8th International Conference on Structures in Fire
Shanghai, China, June 11-13, 2014

EXPERIMENTAL STUDY ON THE EXPLOSIVE SPALLING IN HIGH-PERFORMANCE CONCRETE: ROLE OF AGGREGATE AND FIBER TYPES

Francesco Lo Monte *, Jihad M. Miah, Aktar Shamima, Riccardo Negri, Chiara Rossino*** and Roberto Felicetti***

* Department of Civil and Environmental Engineering, Politecnico di Milano, Milan (Italy)
e-mails: francesco.lo@polimi.it, roberto.felicetti@polimi.it

*** Univ. Paris Est, CSTB, Centre Scientifique et Technique du Bâtiment, Marne la Vallée (France)
e-mail: Jihad.MIAH@cstb.fr

*** CTG Italcement Group, Bergamo (Italy)
e-mail: c.rossino@itcgr.net

Keywords: Aggregate, concrete, fiber, pore pressure, spalling, tensile behavior

Abstract. *A complete description of the mechanical behavior of High-Performance Concrete in fire still requires further efforts to fully understand the tricky phenomenon of spalling, whose complexity comes from the interaction among different phenomena, namely: the microstructural changes occurring in concrete at high temperature, the pressure rising in the pores, and the stress induced by both thermal gradients and external loads. To what extent these different aspects influence each other is still not completely clear, and within this context a comprehensive experimental campaign has been launched at the Politecnico di Milano, focusing on the role played by concrete grade, aggregate type, and fiber type and content. Eleven concrete mixes are investigated considering three grades ($f_c \geq 40$, 60 and 90 MPa), three aggregate types (silico-calcareous, basalt and calcareous aggregates) and different fiber types and contents (steel and monofilament or fibrillated polypropylene fibers).*

1 INTRODUCTION

Explosive spalling is the violent or non-violent breaking off of layers or pieces of concrete from the surface of a R/C structural member when it is exposed to more or less rapidly rising temperatures, as experienced in fires. Low-porosity High-Performance Concrete is more prone to such phenomenon with respect to Normal-Strength Concrete due to the higher values of pore pressure developed during heating [1], as a consequence of material low permeability [2].

Concrete spalling is generally recognized to ensue from the interaction between thermal and load-induced stresses (thermo-mechanical problem, figure 1b) and pore pressure rise due to water vaporization (hygro-thermal mechanism, figure 1c), both aspects being influenced by heat-induced damage and microstructural changes in concrete.

An effective way to reduce concrete spalling sensitivity is to add polypropylene (pp) fiber. Even though the reason way pp fiber reduces spalling risk is not fully understood, it seems to be related to an increase of concrete permeability induced by two main processes: (a) fiber melting at 160-170°C, which leaves free channels for vapor release (furthermore, fiber melting is accompanied by expansion that favors cement past microcracking and the ensuing interconnection among the pores), and (b) further microcracking in the cement matrix due to stress intensification around the edges of the channels left free by fiber melting (notch-effect, sizeable mainly at T ≥ 250-300°C [3,4]), this causing, again, an increase in permeability.

