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Pore pressure development in hybrid fibre – reinforced high strength concrete at elevated temperatures

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Abstract

The present experimental work investigates the build – up of pore pressure at different depths of High Strength Concrete (HSC) and Hybrid-Fibre-Reinforced High Strength Concrete (HFRHSC) when exposed to different heating rates. First, the effect of the measurement technique on maximum pore pressures measured was evaluated. The pressure measurement technique which utilized a sintered metal and silicon oil was found to be the most effective technique for pore pressure measurement. Pore pressure measurements carried out showed that addition of polypropylene fibres is very effective in mitigation of spalling and build – up of pore pressure inside heated HSC. Addition of steel fibres plays some role in pore pressure reduction at relatively higher pressures in deeper regions of concrete during fast heating. Pore pressure development is highly influenced by the rate of heating with fast heating leading to higher pore pressures in the deeper regions of concrete compared to slow heating.

Keywords: Temperature (A); High Performance Concrete (E); Fiber Reinforcement (E); Mechanical properties (C); Spalling

1. Introduction

High strength concrete (HSC) has been increasingly utilized in construction of many civil engineering structures world wide such as bridges, high – rise buildings and tunnels because of its superior performance compared to normal strength concrete due to its low permeability and improved durability. However fire accidents which have occurred involving infrastructures and various studies have shown that high strength concrete performance is highly susceptible to high temperature condition [1 – 5] because of its low permeability. Thermal instability in form of spalling has been observed which leads to breaking off of layers or pieces of concrete from the thermally exposed surface and this significantly compromises the structural integrity of the concrete structures [2, 5, 6].

However, studies by different researchers on the factors influencing the occurrence of explosive spalling are inconsistent and not in agreement with each other. Studies on HSC [7, 8] which used a similar slow heating rate but different pressure measurement techniques observed quite different maximum pore pressures while other studies [9 – 13] using fast heating rates measured significantly different maximum pore pressures. Also some findings [8, 9, 14] are not in agreement with classical theoretical considerations of the effect of heating rate on pore pressure development in concrete where by an increase in heating rate should lead to an increase in maximum pore pressures. Due to its superior performance and increased usage, it is very important to clearly understand factors influencing the occurrence of explosive spalling in HSC when exposed to elevated temperatures.

The purpose of this experimental study is to evaluate the effect of the measurement technique on the maximum pore pressures measured since it has already been observed that researchers have recorded varying maximum pore pressures. Also measurement of the build – up of pore pressure at different depths inside concrete was done as well as evaluating the effect of heating rate on pore pressure development. Furthermore, the effect of hybrid (HY) fibre reinforcement (a combination of polypropylene and steel fibres) on the mitigation of spalling and pore pressure development inside HSC exposed to elevated temperatures has been studied. It has been observed in previous studies [4, 15 – 17] that hybrid fibre reinforced concrete showed better performance of the mechanical properties during and after exposure to elevated temperatures compared to Plain and polypropylene (PP) mixtures hence, there is a need to ascertain whether a hybrid system contributes towards spalling mitigation.

The present study involves the analysis of the thermal – hydral process of different series of concretes at 10, 30 and 50 mm depths using three heating rates of slow, moderate and relatively fast heating. Also, pore pressure measurement using three different measurement techniques was conducted in order to determine the most appropriate pore pressure measurement technique.

2. Experimental procedure

2.1 Materials and mix proportions

Six series of concretes were prepared using OPC (Ordinary Portland Cement) and crushed stone with the maximum nominal size of 13 mm. Some parameters of the mix proportion were kept constant for all series: W/C of 30 %, water content of 170 kg/m^3 and sand to aggregate ratio (s/a) of 50%. Addition of polypropylene (PP) monofilament fibres, steel fibres and a combination of polypropylene and steel fibres was the main differentiation of the series. Two types of steel fibres were used in this experimental study and the basic properties of fibres 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 (slump of 150 – 175 mm). Concrete mix proportions of all series cast are shown in Table 2.

Specimens casted 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 hours, 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 6 – 7.5 % by mass.

2.2 Heating Procedure

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.

Three heating patterns were applied in the experiment. In the first pattern, a slow heating rate (5°C/min), the specimen is set under the heating device and temperature increased gradually at a rate of 5°C/min until it reaches the maximum temperature of 600° C. Then this maximum temperature is maintained for 2 hours. In the second pattern, a moderate heating rate (10°C/min), the specimen is 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 is maintained for 3 hours. In the third pattern, a relatively fast heating rate which is though slower than the ISO 834 fire curve, was conducted by thermally shocking the specimen after the heating device has reached the designated maximum temperature of 800° C. The specimen was exposed to the maximum temperature of 800° C lasting for 4 hours. The three heating patterns and ISO 834 reference pattern are shown in Figure 1.

2.3 Experimental set – up

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×4mm) 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 were 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. Prior to heating, all gauges were filled with silicon oil having a fire 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. The experimental set up is shown in Figure 2.

