers which are in turn connected to the data logger.

Table 1
Characteristics of fibres.

	Polypropylene	Polyvinyl alcohol	Steel (S13)	Steel (S30)
Diameter (mm)	0.018, 0.028	0.016, 0.040	0.16	0.60
Length (mm)	6, 12	6	13	30
Shape	Filament	Filament	Straight	Indent
Density (gr/cm^3)	0.9	1.3	7.8	7.8
T_{melt} (°C)	160–170	200–230	1370	1370
$T_{vapourize}$ (°C)	341	–	–	–

Table 2
Mixture proportions.

Series	W/C (%)	s/a (%)	Fibre vol. (%)			W	C	S	G	SPAE*1 (%×C)
			PP/PVA	(S30)	(S13)	(kg/m^3)				
Plain NSC	50	50	–	–	–	170	340	893	867	0.9
Plain HSC	30		–				567	795	771	
PP 6–18			0.1							
PP 12–18										
PP 12–28										
PVA 6–16										
PVA 6–40										
HY(PP 6–18)				0.4	0.1			788	764	
HY(PVA 6–40)				0.4	0.1			788	764	

SPAE*1: Super plasticiser and air entraining agent.

3. Results and discussions

3.1. General observations

Fresh and hardened properties of all the series of concrete measured at room temperature are shown in Table 3. It was observed that PP series had a higher air content compared with PVA and HY series. This is probably because of their poor bonding properties with concrete resulting in air voids. It was also generally observed that addition of organic fibres reduced the workability of concrete which may have been caused by intertwining of the fibres during mixing hence a reduction in slump. Furthermore, a reduction in compressive strength was observed in all fibre-reinforced HSC series compared with Plain HSC probably because of addition of fibres which led to more interfacial transition zones (ITZs) which in turn affected the compressive strength.

The thermal behavior of heated HSC is shown in Fig. 2. All other concrete series tested showed a similar behavior during heat exposure. It has been observed in past studies [5] that fibres had a low effect on the thermal properties of concrete and that the thermal diffusivity of concrete is mainly influenced by the aggregate type used [15]. Thus, since the same type of aggregates was used for all series in this experiment, a similar thermal behavior of all series confirms that aggregates are the main influence on thermal diffusivity of concrete.

Fig. 3 shows the pressure rise with time inside both Plain NSC and Plain HSC. The two series did not have any fibres added in their mixes. A higher maximum pore pressure of 5.0 MPa was observed in Plain HSC at a depth of 30 mm while a lower maximum pore pressure of 2.1 MPa was observed in Plain NSC at a depth of 10 mm. This confirmed the effect of permeability already discussed by Bentz [16] on pore development inside heated concrete. NSC which is less dense than HSC has a higher permeability and porosity due to its higher water cement ratio. This result in higher moisture vapour escape during heating hence better pore pressure relief and subsequently lower pore pressures being measured in NSC compared to HSC. Therefore, the transport properties of concrete significantly influence the build-up of pore pressure and consequently the likelihood of spalling in heated concrete. However, a

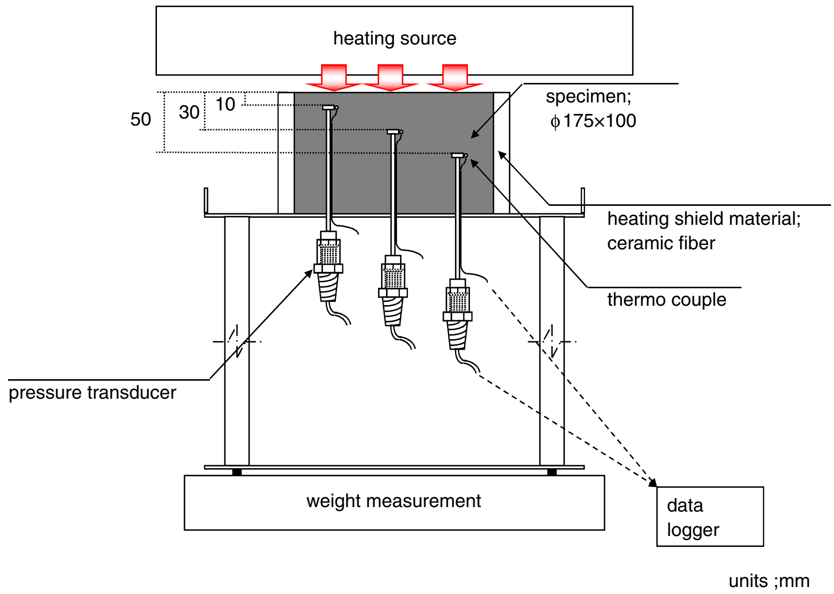

Fig. 1. Experimental test set-up.

rather low pressure of 1.7 MPa was measured in Plain HSC at a depth of 10 mm due to the occurrence of surface cracking. This led to moisture vapour rapidly escaping to the outside of the specimen and thus a lower than expected pressure was measured nearer the surface of the heated Plain HSC.