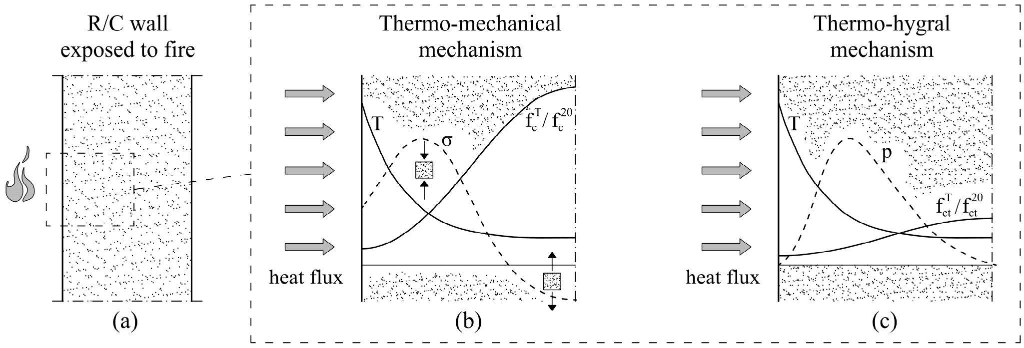


Figure 1. (a) Concrete spalling mechanisms in a heat-exposed wall; qualitative plots of: (b) temperature T, thermal stress σ and normalized compressive strength f_c^T / f_c^{20}; and (c) pore pressure p and normalized tensile strength f_{ct}^T / f_{ct}^{20}.

Even though some studies regarding pore pressure mechanism have been carried out in the past, how pore pressure affects concrete tensile strength and how mix design influences the interaction between the former two quantities are still open issues. Within this context, a few experimental investigations have been conducted showing that the decay of the "apparent" indirect tensile strength due to pore pressure can be equal to - or even exceed - the value of the pressure itself [5,6]. Furthermore, the role played by the main constituents of the mix design (first of all aggregate and fiber) on the tensile strength-pore pressure relationship have to be tackled, with the aim of giving to designers and contractors useful tools to assess spalling sensitivity of a given concrete and to optimize the mix design [7,8].

To this aim, a comprehensive experimental campaign has been recently launched at the Politecnico di Milano, involving eleven concrete mixes (see [8] for more details): three grades have been considered ($f_c \geq$ 40, 60 and 90 MPa, silico-calcareous aggregates); for the intermediate class, also calcareous and basalt aggregates were used, and in the case of silico-calcareous aggregates, both plain and fiber-reinforced mixes were cast (with steel and monofilament or fibrillated polypropylene fibers).

2 TEST PROCEDURE

In order to investigate concrete spalling sensitivity and the role played by aggregate and fiber types, compressive tests in residual conditions and splitting tests under different levels of sustained pore pressure have been performed on the eleven mixes.

Compressive behavior has been characterized at room temperature and after heating to 105, 250, 500 and 750°C. Thermal cycles have been defined in order to induce in each specimen a uniform thermal field in order to consider the heat-induced damage uniformly distributed; to this end, reference to the indications given in RILEM TC 129-MHT Committee (1995) was made. Then, all specimens were slowly heated to the reference temperature (heating rate = 1°C/minute), at which they rested for two hours to guarantee the uniformity of the thermal field. Afterwards, the specimens were slowly cooled down to 200°C in controlled conditions (cooling rate = 0.25°C/minute) and to 20°C in natural conditions (inside the closed furnace). The thermal cycles are plotted in figure 2a.

For all mixes, fifteen cylinders were cast (∅ = 10 cm, h = 20 cm, figure 2b), so that three specimens were available for each mix and reference temperature. All tests in compression were displacement-controlled and the strain of the specimens was measured via 3 resistive gauges placed at 120° astride the mid-height section (base length 5 cm); moreover, 3 LVDTs measured the platen-to-platen distance of the press to monitor the post-peak behavior (see figure 2b). In all tests in compression, stearic acid was smeared on the end sections of the specimens to reduce the platen-to-concrete friction.

An electro-mechanical press was used (Schenck, capacity = 1000 kN) and the loading rate was defined according to EN 12390-3 (2009). The stiffness (elastic modulus, E_c) was evaluated from the stress-strain curves in compression as secant modulus ($\sigma_c \leq 0.5\ f_c$).

