Pore pressure test for fiber-reinforced self-consolidating concrete exposed to high temperature

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Abstract: Pore pressure is one of the main mechanisms for the explosive spalling of concrete exposed to fire. However, the research on the pore pressure of fiber-reinforced self-consolidating concrete (FRSCC) during fire exposure is very limited. The present experimental work investigates the build-up of pore pressure at different depths of FRSCC when exposed to ISO 384 fire heating curve. Micro polypropylene fiber, macro polypropylene fiber, steel fiber and their hybridizations reinforced SCC were investigated. Pore pressure measurements indicated that micro polypropylene fiber is more effective in mitigating maximum pore pressure development compared to macro polypropylene fiber while steel fiber has a slightly low effect. Steel fiber plays some roles in pore pressure reduction in deeper regions, while the macro PP fiber has a better effect in shallow regions than in deep regions during fire exposure. The positive hybrid effect in pore pressure reduction of steel and micro PP fiber is better than that of steel fiber hybrid macro PP fiber reinforced SCC. Fire exposure will lead to larger internal destruction in SCC. This is likely the reason that the pore pressure in SCC exposed to fire is obviously lower than that of other concrete exposed to electric heating.

Key words: pore pressure; fire; self-consolidating concrete; fiber reinforcement; spalling

1. INTRODUCTION

Fire poses one of the most serious disasters to tunnels and concrete structures. The usage of self-consolidating concrete (SCC) further aggravates this situation because it often results in spalling (Noumowe, 2005., Hans, 2006), as shown in Figure 1. Two main mechanisms can simulate and characterize explosive spalling in concrete (Hertz, 2003., Liu, 2008., Ye, 2007., Mitsuo, 2012). One is related to the thermo-mechanical process, which is directly associated with the temperature field in concrete, as illustrated in Figure 2a. The other one is related to the thermo-hydral process, which is directly associated with the mass transfer of vapor, water and air in the porous network. This thermo-hydral process will result in building up high pore pressures and pressure gradients, as shown in Figure 2b.

Fig. 1 Fire hazard in concrete shield tunnel.

Quantitative analysis of thermo-hydral process mechanism is one of the difficulties to investigate the spalling of SCC. A lot of previous research focus on the pore pressure development of ordinary concrete and high-strength concrete exposed to electric heating (Kalifa, 2000, 2001., Bangi, 2011, 2012 Mindeguia, 2010). The similar study on SCC during fire exposure is very limited (Ye, 2007., Jansson, 2006., Mindeguia, 2007., Jansson, 2007). This paper will present an experimental study on pore pressure development in fiber reinforced self-consolidating concrete during fire exposure. Steel fiber, micro polypropylene fiber, macro polypropylene fiber and their hybridizations reinforced self-consolidating concrete were investigated.

2. EXPERIMENTAL PROCEDURE

Cement (P·O 52.5R), fly ash, fine sand, crushed stone, steel fiber, micro polypropylene (PP) fiber and macro PP fiber were the raw materials used in this study. Their basic properties are shown in Table 1. The mix proportions of plain SCC and fiber reinforced SCC are given in Table 2 and Table 3, respectively.
The specimens with a size of 150mm×150mm×550mm were used for pore pressure tests. After casting, all the specimens were stored in a standard curing room of concrete with molds for 24 hours; thereafter they were demoulded, subjected to 20 °C water and cured for 28 days. The initial moisture of the specimens was between 4 and 5% by mass.
The experimental set-up developed by Kalifa et al. was employed (Kalifa, 2000, 2001), as shown in Figure 3a. Thermal load was applied on one face of the concrete specimen by means of burning liquefied natural gas. The heating pattern is according to ISO 834-1 fire curve, as shown in Figure 3b. In order to investigate the fire spalling and pore development of SCC, the specimen was just exposed to the maximum temperature of 600 °C and lasting for 120 min.

![Fig. 3 Fire test set-up (a) and experimental heating curve (b) for pore pressure measurement.](image)

### 3. RESULTS AND DISCUSSION

#### 3.1 Influence of fiber type on pore pressure development

Figure 4 presents the pore pressure development measurements of plain SCC and mono-fiber reinforced SCC at different depths. It can be observed that the maximum pore pressures measured in plain SCC at all depths are much higher than those of fiber reinforced SCC. The times at maximum pore pressure of fiber reinforced SCC at all depths are longer than that of plain SCC. Micro PP fiber plays a more significant role in reducing pore pressure than macro PP fiber and steel fiber. For all series, the pore pressure in 30 mm depth is the highest. Comparing Figure 4c and other figures, it clearly shows that the addition of steel fiber plays some roles in pore pressure reduction in deeper regions of SCC exposed to fire. This observation is also confirmed by M. R. Bangi in his latest research paper (Bangi, 2011). Macro PP fiber is used more and more widely in concrete construction, therefore, its fire resistance is concerned gradually. From Figure 4d, it can be seen that macro PP fiber plays a more efficient role in pore pressure reduction than steel fiber. Comparing macro PP fiber with steel fiber and micro PP fiber, it seems that the addition of macro PP fiber has a better effect in shallow regions than in deep regions during fire exposure. This is likely a result of the geometric size of macro PP fiber.