Fig. 4 shows the pore pressures measured at depths of 10, 30 and 50 mm in all series of plain and fibre-reinforced concretes tested. The significant effect of organic fibre addition towards pore pressure reduction in heated HSC, regardless of organic fibre type and geometry, is clearly illustrated since relatively lower pore pressures were measured in all fibre-reinforced HSC series compared to Plain HSC. This is supported by simulations of Bentz [16] which showed that for an un-percolated system, addition of fibres was nearly five times more effective in creating percolated pathways than adding more aggregates to the system.

3.2. Influence of fibre geometry on pore pressure development

Fig. 5 shows pressure rise with respect to time inside concrete containing PP fibres of varying lengths and diameters. A comparison between Fig. 5(a) showing concrete containing PP 6–18 (length 6 mm and diameter of 18 μm) and Fig. 5(b) containing PP 12–18 (length 12 mm and diameter of 18 μm) was carried out. It was observed that higher maximum pore pressures were measured for PP 6–18 than PP 12–18 at all depths of concrete. The main difference between the two PP fibres is the length. This shows that longer PP fibres are more effective in mitigating pressure rise inside concrete compared to shorter ones. Furthermore, a comparison between PP 12–18 and PP 12–28 as shown in Fig. 5(b) and Fig. 5(c) respectively, whose main differentiation is the diameter, showed lower maximum pore pressures for PP 12–18 than PP 12–28 at all depths of concrete. This simply means that smaller diameter PP fibres are more effective compared to bigger diameter fibres in mitigating pressure rise inside heated concrete.

Similarly, when comparing PVA 6–16 and PVA 6–40 which have the same lengths but different diameter as shown in Fig. 6(a) and (b) respectively, it can also been seen that smaller diameter PVA fibres performed better than the larger diameter ones at all depths of concrete.

Thus, fibre geometry (dimensions) plays an important role in mitigating pore pressure rise inside heated concrete. Fibre geometry directly affects the cumulative length and cumulative surface area of fibres inside concrete which in turn significantly affects the creation of reservoirs (micro-cracks) and continuous channels which are very effective as pressure release mechanisms [16]. Cumulative length and cumulative surface area are also dependent on the fibre content since they increase with increasing fibre content. For this experimental study, an organic fibre content of 0.9 kg/m^3 (0.1% by volume) was used. Previous studies carried out using PP fibres have found a fibre content of 0.9 kg / m^3 to be sufficient in mitigating spalling in heated HSC [1,3,6].

In Fig. 5(a) and (b), the diameter of PP fibres was fixed at 18 μm and then the lengths were set at 6 and 12 mm respectively. The longer fibres showed better performance compared to the shorter ones. It is believed that longer lengths provided better interconnectivity of the fibres than the shorter ones which resulted in a well connected network of spaces inside concrete during heating. This led to a better mitigation of pressure rise and better performance of longer fibres compared to shorter ones through increased evacuation of moisture vapour. Similar results were observed by simulations of Bentz [16] which showed that longer 20 mm fibres were slightly more efficient than shorter 10 mm fibres in both percolating the un-percolated system and in increasing the connectivity of the partially percolated one. Also simulation by Garboczi et al. [17], when considering fibres as ellipsoids, showed that fibres with a 50:1 aspect ratio need about 1.5% by volume of fibres to form percolated pathways across a three-dimensional microstructure. However, the volume fraction reduced to 0.7% and 0.3% for aspect ratios of 100:1 and 200:1 respectively, which implied that longer fibres should be more efficient in causing percolation of un-percolated systems. Furthermore, as discussed by Kalifa et al. [5], fibre length of 12 mm is very close to that of the maximum nominal aggregates of size 13 mm. It is expected that the

Table 3
Fresh and hardened properties of concrete.