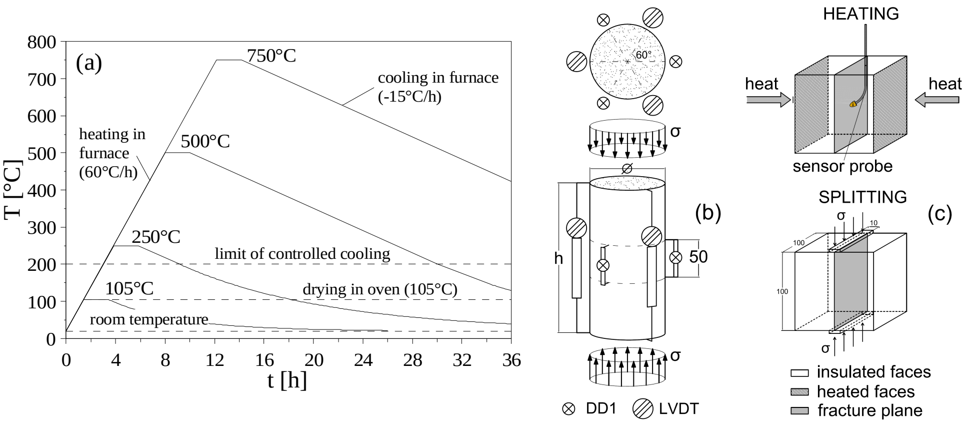


Figure 2. Tests in compression: (a) adopted thermal cycles and (b) typical specimen ready to be tested (the top platen is connected to a self-blocking spherical head). (c) Scheme of the splitting test under sustained pore pressure.

Splitting tests under sustained pore pressure have been performed on cubic specimens (L = 10 cm) for all the mixes except steel fiber-reinforced concretes. Heating was applied on two opposite faces, while the other four faces were sealed and insulated in order to instate a transient unidimensional hygro-thermal flux (figure 2c); pore pressure and temperature were measured in the centroid of the specimens by means of customize probes and when peak pressure was reached, splitting test was performed forcing the fracture plane to coincide with the symmetry plane, according to the procedure described in [5,6,8].

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Stress-strain curves in compression in residual conditions

The mean stress-strain curves in uniaxial compression are shown in figure 3, comparing for each temperature the curves related to all mixes.

As expected, pp fiber does not influence significantly compressive strength in neither virgin nor residual conditions (the differences are mainly related to the scattering that characterizes a heterogeneous material such as concrete). On the contrary, the addition of pp fiber brings a greater heat-sensitivity with respect to plain concrete in terms of stiffness, mainly after exposure to 250 and 500°C, where it seems clear that the higher the fiber content, the lower the stiffness; this can be ascribed to the microcracking favored by fiber melting and expansion (at 160-170°C), and by stress intensification at the edges of the channels left free by melt fiber (notch-effect, for T ≥ 250-300°C).

Steel fiber sizably affects compressive strength after heating to 500 and 750°C, leading to definitely higher values than in plain mix; this is due to the increased dilatancy of damaged concrete and to the effective confinement provided by steel fibers. On the contrary, there is no influence on concrete stiffness. (Note that increasing steel fiber content above 40 kg/m^3 gives no further beneficial effects).

Aggregate type proves to play a major role. In virgin conditions calcareous concrete exhibits a compressive strength comparable to that of silico-calcareous concrete, while the elastic modulus of the former is definitely higher (f_c^{20} = 68.7 and 63.7 MPa, E_c = 40.8 and 31.7 GPa, respectively). After heating, however, calcareous aggregate brings in the highest thermal sensitivity in terms of compressive strength and elastic modulus, this being probably caused by a more pronounced microcracking induced by heating. Basalt concrete shows the highest compressive strength in virgin conditions (f_c^{20} = 78.8 MPa), but also the lowest elastic modulus (E_c = 26.2 GPa). Basalt concrete, however, proves clearly to be the least heat-sensitive in terms of both strength and elastic modulus. Hence, it is possible to state that moving from basalt to silico-calcareous and calcareous aggregates, concrete solidness at high temperature decreases due to increasing microcracking.