#### 3.2 Influence of fiber hybridization on pore pressure development

Figure 5 shows the pore pressure development of hybrid fiber reinforced SCC. Compared Figure 4b, 4c and Figure 5a, it can be observed that the hybridization of steel and micro PP fiber further reduces the maximum pore pressure at all depths, which presents an obvious positive hybrid effect in pore pressure reduction. The inclusion of steel and macro PP fiber results in a slightly lower pore pressure of 0.75 MPa compared to 0.9 MPa measured in mono-macro PP fiber reinforced SCC at the depth of 30 mm. The positive hybrid effect in pore pressure reduction of steel and macro PP fiber is better than that of steel fiber hybrid macro PP fiber reinforced SCC. From Figure 5c, it can be observed that the addition of steel fiber, micro PP fiber and macro PP fiber don’t present a further pore pressure reduction compared to steel fiber hybrid micro PP fiber reinforced SCC. This likely indicates that micro PP fiber plays more important role in reducing pore pressure of SCC during fire exposure.
3.3 Temperature at maximum pore pressure

Figure 6-8 present the results of time and temperature at maximum pore pressure in different depths. From Figure 6, it can be observed that the maximum pore pressure occurs during 13 to 19 min in the depth of 10 mm during exposed to ISO 834 fire curve, while the range of temperature at maximum pore pressure is about 200 to 280 °C. The addition of fibers prolongs the time of observing the maximum pore pressure in all depths. For all series, the pore pressure at the depth of 30 mm is the highest. As shown in Figure 8, it is further importantly observed that the maximum pore pressure occurred in the temperature ranges of 200-230 °C. It seems that the pore pressure relief occurs after melting of PP fibers, since the melting temperature of PP fiber is around 170 °C. This observation is somehow different with M. R. Bangi’s results (Bangi, 2012). The difference of heating pattern (electric radiant heater and fire) and heating rate may lead to this distinction.

Fig. 4 Pore pressure development for plain SCC and mono-fiber reinforced SCC at different depths.

Fig. 6 Time and temperature at maximum pore pressure in 10 mm depth.
3.4 Comparison between electric heating and fire exposure
The main difference between electric heating and fire exposure is the heating rate. Mindeguia et al found that concrete spalling mostly because of the internal cracking during fast heating, i.e. fire (Mindeguia, 2007). This viewpoint was also confirmed by Jansson et al. They found that the residual permeability of concrete exposed to fire was twice that of the concrete exposed to slow heating (Jansson, 2007). These results indicate that fast heating will lead to larger internal destruction in the concrete. This is likely the reason that all the test results of pore pressure in SCC exposed to fire are obviously lower than that of other concrete exposed to electric heating. However, it doesn’t mean that SCC exposed to fire will not spalling. It seems that there is no simple correlation between the magnitude of pore pressure and spalling in SCC exposed to fire. The spalling mechanism of SCC during fire exposure is more complex and further research should be carried out in the future.

4. CONCLUSION
This paper presented an experimental study on pore pressure development in fiber reinforced self-consolidating concrete during fire exposure. Steel fiber, micro polypropylene fiber, macro polypropylene fiber and their hybridizations reinforced self-consolidating concrete were investigated. The following conclusions can be drawn from this study.
1. Micro polypropylene fiber is more effective in reducing pore pressure than macro polypropylene fiber or steel fiber.
2. Steel fiber plays some roles in pore pressure reduction in deeper regions, while the macro polypropylene fiber has a better effect in shallow regions than in deep regions during fire exposure.
3. The positive hybrid effect in pore pressure reduction of steel and micro polypropylene fiber is better than that of steel fiber hybrid macro polypropylene fiber reinforced SCC.
4. The pore pressure in SCC exposed to fire is obviously lower than that of other concrete exposed to electric heating. Larger internal destruction in SCC during fire exposure maybe explains this phenomenon.
Acknowledgements
The authors acknowledge the National Natural Science Foundation of China (Grant: 51578109), the National Natural Science Foundation of China (Grant: 51121005), DUT and Fundaçãopara a Ciência e a Tecnologia (SFRH/BPD/22680/2005), the FEDER Funds through “Programa Operacional Factores de Competitividade - COMPETE” and by Portuguese Funds through FCT-within the Projects PEst-C/CMAT/UI0013/2011 and PTDC/MAT/112273/2009.

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