Series	Fresh properties		Hardened properties		
	Slump (mm)	Air content (%)	f′c (MPa)	f t (MPa)	UPV (km/s)
Plain NSC	139	4.6	32.87	3.54	4.27
Plain HSC	198	1.8	89.70	5.31	4.76
PP 6–18	74	3.5	70.49	5.58	4.52
PP 12–18	47	2.6	65.41	5.73	4.57
PP 12–28	145	4.0	66.78	5.24	4.56
PVA 6–16	209	1.7	79.23	5.56	4.63
PVA 6–40	49	1.7	69.14	5.60	4.57
HY(PP 6–18)	99	1.0	71.04	6.28	4.62
HY(PVA 6–40)	70	2.4	72.08	6.07	4.61

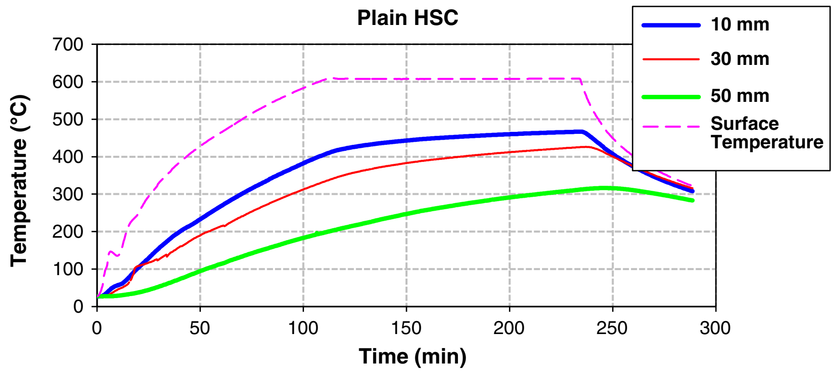

Fig. 2. Evolution of temperature with time at various depths in HSC.

interfacial transition zones (ITZs) of two aggregates can be connected since the probability of a fibre touching two aggregates is very high. However, as shown by Young-Sun et al. [9], too short (<9 mm) as well as too long nylon fibres (>19 mm) led to spalling of the fibre-reinforced concrete. Therefore an optimal organic fibre length is required which is long enough to achieve sufficient interconnectivity of fibres while at the same time the fibres should not be too long to affect the desired dispersion and cause workability related problems through tangling of fibres during mixing. Furthermore, for a given fibre content, selection of an optimal fibre length plays a more dominant role than the number of fibres per unit volume in mitigation of pressure rise since it was observed that the longer (12 mm) length fibres showed better performance than the shorter (6 mm) length fibres despite the fact that the shorter fibres lead to a higher number of fibres per unit volume compared to the longer fibres.

In Fig. 5(b) and (c), the length of PP fibres was fixed at 12 mm and then the diameters were set at 18 and 28 μm respectively. The smaller diameter PP fibres were more effective compared to larger diameter fibres in mitigating pressure rise inside heated concrete. This is because, for a fixed fibre content of 0.9 kg/m^3 and a fixed length of 12 mm, the smaller diameter fibres led to a higher number of fibres per unit volume. This in turn led to a higher total length and cumulative surface area for the smaller diameter fibres compared to the larger diameter ones. The same phenomenon was observed for PVA fibres of same lengths of 6 mm but different diameters of 16 and 40 μm as shown in Fig. 6(a) and (b) respectively. Similar observations by Bentz [16] showed that when the fibre diameter for the system were reduced from 0.25 mm to 0.1 mm but maintaining the same lengths of either 10 mm or 20 mm, the percolated volume fractions of aggregates and ITZ regions required slightly reduced suggesting that smaller diameter fibres were more efficient than larger ones. Thus, for a given optimal length and fibre content of organic fibres, the number of fibres per unit volume will mainly depend on the diameter of fibres since a smaller diameter will lead to an increased total length of fibres and their total surface area per unit volume compared to larger diameters. Thus total length of fibres and their total surface area per unit volume, which are affected by the diameter, are one of the most important parameters which affect the effectiveness of organic fibres in pore pressure rise mitigation inside heated HSC.

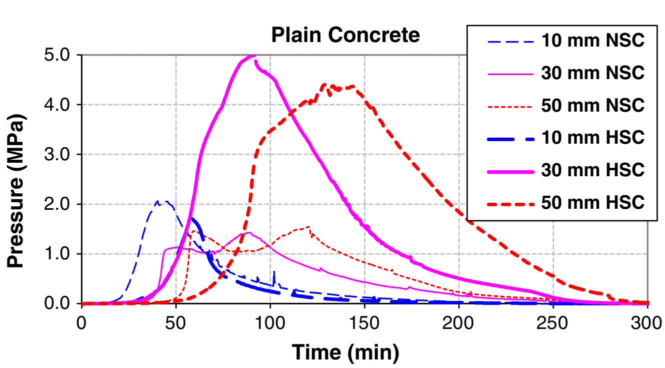

Fig. 3. Pressure rise with respect to time in Plain NSC and HSC.