2.4 Set – up for study on measurement techniques

Pore pressure measurement using three different measurement techniques was studied. The first technique involved gauges made of a porous sintered metal encapsulated into a metal cup that is brazed to a metal tube which was the same as in Section 2.3 above. The second technique consisted of a metal cup that is brazed to a metal tube but with out a porous sintered metal. The third technique consisted of just a metal tube with out both the metal cup and a porous sintered metal. The three different gauges are shown in Figure 3. All three different gauges for the three measurement techniques were instrumented in the same specimen at the same depth of 30 mm from the heated face using plain concrete. Prior to heating, one set of specimens was filled with silicon oil while the others were left empty in order to clarify the effect of a medium used in the pipe to transform pressure to the outside on pore pressure measured. Silicon oil and air are the two types of media used in the present study.

The specimens for this test were cured for 6 months in order to insure that a fully saturated moisture condition was achieved and a moderate heating rate (10°C/min) was applied.

3. Results and discussions

3.1 Specimens' Properties

Fresh and hardened properties of all the series of concrete were measured at room temperature and the properties are showed in Table 3. It was observed that PP concrete had the lowest mechanical properties among all series tested. Thus addition of only PP fibres in concrete reduces the mechanical properties of concrete at room temperature.

3.2 Study on pressure measurement techniques

Figures 4 and 5 shows results of the investigation on the effect of the measurement technique on the amount of maximum pore pressures measured. Three different types of pressure gauges already described in Section 2.4 and showed in Figure 3, which have been used by different researchers in the past to measure pore pressures inside heated concrete, are examined under the same boundary conditions. The effect of the medium used in the pipe to transform pressure to the outside of the specimen was also investigated. The gauges of some specimens were filled with silicon oil and the pore pressures measured are shown in Figure 4 while the pore pressures measured when the gauges were left empty are showed Figure 5. Thus, Silicon oil and air were the two media studied for pressure transformation to the outside of the heated specimen.

As shown in Figures 4 and 5, there is significant effect of using a pressure gauge comprising of a cup with sintered metal since it measures a higher amount of pore pressure compared to the other two types of gauges for all tests done. This clearly shows that a sintered metal play an important role in pore pressure measurement and should be added to the pressure gauges used for measuring pore pressures inside concrete exposed to elevated temperatures.

Furthermore, it was observed that higher pore pressures were measured for specimens filled with silicon oil as shown in Figure 4 compared to specimens with empty gauges as shown in Figure 5, for all different types of pressure gauges used. This shows that addition of silicon oil in pressure gauges during pore pressure measurement leads to better results compared to when the gauges are empty.

Thus, it can generally be concluded that pressure gauges comprising of a cup with sintered metal which are filled with silicon as a medium for pressure transfer to the outside of the heated specimen is the most effective technique for pore pressure measurement inside heated concrete.

3.3 Thermal Instability

For all concrete series tested, explosive spalling was only observed in plain concrete during a slow heating rate at 10 mm depth with a maximum pore pressure of 4.009 MPa as shown in

Figure 6 (a). This can seen as a sudden drop in pressure from 3.8 MPa to 0 at a depth of 10 mm which was caused by the breaking–off of pieces of concrete from the heated surface which resulted in moisture vapour rapidly escaping to the atmosphere and hence an abrupt drop in pore pressure. For all other specimens that did not spall, bell – shaped pressure curves were observed. The pressure rising part of the bell – shaped curves could be explained to be a result of the formation of fully saturated layer during moisture transport towards deeper colder regions of heated concrete which prevents a further transport of moisture vapour leading to a build up of pore pressure at the saturated front [18]. Since the moisture vapour transport can not go through the saturated front, it moves towards the exposed side of concrete. Initiation of micro – cracks and increased permeability causes the region of concrete between the saturated front and the exposed side to dry and dehydrate. When the rate of vapour escaping from the pores exceeds that filling the pores, the pressure starts to drop hence the bell – shaped pressure curves.

3.4 Build – up of Pore Pressure

Evolution of pore pressure with time at different depths for a slow and fast heating patterns in different concrete series are shown in Figure 6 and Figure 7 respectively. It can be observed that the maximum pressures measured in plain concrete for all heating rates at all depths are much higher than those of PP and HY concrete series. Since all the other series of concrete contain PP fibres except Plain concrete, it clearly shows the effectiveness of PP fibres and the significant role they play in mitigating the build – up of pore pressure and consequently the likelihood of spalling occurrence in concrete under exposure to a high temperature environment.

During a slow heating rate, plain concrete experienced explosive spalling with a pressure of 3.8 MPa at a depth of 10 mm after 110 minutes as shown in Figure 6 (a). Then after spalling, pore pressures of 2 MPa after 160 minutes in Figure 6 (b) and 2.17 MPa after 234 minutes in Figure 6 (c) were measured at depths of 30 and 50 mm respectively. It can be seen that after spalling, pore pressure begins to rise again with increasing time as one move deeper inside concrete away from the heated and spalled surface. This shows that even after the initial spalling, if concrete continues to be exposed to high temperature, pore pressure will again build – up with time in the deeper undamaged regions which will lead multiple spalling of concrete layers.

Figure 8 shows the time it takes to reach the maximum pore pressures in plain concrete at different depths for the different heating rates. It was observed that at all depths; a fast heating rate takes relatively a shorter time to reach the maximum pore pressure while a slow heating rate takes longer time. Similar trend was observed for all concrete series. This shows that moisture vapour is quickly driven to deeper region of concrete with regard to the heating rate. Thus, it simply means that vapour transport speed is faster in high heating rates and slower in low heating rates.