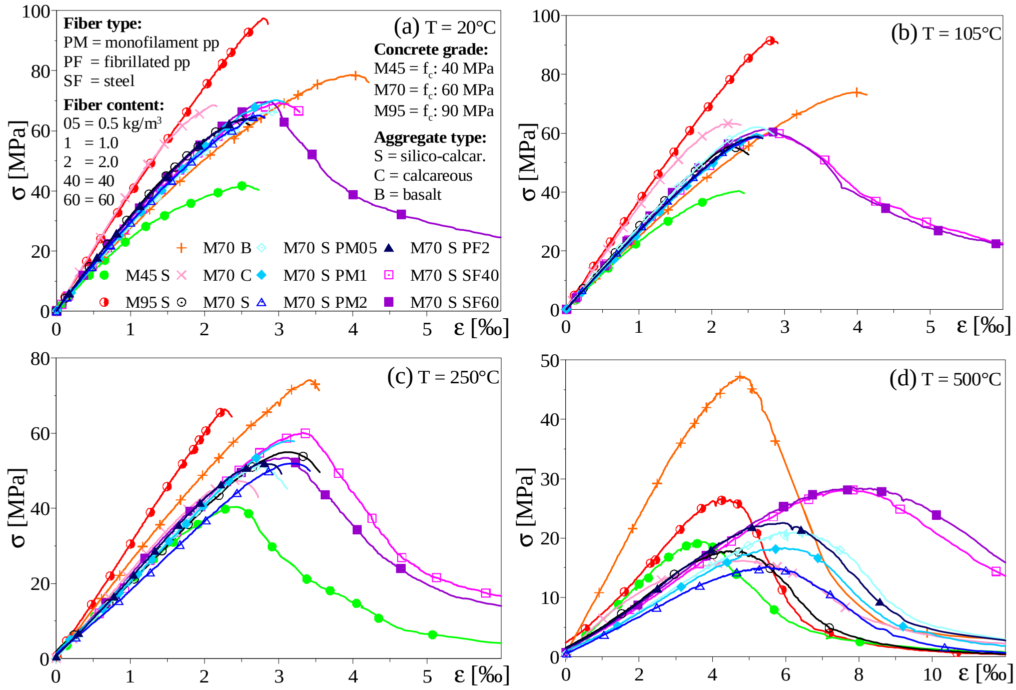


Figure 3. Mean stress-strain curves in uniaxial compression for all the mixes at different temperatures.

3.2 Splitting tests under sustained pore pressure

Splitting tests under sustained pore pressure on 10cm-side cubes have been performed on all mixes, except steel fiber-reinforced concretes. In figure 4 the pressure development in the centroid of the specimens is plotted as a function of the temperature together with the vapor saturation pressure curve P_{SV} (Clausius-Clapeyron equation). Generally speaking, the scattering among the tests is rather limited and it is higher for fiber-concrete due to the random dispersion of the fibers in the cement matrix. The experimental curves, however, are rather close to P_{SV} (as in [5]).

As concern the peak pressure reached by each concrete mix, Figure 5a shows that: (1) the higher the concrete grade, the higher the maximum pore pressure (compare M45 S and M70 S for HR = 2°C/min, and M70 S and M95 S for HR = 0.5°C/min), due to the decrease of porosity and permeability and the ensuing increase in compactness; (2) basalt and silico-calcareous concretes yield similar results, while calcareous concrete is characterized by a lower value; (3) adding increasing amount of monofilament pp fiber leads to a sizable decrease of pore pressure due to the increase of concrete permeability (and the subsequent decrease in compactness); (4) monofilament pp fiber is definitely more effective than fibrillated pp fiber in reducing the pressure (0.5 kg/m^3 of the former are more efficient than 2 kg/m^3 of the latter).

In figures 5b,c,d the values of the apparent indirect tensile strength are plotted for all the tests against the pore pressure measured during the splitting test. For the nine mixes, a linear regression was performed in order to investigate the influence of pore pressure on concrete fracture behavior. In the insert of figure 6, the absolute values of slope k and intercepts f_{sp}^{th} (that can be considered as the tensile strength of concrete for zero pressure) of the linear regressions are shown together with the maximum pore pressure p_{max} reached by each mix and the experimental tensile strength by splitting in virgin conditions f_{sp}^{20}.