It can therefore generally be concluded that when using organic fibres to mitigate pore pressure rise inside heated HSC, regardless of the type of fibres, longer fibres made of smaller diameters generally perform better than shorter ones made of larger diameters.

3.3. Influence of fibre type on pore pressure development

In order to study the effect of the type of fibre on pressure rise inside concrete, two types of organic fibres with almost similar geometry but different bonding properties with concrete as well as different melting temperatures were used. Polypropylene fibres of length 6 mm and diameter of 18 μm (PP 6–18) and polyvinyl alcohol (PVA) fibres of length 6 mm and diameter of 16 μm (PVA 6–16) were selected. Polypropylene fibres, with a melting temperature of 160–170 °C, are hydrophobic in nature leading it to repel and tend not to combine with water resulting in a poor bonding at the fibre–concrete interface. However polyvinyl alcohol fibres, with a melting temperature of 200–230 °C, are hydrophilic in nature having a high affinity for water resulting in a good bonding at the fibre–concrete interface.

Figs. 5(a) and 6(a) show pressure rise with respect to time inside concrete when incorporating PP and PVA fibres respectively. Pressures measured inside PP concrete are relatively low with a maximum pressure of 1.1 MPa at a depth of 50 mm. However, pressures inside PVA concrete are higher with a maximum pressure of 1.5 MPa at a depth of 30 mm. This shows that PP fibres are more effective in mitigating pressure rise inside heated concrete. Furthermore, as shown in Fig. 7 (a) and (b) for hybrid-fibre reinforced concretes, a lower maximum pore pressure of 0.9 MPa was measured at a depth of 50 mm for HY PP 6–18 series containing steel and PP fibres compared to 2.7 MPa for HY PVA 6–40 series at a depth of 30 mm containing steel and PVA fibres. Thus, PP performed better than PVA fibre-reinforced high strength concrete during exposure to high temperatures.

The above observations show that the type of organic fibres in relation to its bonding properties with concrete could play some role in mitigating pressure rise and hence consequently mitigating the possibility of spalling inside heated concrete. The better performance of PP compared to PVA fibre-reinforced high strength concrete is probably partly as result of the effect of bonding at the fibre–concrete interface which is thought to result in the pressure-induced tangential space (PITS) mechanism [18]. It is believed that the pressure that will be developed from about 100 °C during heating, even before the melting of PP fibres, will be able to cause the rapture of the poor fibre–concrete interfacial contact in PP fibre-reinforced concrete resulting in the pressure-induced tangential spaces through which moisture vapour