3.5 Pore pressure and Saturated Vapour Pressure (SVP)

Pore pressure development in relation to Saturated Vapour Pressure (SVP) during a fast heating rate is shown in Figure 9. In plain concrete as shown in Figure 9 (a), it was observed that pore pressure exceeded SVP during a fast heating rate and it occurred in the deeper regions at 50 mm depth. This is because a fast heating rate leads to a rapid build up of moisture vapour which is quickly driven into the deeper regions of concrete. Pore pressures in PP and HY1 series (same behavior for all HY series) are much lower than SVP at all the depths of concrete as shown in Figures 9 (b) and (c) and this further clearly illustrates the role of PP fibres in the mitigation of pressure rise inside concrete and thus reducing the likelihood of explosive spalling in concrete since all HY series contain PP fibres. Thus, SVP normally exceeds pore pressure in plain concrete especially in the deeper regions when exposed to fast heating.

3.6 Effect of Heating Rate

PP concrete series under slow and fast heating rates are shown in Figure 10 (a) and Figure 10 (b) respectively. It was observed that pore pressure near the surface of concrete at a depth of 10 mm from the heated surface was nearly the same for both slow and fast heating rates at 0.3 and 0.35 MPa respectively. However, it was observed that in deeper regions of concrete at a depth of 50 mm from the heated surface, a fast heating rate leads to a much higher pore pressure of 2 MPa which is more than twice that of a slow heating rate at 0.9 MPa. Similar trend was observed in Plain concrete as shown in Figure 6 (c) and Figure 7(c) for slow and fast heating respectively. This clearly showed that a fast heating rate leads to higher pore pressures in the deeper regions of concrete compared to a slow heating rate. Pore pressures near the surface being nearly the same for both heating rates is attributed to surface cracking of concrete which was observed on concrete specimens exposed to a fast heating rate which resulted in high amounts of water vapour escaping outside the specimen and thus a low build-up in pore pressure near the surface compared to deeper regions of concrete under a fast heating rate. This is in agreement with classical theoretical considerations which show that under normal conditions, an increase in the heating rate should leads to an increase in vapour transport speed and increased accumulation of moisture vapour resulting in the formation of a saturated zone hence increasing pore pressures. However during fast heating, surface cracking and severe concrete damage lead to high amount of water vapour escaping to the outside of the specimen as well as rapid evaporation of vapour from the regions near the heated surface. This will be able to mitigate the build up of high pore pressures in the regions near the surface of heated concrete. However in the deeper regions where there is no mitigation of pore pressure rise by cracking and evaporation, a higher and faster accumulation of moisture vapour occurs resulting in higher pore pressures and hence increased possibility of spalling. Therefore during fast heating, the specimen size and consequently the depth from the heated surface at which pore pressures are measured affect the amount of pore pressures observed and this emphasizes why small size specimens normally do not spall compared to large size specimens and actual concrete structures. Some research studies [8, 9, 14] have observed higher pore pressures during slow heating compared to fast heating probably because of the effect of cracking and evaporation during fast heating as discussed above and therefore if there was no surface cracking and evaporation during a fast heating, it is expected that pore pressures would increase with increasing heating rates for all regions of concrete. Therefore the deeper regions provide a more accurate trend of the effect of the heating rate on pore pressure development in concrete.

Thus pore pressure development in concrete is highly dependent on the severity of the fire which affects the rate and the amount of vapour migrating to the inner regions of concrete and hence surface cracking and increase in porosity due to dehydration processes are very important aspects of the fire severity. It can also be observed that surface cracking, a fire severity dependent degradation of concrete, is limited to a relatively thin layer of concrete near the heated surface but will increase slowly with increasing time of exposure to fire.

Furthermore, it was observed that 0.1 % (0.9 kg/m^3) dosage of only PP fibres is not sufficient in pore pressure reduction for a fast heating rate since a high pore pressure of 2 MPa was measured in PP concrete series. As already observed that the fast heating rate used in this study is slower than the ISO 834 curve as well as small scale tests were done, it is believed that large scale tests experiencing severe heating could possibly develop higher pore pressures especially in deeper regions which would increase the possibility of spalling when using lower fibre dosage of only PP fibres. Therefore in such conditions, there would be need to increase the optimum PP fibre volume in relation with increasing severity of fire especially when only PP fibres are added to concrete.

3.7 Role of steel fibres in pressure reduction

Pore pressure development in deeper regions of concrete at 50 mm depth for the different series during slow and fast heating is shown in Figures 6(c) and 7(c) respectively. Comparing PP and Hybrid concrete series under fast heating as shown in Figure 7 (c), it was observed that in deeper regions, Hybrid concrete series had a maximum pore pressure of 1.0 MPa which is at least half (½) that in PP concrete series at 2 MPa. However, there is no major difference in pore pressure between PP and HY series under slow heating as shown in Figure 6 (c). This clearly shows that addition of steel fibres plays some role in pore pressure reduction in deeper regions of concrete under a fast heating rate. This probably due to the creation of discrete bubbles during the mixing process which act as a kind of discontinuous reservoirs for pressure relief. Also since this pressure mitigation phenomenon occurs in a relatively high pressure zone, it implies the possibility of pressure – induced tangential space (PITS) mechanism which is a result of poor interfacial adhesion between steel fibres and concrete plus the increased interconnectivity of the spaces as a means of pressure relief.