Note that for the adopted heating rate (0.5°C/min), the thermal stress and the ensuing microcracking are negligible.

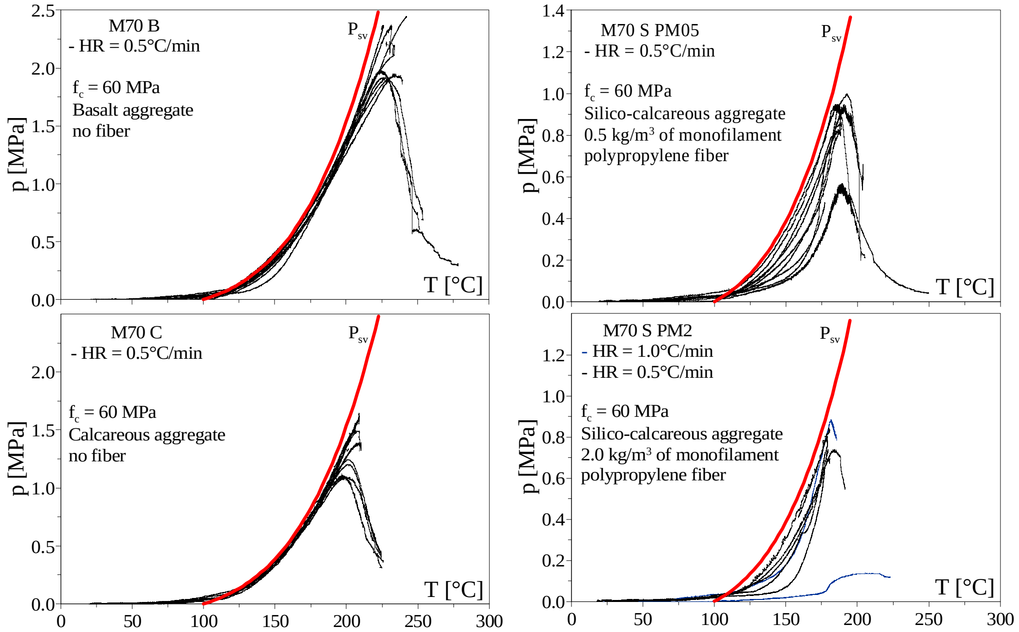


Figure 4. Pressure as a function of the temperature in the centroid of the specimen, together with the vapor saturation pressure curve P_{SV} (Clausius-Clapeyron equation), for two plain and two pp fiber concretes.