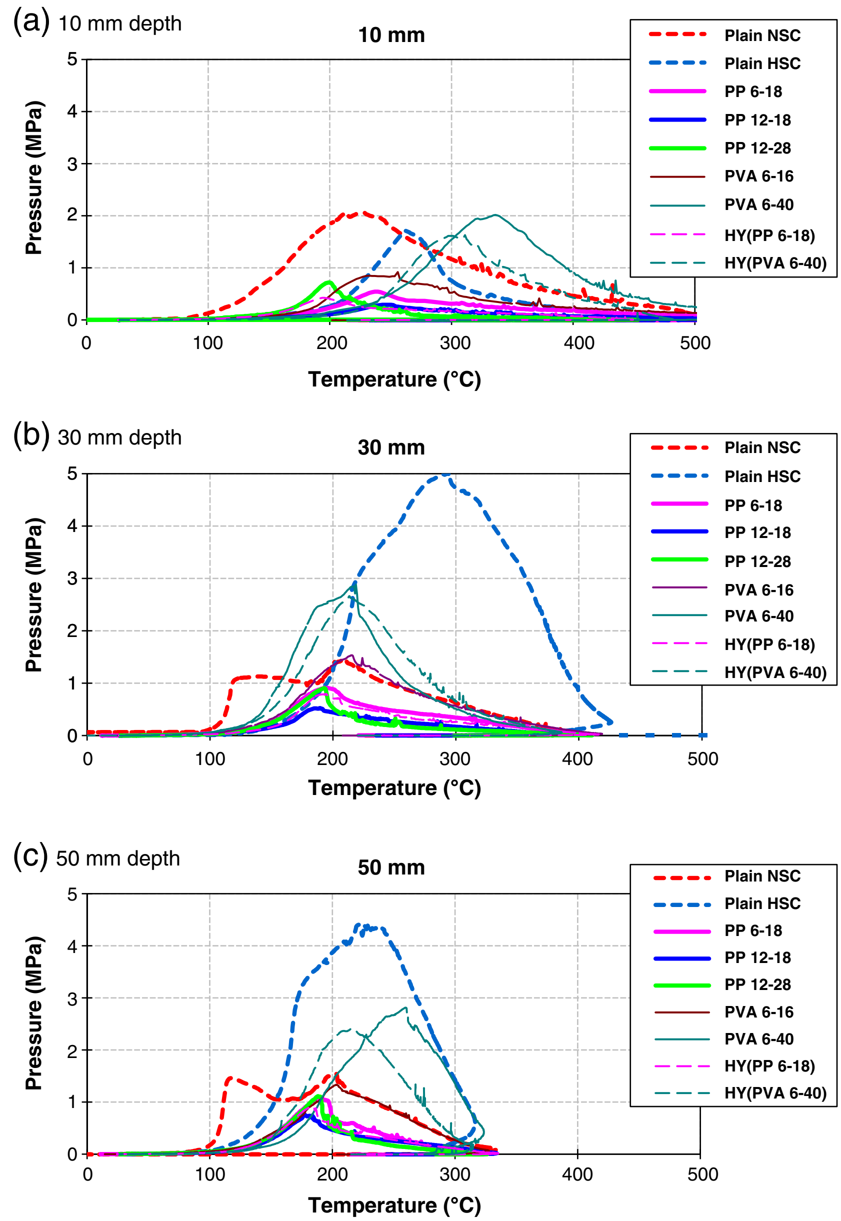

Fig. 4. Pressure rise with respect to temperature for series at different depths. (a) 10 mm depth. (b) 30 mm depth. (c) 50 mm depth.

will be able to escape hence pressure relief. This mechanism is expected to continue even after the melting of PP fibres. However, the above mechanism will not apply in PVA fibre-reinforced concrete due to the good fibre–concrete interfacial contact. Thus PVA fibre-reinforced concrete will be able to resist and withstand the accumulated pressure resulting in a higher pressure rise and consequently increasing the possibility of spalling.

Furthermore, it was observed that maximum pressures in PP 6–18 series occurred at a depth of 50 mm after 114 min while for PVA 6–16 series, it occurred at depth of 30 mm after 79 min. This shows that PP fibres provide better pressure relief mechanisms inside heated concrete because it is easier for moisture vapour to escape in PP than PVA fibre-reinforced concrete. This results in maximum pressures taking longer times to accumulate and occurring further deeper inside PP than PVA fibre-reinforced concrete. As shown in Table 4, a similar phenomenon was observed regardless of fibre geometry, with all PP and PVA fibre-reinforced concrete experiencing maximum pressures at 50 mm and 30 mm depths respectively. This simply means that the saturated front, explained by Harmathy et al. [19], is likely to occur nearer to the surface of heated HSC and at an earlier time for concrete with poor pressure relief mechanisms compared to that with better relief mechanisms. However, as already discussed in Section 3.1, Plain HSC experienced a maximum pore pressure of 5.0 MPa at a depth of 30 mm after 91 min. It would normally have been expected for the maximum pore pressure to occur nearer the surface of heated Plain HSC at 10 mm depth and after a shorter time. However due to the occurrence of surface cracking, a lot of moisture vapour escaped to the outside of the specimen and therefore a lower pore pressure was observed at 10 mm depth compared to 30 and 50 mm depths. Therefore, it is expected that maximum pore pressures i.e. saturated front will occur nearer to the surface and at an earlier time for heated Plain HSC and will move further deeper and take longer time in PVA and finally in PP fibre-reinforced concrete. Hence the depth from the heated surface and time at which maximum pore pressures occur increases with increasing effectiveness of pore pressure relief mechanisms inside heated concrete.