4. Conclusions

This paper presented an experimental study on mitigation of spalling and pore pressure development in hybrid fibre – reinforced high strength concrete exposed to elevated temperatures using different heating rates as well as the effect of a measurement technique on the amount of pore pressure measured. The following conclusions are drawn based on the experimental findings:

1. Generally, the pressure measurement technique containing a combination of a pressure gauge comprising of a cup with sintered metal and utilization of silicon as a medium for pressure transfer to the outside of the heated specimen is the most effective technique for pore pressure measurement inside heated concrete.

2. It was found that PP fibres are very effective in mitigating the build-up of pore pressure inside concrete which consequently reduces the likelihood of occurrence of spalling in concrete under exposure to high temperatures.

3. Fast heating leads to higher pore pressures in the deeper regions compared to slow heating which is in agreement with classical theoretical considerations which show that increasing heating rate leads to increasing pore pressures. However pressures near the heated surface were almost similar for both heating rates probably due to surface cracking which occurred during fast heating resulting in water vapour escaping to the outside of the specimen hence a low build – up of pore pressure. Therefore, Pore pressure development is highly influenced by severity of heating and surface cracking of concrete resulting from the severity of heating is limited to a thin layer of concrete near the heated surface but increases slowly with increasing time of exposure to elevated temperature.

4. Duration of exposure of concrete to elevated temperatures especially for Plain HSC greatly contributes to its deterioration by spalling because of the increased likelihood of occurrence of multiple spalling of layers of concrete due to the continuous build – up of pore pressure with time in the deeper undamaged regions during exposure to elevated temperatures.

5. Vapour transport speed increases with increasing heating rate and this phenomenon results in pore pressure exceeding SVP during fast heating in the deeper regions of concrete because of moisture vapour being quickly driven into deeper regions of concrete during fast heating.

6. Addition of steel fibres plays some role in pore pressure reduction in deeper regions of concrete during fast heating. This mitigation phenomenon occurs in a relatively higher pressure zone which implies the possibility of pressure – induced tangential space (PITS) mechanism as a

result of poor interfacial adhesion between steel fibres and concrete plus the increased interconnectivity of the spaces as a means of pressure relief.

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Table 1. Characteristics of fibres

	Polypropylene	Steel (S13)	Steel (S30)
Diameter (mm)	0.018	0.16	0.6
Length (mm)	6	13	30
Shape	Filament	Straight	Indent
Density (gr/cm^3)	0.9	7.8	7.8
T_{melt} (℃)	160 – 170	1370	1370
$T_{vaporize}$ (℃)	341	-	-

Table 2. Mixture proportions

Series	W/C (%)	s/a (%)	Fibre vol. (%)			W (kg/m^3)	C (kg/m^3)	S (kg/m^3)	G (kg/m$^{3)}$	SPAE^{*a} (%×c)
			PP	(S30)	(S13)					
Plain	30	50	-	-	-	170	567	796	781	0.9
PP			0.1					795	780	
HY1				0.3				790	776	
HY2				0.5				788	773	
HY3				0.2	0.1			790	776	
HY4				0.4				788	773	

SPAE^{*a}: Super plasticizer and air entraining agent

Table 3. Fresh and hardened properties of concrete

	FRESH PROPERTIES		HARDENED PROPERTIES			
Series	Slump (mm)	Air content (%)	Density (g/cm^3)	f 'c (MPa)	f t (MPa)	E (GPa)
Plain	215	3.5	2.42	93.08	5.90	40.4
PP	208	2.1	2.47	75.13	4.81	35.7
HY1	145	3.0	2.47	76.53	5.11	43.3
HY2	178	3.3	2.46	89.46	6.47	37.4
HY3	195	3.2	2.46	83.97	5.21	35.5
HY4	193	1.6	2.50	92.19	6.03	37.7