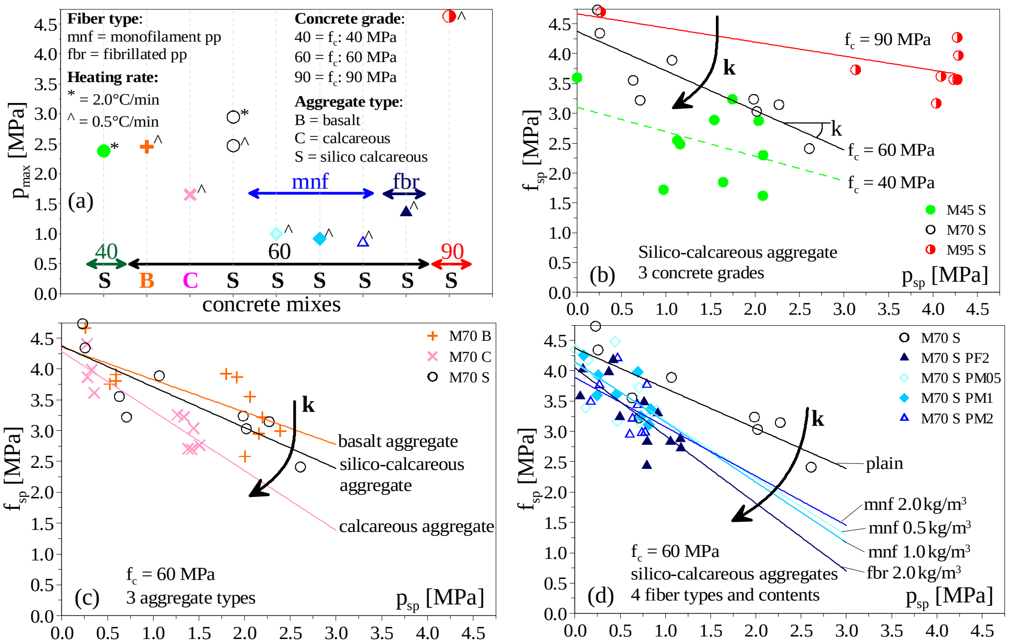


Figure 5. Plots of: maximum pore pressure reached by each concrete mix (a); indirect tensile strength by splitting with respect to the pressure in the centroid of the specimen during the splitting test - three concrete grades (b); three aggregate types (c); and concrete with and without monofilament/fibrillated polypropylene fibers (d).

It is worth noting that both the maximum pore pressure and the slope k (i.e. the magnitude of the tensile strength loss per unit value of pore pressure) are related to concrete microstructure (porosity, microcracks pattern and permeability); this is reasonable because both mass transport phenomena and fracture mechanics are influenced by concrete microstructure.

In all the cases, the values of k are definitely higher than the value of the porosity and in five cases approach the unit value (for calcareous and pp fiber concretes).

As regards concrete grade, no specific trends appear evident. However, neglecting the results regarding the lowest grade (f_c = 40 MPa), whose sizable scattering makes any comment hardly possible, a trend linking concrete grade and k looks possible: the higher the concrete grade (and, therefore, the higher the compactness), the lower the influence of pore pressure on the tensile strength.

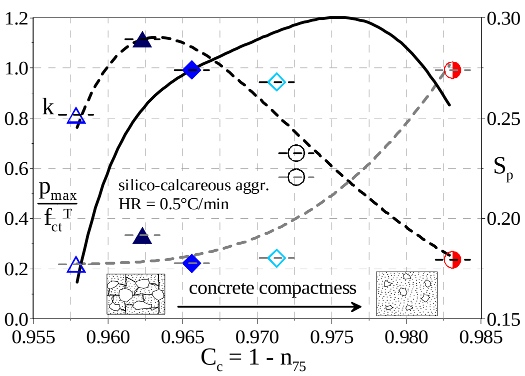
This can be explained by recalling Biot's coefficient for porous media and making an analogy with Soil Mechanics. In fact, for heavily-cemented sedimentary rocks, Biot's coefficient is close to the value of the porosity, while for lightly-cemented sedimentary rocks is close to the unit value. Assuming for high- and low-porosity concretes a likeness to lightly- and heavily-cemented sedimentary rocks, respectively, an explanation can be found for the abovementioned trend. This hypothesis is consistent, also, with the value of k for fiber concretes, where k is close to the unit value (fiber concretes are characterized by higher values of porosity compared to plain concretes).

The same comment can be made regarding aggregate type: basalt concrete shows lower thermal sensitivity (hence, higher compactness at high temperature) and a lower value of k, while calcareous concrete exhibits the largest thermal sensitivity and the highest value of k. This suggests, once more, that the higher the compactness, the lower k.

In figure 6 the plots of the fitting curves for slope k and normalized maximum pore pressure p_{max}/f_{ct}^T are drawn together with the experimental data related to silico-calcareous concretes heated at the rate of 0.5°C/min, as a function of concrete compactness C_c (= 1 – n_{75}, where n_{75} is the porosity related to the pores with radius greater than 75 nm, evaluated after exposure to 250°C).

The critical pore radius of 75 nm has been chosen assuming that permeability and strength are influenced by large-radius pores rather than by the total porosity, as shown in the works by Goto and Roy [9], and Mehta and Manmohan [10], where the values of the threshold pore radius affecting concrete water permeability were found to be 75 and 66 nm, respectively.