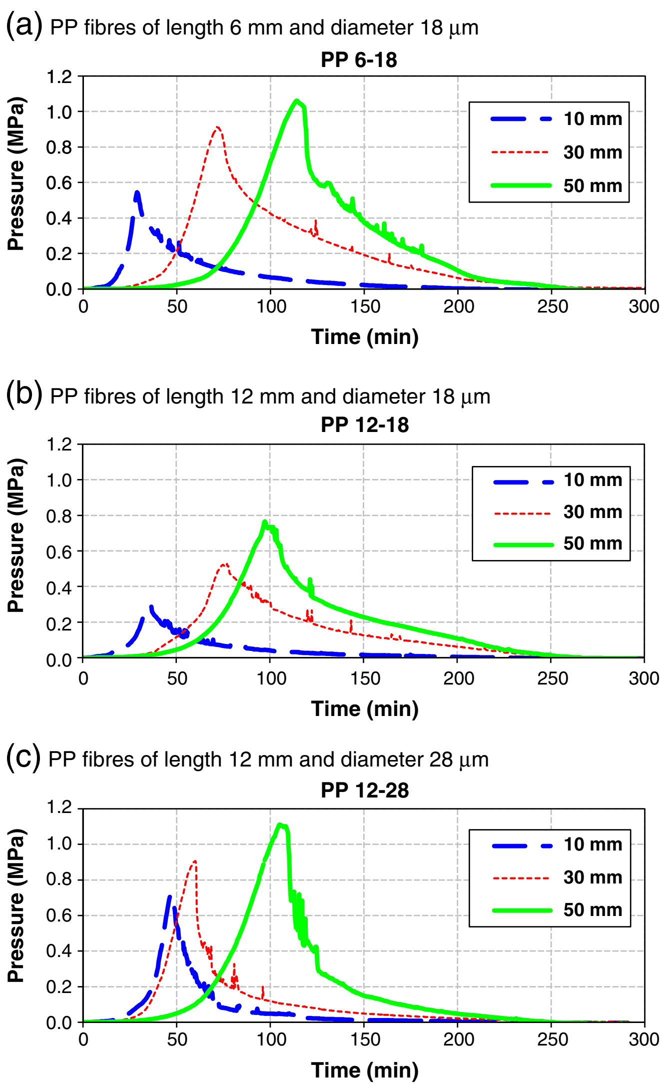

Fig. 5. Pressure rise with respect to time in PP fibre concrete of different lengths and diameters. (a) PP fibres of length 6 mm and diameter 18 µm. (b) PP fibres of length 12 mm and diameter 18 µm. (c) PP fibres of length 12 mm and diameter 28 µm.

Also as shown in Fig. 4 and summarized in Table 4, it was further importantly observed that the maximum pressures occurred in the temperature ranges of 177–190 °C and 213–219 °C for PP and PVA fibre-reinforced concrete respectively. This is around the melting temperatures of PP and PVA fibres at 160–170 °C and 200–230 °C respectively. This seems to show that pressure relief occurs at or immediately after melting of the fibres with lower maximum pressures being observed further deeper inside PP compared to PVA fibre-reinforced concrete. The better performance at melting of PP compared to PVA fibres could be because of their lower melting temperature and it is also expected that their volumetric expansion on melting of about 10% will lead to creation of micro-cracks which will contribute to pressure relief inside concrete. In addition, since spalling of HSC normally occurs in the temperature range of 190–250 °C [5], organic fibres which melt prior or around the lower limit of spalling temperature range are likely to be more effective in mitigating pressure rise and consequently the possibility of spalling of HSC because they will provide an earlier mitigation of pressure rise. Thus, PP concrete performed better than PVA concrete since they experienced maximum pressures at a lower temperature range of 177–190 °C compared with that of PVA concrete at 213–219 °C.

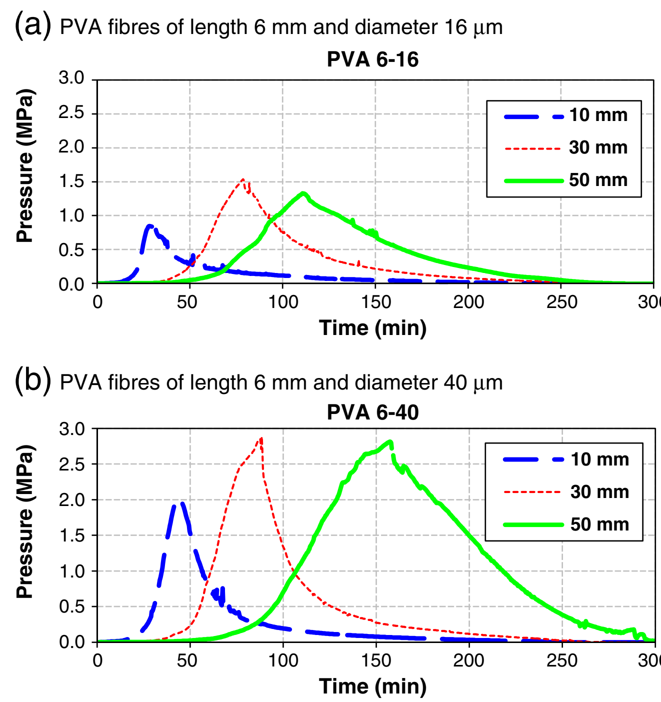

Fig. 6. Pressure rise with respect to time in PVA fibre concrete of different diameters. (a) PVA fibres of length 6 mm and diameter 16 µm. (b) PVA fibres of length 6 mm and diameter 40 µm.