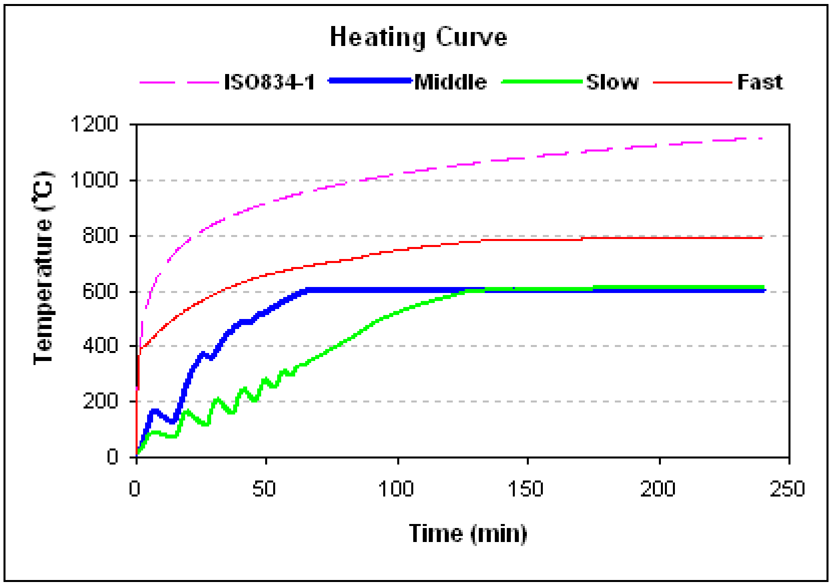


Figure 1. Heating patterns for pore pressure measurement test and ISO 834

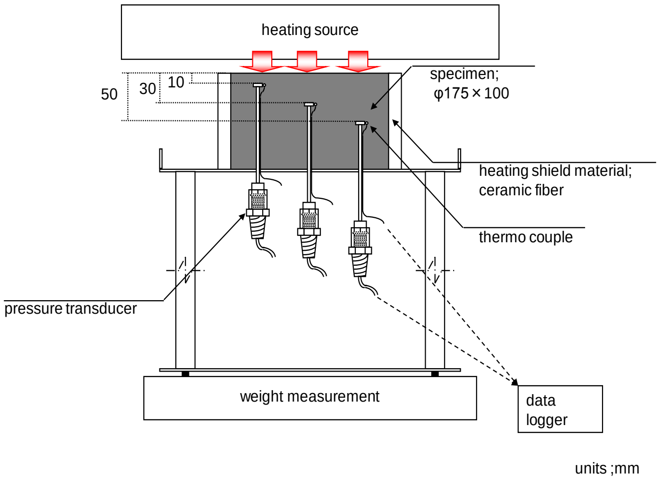


Figure 2. Experimental test set-up

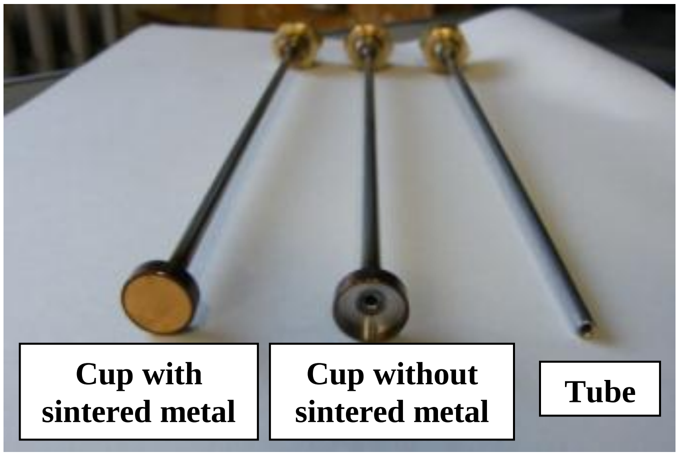


Figure 3. Different pressure gauges

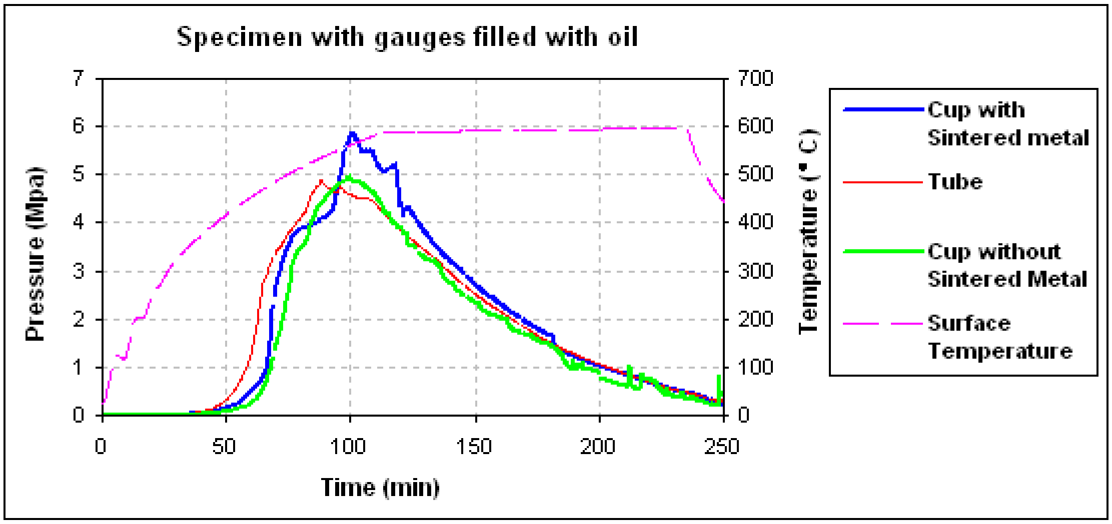


Figure 4. Increase of pressure and temperature with time for specimen with gauges filled with silicon oil