Figure 6 shows that, with a good approximation, increasing values of concrete compactness are associated with increasing values of the maximum pore pressure, and decreasing values of the slope k.



	Mix	k [-]	p_{max} [MPa]	f_{sp}^{th} [MPa]	f_{sp}^{20} [MPa]
	M45 S	0.411	2.38	3.10	3.98
	M70 B	0.526	2.45	4.35	4.97
	M70 C	0.967	1.65	4.28	4.57
	M70 S	0.661	2.47	4.37	4.70
	M70 S PM05	0.944	1.00	4.12	4.71
	M70 S PM1	0.992	0.92	4.15	4.63
	M70 S PM2	0.813	0.85	3.89	5.31
	M70 S PF2	1.115	1.35	4.05	4.89
	M90 S	0.236	4.63	4.67	5.39

$S_p = k \cdot \left(\frac{p_{max}}{f_{ct}^T}\right) = \frac{\Delta f_{ct}}{f_{ct}^T}$ $k = \frac{\Delta f_{ct}}{p}$ $\frac{p_{max}}{f_{ct}^T}$

Figure 6. Plots of the fitting curves for slope k, normalized maximum pore pressure p_{max}/f_{ct}^T and spalling sensitivity index S_p, together with the experimental data for silico-calcareous mixes heated at 0.5°C/min, as a function of concrete compactness $C_c = 1 – n_{75}$. n_{75} = volume of the pores with radius ≥ 75 nm, per unit volume of concrete (after exposure to T = 250°C); k = slope of the regression lines of figure 5; p_{max} = maximum pore pressure, $f_{ct}^T = f_{sp}^{th}$ = indirect tensile strength for zero pressure (intercept of the regression lines of figure 5); f_{sp}^{20} = indirect tensile strength by splitting in virgin conditions.

The index S_p related to pore-pressure role in triggering concrete spalling can be defined as the product between the normalized maximum pore pressure reached by the given concrete mix and the value of k (S_p = maximum normalized decay of concrete tensile strength due to pore pressure [8]):

$$S_p = k \cdot \frac{p_{max}}{f_{ct}^T} = \frac{\Delta f_{ct}}{p_{max}} \cdot \frac{p_{max}}{f_{ct}^T} = \frac{\Delta f_{ct}}{f_{ct}^T} \tag{1}$$

where f_{ct}^T is the indirect tensile strength at the temperature T for zero pressure, assumed to be equal to the intercept of the regression lines in figure 5.

A qualitative plot of S_p, obtained by multiplying the fitting curves of slope k and normalized maximum pressure p_{max}/f_{ct}^T, is reported in figure 6 as a function of concrete compactness. Since k and p_{max} have opposite trends with respect to concrete compactness (the former decreases, while the latter increases), any possible change of S_p related to concrete type cannot be foreseen.

As regards the effect of pp fiber, moving from plain concrete to concretes containing increasing amounts of monofilament pp fiber, the normalized index S_p decreases (from 0.37 in plain concrete to 0.23, 0.22 and 0.18 for 0.5,1 and 2 kg/m^3 of pp fiber, respectively), as a demonstration of the decreasing spalling risk brought in by adding pp fiber. (No reduction can be observed when adding fibrillated pp fiber, being S_p = 0.37 for both plain mix and concrete with 2 kg/m^3 of fibrillated pp fiber).

No clear trends appear with concrete grade (S_p = 0.32, 0.37 and 0.23, for f_c = 40, 60 and 90 MPa, respectively). Nevertheless, note that S_p gives information just about the activation of spalling induced by pore pressure, but no indications about fracture propagation when spalling occurs. Concerning this issue, the higher brittleness and the markedly higher pore pressure typical of High-Performance Concrete, make this material more prone to explosive spalling compared to Normal-Strength Concrete, with more violent fracturing processes.