3.4. Contribution of steel fibres on pore pressure development

Comparing PP 6–18 and HY PP 6–18 series as shown in Figs. 5(a) and 7(a) respectively, whose main difference is the addition of steel fibres in the hybrid series, it can be observed that a slightly lower

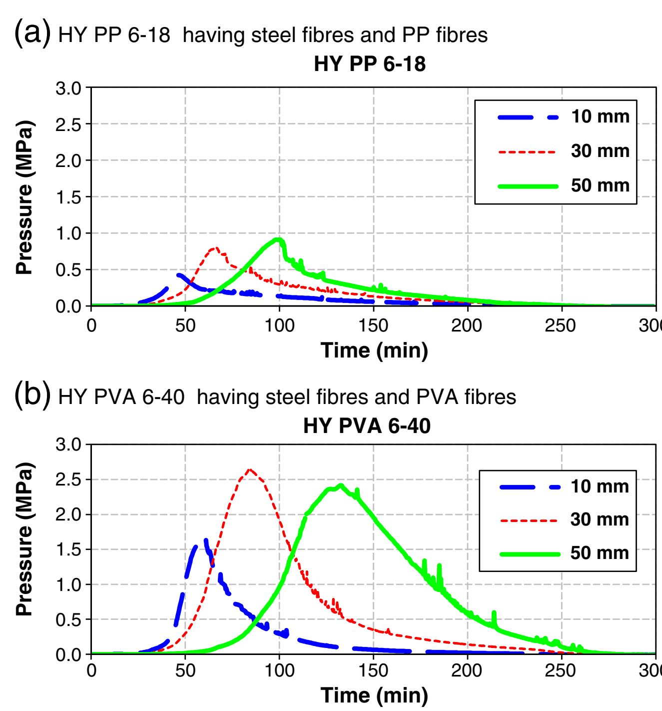

Fig. 7. Pressure rise with respect to time in hybrid fibre concretes. (a) HY PP 6–18 having steel fibres and PP fibres. (b) HY PVA 6–40 having steel fibres and PVA fibres.

Table 4
Time and depth at which maximum pressures occur.

Series	Length (mm)	Diameter (mm)	Max. pressure (MPa)	Temp at max. pressure (°C)	Time at max. pressure (°C)	Depth at max. pressure (mm)
Plain NSC	–	–	2.1	229	46	10
Plain HSC	–	–	5.0	235	91	30
PP 6–18	6	0.018	1.1	191	114	50
PP 12–18	12	0.018	0.8	177	97	50
PP 12–28	12	0.028	1.1	188	105	50
PVA 6–16	6	0.016	1.5	215	79	30
PVA 6–40	6	0.040	2.9	219	88	30
HY(PP 6–18)	6	0.018	0.9	185	100	50
HY(PVA 6–40)	6	0.040	2.7	214	84	30

pressure of 0.9 MPa was measured in HY PP 6–18 series compared to 1.1 MPa measured in PP 6–18 series. The same behavior was observed in PVA 6–40 and HY PVA 6–40 series as shown in Figs. 6(b) and 7(b) respectively. This shows that addition of steel fibres contributes in pore pressure reduction in heated concrete. The contribution of steel fibres in pore pressure reduction increases with increasing heating rates and maximum pore pressures as shown in previous studies [20].