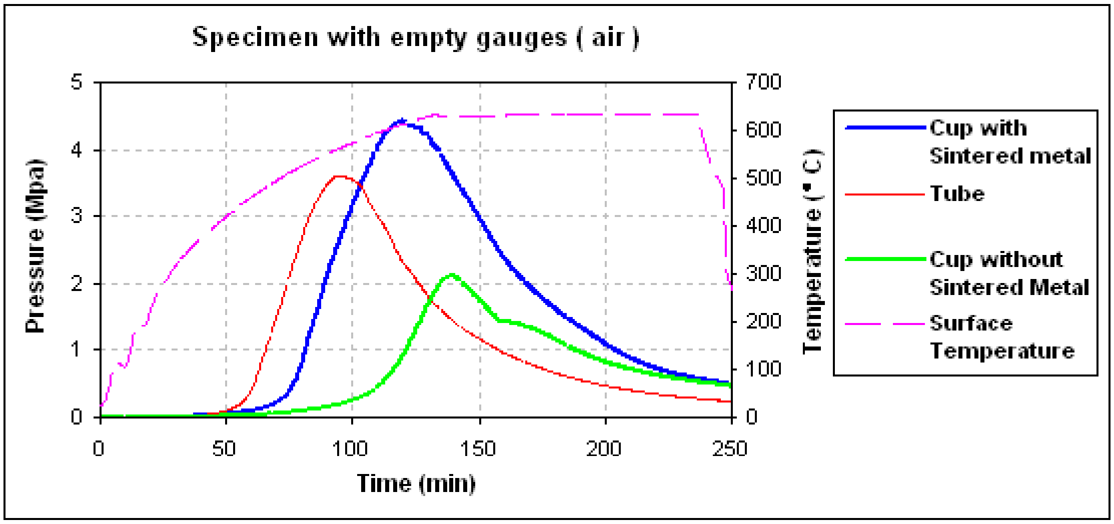
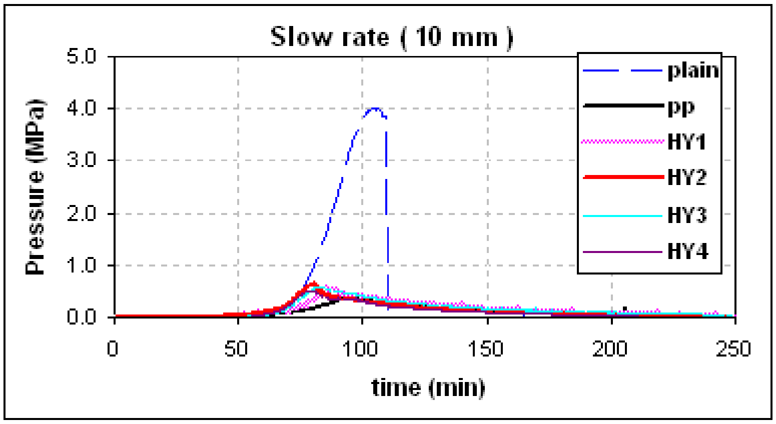
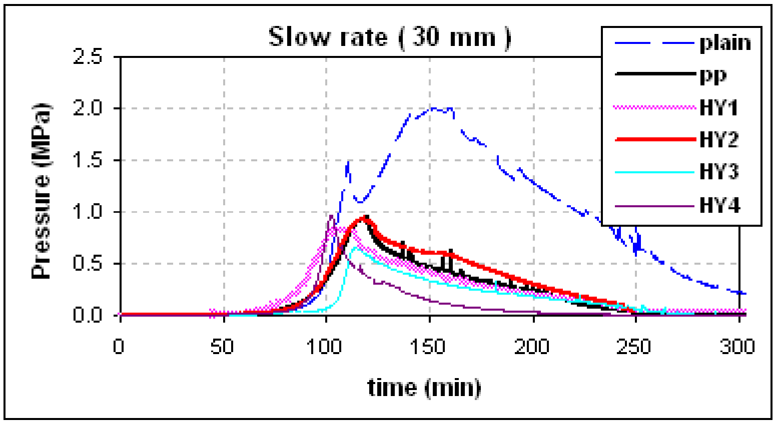


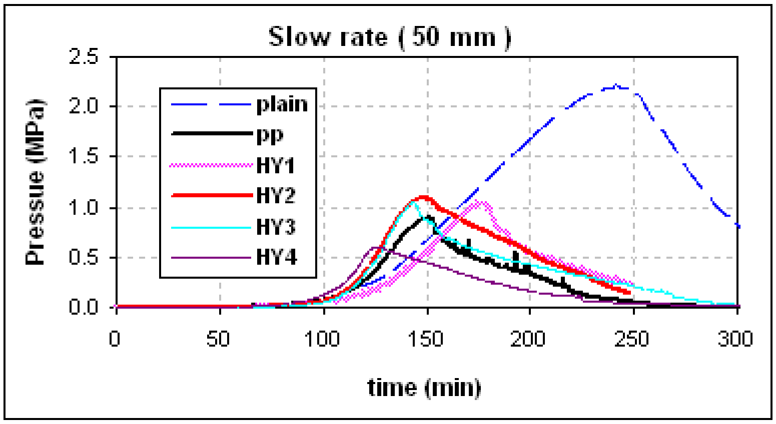
Figure 5. Increase of pressure and temperature with time for a specimen with empty gauges (filled with air)



(a) Slow heating rate at 10 mm depth

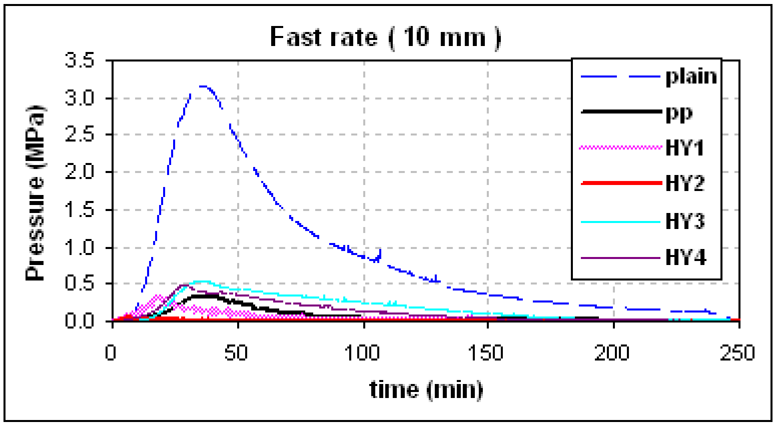


(b) Slow heating rate at 30 mm depth

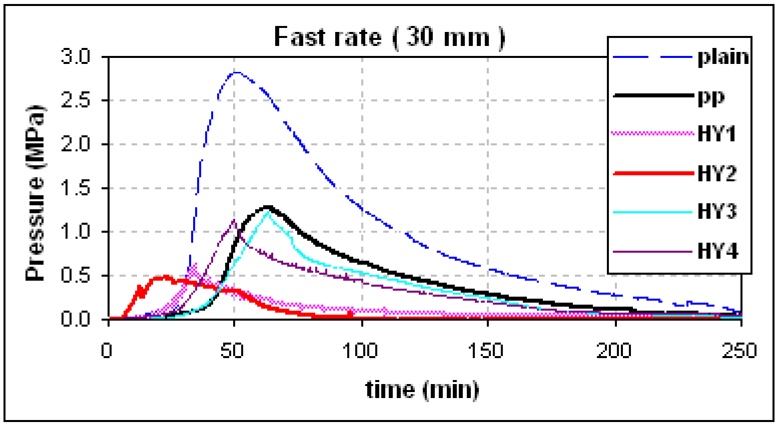


(c) Slow heating rate at 50 mm depth

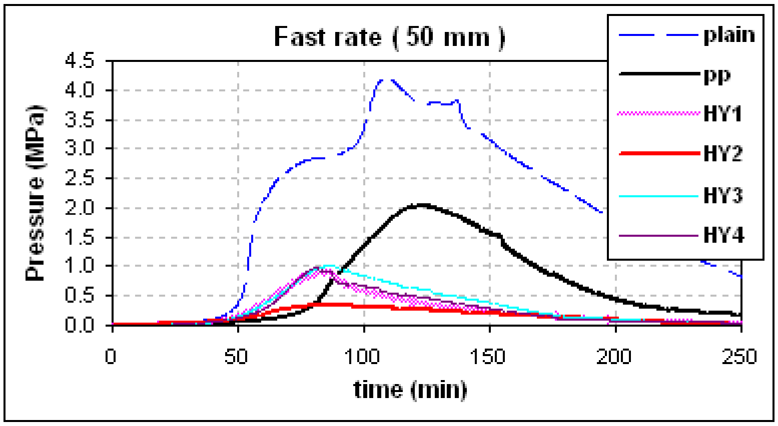
Figure 6. Build – up of pore pressure with time for slow heating rate at different depths of concrete



(a) Fast heating rate at 10 mm depth



(b) Fast heating rate at 30 mm depth



(c) Fast heating rate at 50 mm depth

Figure 7. Build – up of pore pressure with time for fast heating rate at different depths of concrete

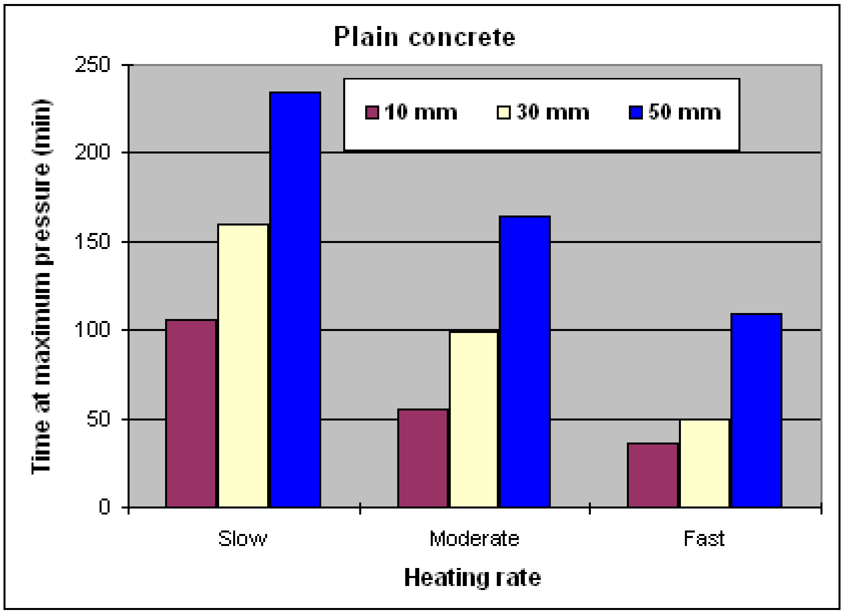
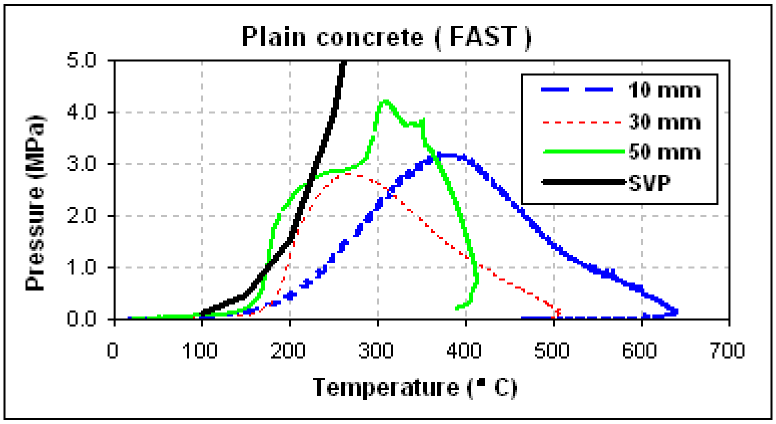
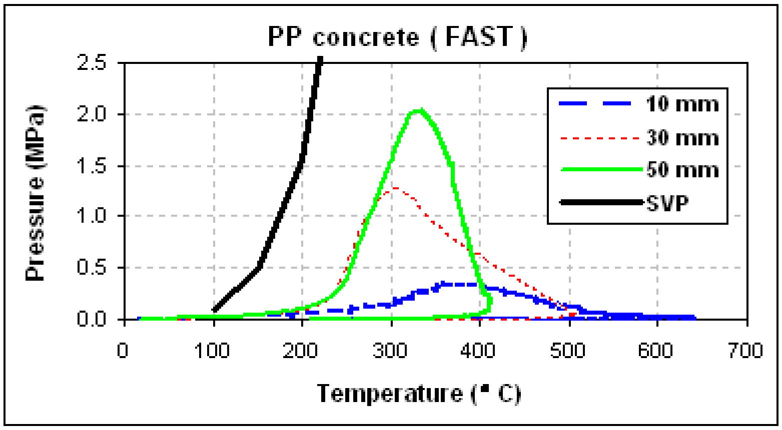