3.5. Prediction of relative maximum pressures in heated concrete

Based on the knowledge of the influence of fibre geometry and type on pore pressure development in heated concrete, a relationship to predict relative maximum pressures was developed which takes into account parameters such as concrete strength, fibre type and fibre geometry. The relative predicted maximum pressure ($P_{r.p}$) is calculated using the relationship developed by multiple regression analysis as shown below:

$$P_{r.p} = 0.0113 f'_{C} - 0.05T_f - 0.01\ L_f - 0.0021\ S.A_{OF} - 0.001\ S.A_{SF}$$

where f'_C is the compressive strength of concrete, T_f is a constant for type of organic fibre with values of 1 and 0.2 for PP and PVA fibres respectively, L_f is length of organic fibres, $S.A_{OF}$ is the cumulative surface area of organic fibres and $S.A_{SF}$ is the cumulative surface area of steel fibres. T_f is dependent on other factors such as bond strength between concrete and fibres, melting point and vapourization of fibres but their effect has not been included in the current relative maximum pressure prediction relationship. Relative maximum pressures are derived from dividing maximum pressures measured for the different types of concrete with the maximum pressure measured in Plain HSC e.g. relative maximum pressure in PP concrete = (maximum pressure in PP concrete / maximum pressure in Plain HSC). A relative value of pressure is used instead of the directly measured values in order to minimize the effect of measurement techniques and equipment errors since different researchers use different measurement set-ups.

A comparison between relative measured and relative predicted maximum pressures was carried out on results from this experimental study and from other researchers [5,21] who used a heating rate of 5 °C/min which was comparable to 10 °C/min used in this experimental study. As shown in Fig. 8, a strong correlation was observed between the relative measured and predicted maximum pressures from different researchers.

Thus when equipped with information about the maximum pressures in Plain HSC, strength of concrete as well as fibre geometry and type, it could be possible to roughly predict the expected maximum pressures in different types and mixes of concrete when exposed to elevated temperatures. Therefore it could be possible to determine the most effective mix of concrete in different regions depending on the fibre geometry and type available on the market.

It must however be observed that this relationship for predicting maximum pressures is still a rough one which needs to be further refined through conducting more research to include other parameters such as effect of heating rate, melting and optimal length of organic fibre, bond strength between concrete and fibres, specimen size effect, moisture content, etc. Furthermore, in order to utilize this relationship in mix designs, a threshold maximum pressure must be determined above which spalling will be expected to occur.

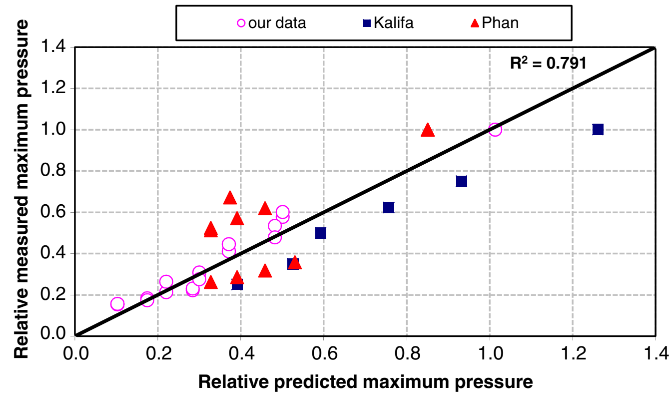

Fig. 8. Relationship between relative measured and predicted maximum pressures from different researchers.

4. Conclusions

1. Addition of organic fibres, regardless of fibre type and geometry, significantly contributes towards pore pressure reduction in heated HSC since relatively lower pore pressures were measured in all fibre-reinforced HSC series compared to Plain HSC.
2. Generally when using organic fibres to mitigate pore pressure rise inside heated HSC, regardless of the type of fibres, longer fibres of length 12 mm made of smaller diameters of 16 and 18 μm generally perform better than shorter ones of length 6 mm made of larger diameters of 28 and 40 μm.
3. PP fibre-reinforced high strength concrete performed better during exposure to high temperatures compared to PVA fibre-reinforced high strength concrete. Therefore, the type of organic fibres in relation to its bonding properties with concrete as well as its melting temperature is important in mitigating pressure rise and consequently the possibility of spalling inside heated concrete.
4. The depth from the heated surface and time at which maximum pore pressures and/or saturated front are experienced increases with increasing effectiveness of pore pressure relief mechanisms inside heated concrete.
5. Pressure relief inside fibre-reinforced concrete occurred at or immediately after melting of the fibres. Organic fibres with lower melting temperatures are likely to perform better than those with higher melting temperatures. Furthermore, organic fibres which melt prior or around the lower limit of the spalling temperature range of 190–250 °C are more likely to be effective in mitigating pressure rise and consequently the possibility of spalling of HSC because they will provide an earlier mitigation of pressure rise.
6. Addition of steel fibres in HSC slightly contributes in pore pressure reduction in heated concrete.
7. When equipped with information about the maximum pressures in Plain HSC, strength of concrete as well as fibre geometry and type, it could be possible to roughly predict the expected maximum pressures in different types and mixes of concrete when exposed to elevated temperatures.

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