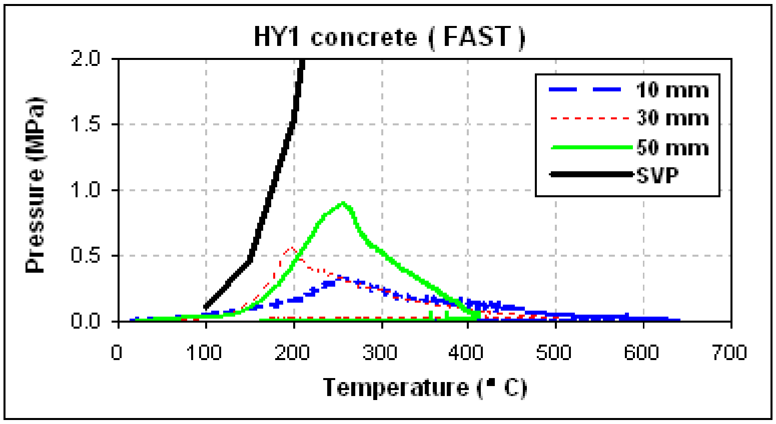
Figure 8. Relationship between times taken to reach maximum pore pressures with respect to heating rates at depths of 10, 30 and 50 mm



(a) Plain concrete

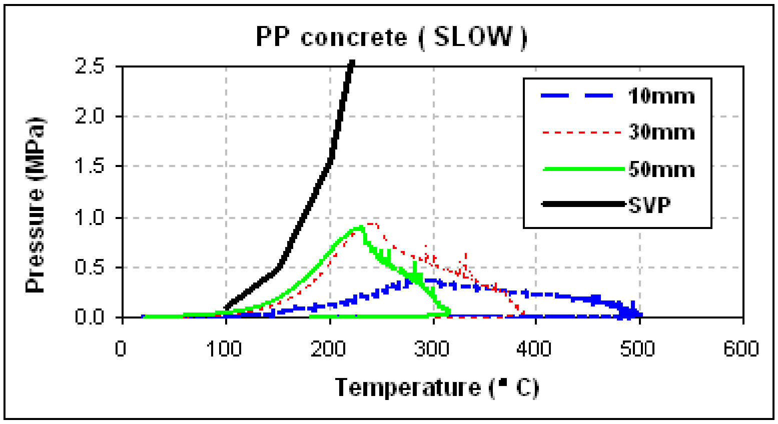


(b) PP concrete

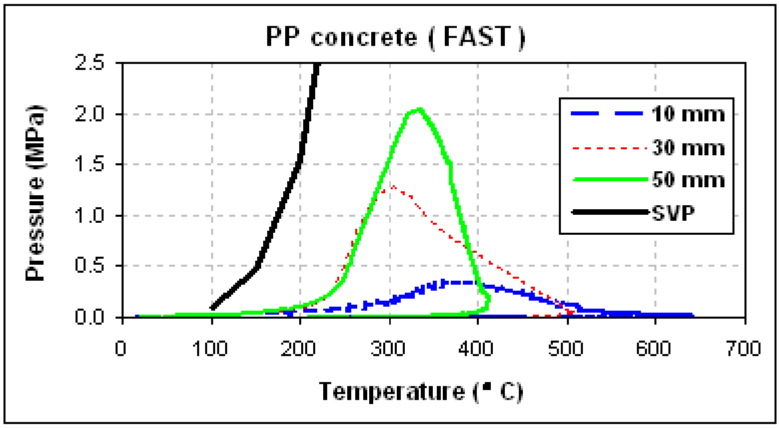


(c) HY1 concrete

Figure 9. Pore pressure and SVP with respect to temperature during fast heating



(a) Slow heating rate



(b) Fast heating rate

Figure 10. Build – up of pore pressure with temperature in PP concrete at different depths of concrete