As concerns the aggregate type, the index S_p is equal to 0.30 in basalt concrete and 0.37 in calcareous and mixed-aggregate concretes, showing that the pore-pressure related spalling risk is almost the same in these latter two mixes, and lower in basalt concrete.

4 CONCLUDING REMARKS

The influence of transient hygro-thermal conditions in concrete fracture response has been investigated with two objectives: firstly, to quantify the influence of pore pressure on the tensile-strength decay, and secondly, to understand the role played by concrete grade, aggregate type, fiber type and content in the relationship between pore pressure and tensile behavior.

The experimental results show that adding 0.5 kg/m^3 of polypropylene fibers is sufficient to reduce dramatically the risk of spalling (even more than adding 2 kg/m^3 of fibrillated polypropylene fibers), for the heating rates considered in the present study. The rate k of the strength loss in tension, $\Delta f_{ct}^T = k \cdot p(T)$, due to pore pressure p(T), depends on concrete microstructure: the higher the compactness, the lower k, according to Soil Mechanics analogy. In particular k decreases for higher concrete grades, while increases when polypropylene fibers are added and if calcareous or mixed aggregate are preferred to basalt aggregate. Pore pressure exhibits an opposite trend with respect to k: the higher the compactness, the higher the maximum pore pressure;

The index of spalling sensitivity S_p, related to pore-pressure contribution to spalling activation can be defined as the product between the slope k and the normalized maximum pore pressure (S_p = maximum normalized tensile-strength loss induced by pore pressure). The experimental results show that:

- the spalling sensitivity index S_p decreases moving from plain concrete to concretes containing increasing amounts of monofilament polypropylene fiber;
- adding fibrillated polypropylene fiber is less effective than adding similar or lower amounts of monofilament polypropylene fiber;
- using basalt aggregate instead of calcareous or mixed aggregates decreases spalling sensitivity;
- no particular trends are evident in terms of how concrete grade affects spalling sensitivity.

Note that explosive spalling should occur when the index S_p reaches the critical value of 1, which means that the tensile-strength decay is equal to the tensile strength itself. In this work, however, the maximum value of S_p was only 0.37, suggesting that pore pressure as such is unable to trigger concrete spalling and that other factors should come into play (like thermal and load-induced stresses).

Furthermore, the index S_p gives no information on fracture propagation when spalling occurs, this limitation being critical in the case - for instance - of High Performance Concrete, which is more prone to explosive spalling because of the dramatically higher values of pore pressure (as confirmed by the splitting tests performed by the author, which demonstrate that even relatively small pore pressure values make the fracture process increasingly faster). The conclusion is that the interaction among the various actors playing a role in concrete spalling - pore pressure in the front line - is still an open problem in need of further - and hopefully exhaustive - experimental evidence.

ACKNOWLEDGMENTS

The authors would like to thank Professor Pietro G. Gambarova (Politecnico di Milano, Milan, Italy) for all suggestions and discussions helpful in the development of the present work.

The experimental campaign was financed by CTG Italcementi Group (Bergamo, Italy), which cast all the specimens, within the Project “Thermo-Mechanical and Spalling Sensitivity of High-Performance Concretes subjected to High Temperature” (2012-2014).

REFERENCES

[1] Khoury A. G., “Effect of fire on concrete and concrete structures”, *Progress in Structural Engineering and Materials*, 2, 429-447, 2000.

[2] Kalifa P., Menneteau F. D. and Quenard D., “Spalling and Pore Pressure in HPC at High Temperatures”, *Cement and Concrete Research*, 30, 1915-1927, 2000.

[3] Pistol K., Weise F., Meng B. and Schneider U., “The Mode of Action of Polypropylene Fibres in High Performance Concrete at High Temperatures”, *Proc. of the 2nd Int. W. Concrete Spalling due to Fire Exposure*, October 5-7, Delft (the Netherlands), 289-296, 2011.

[4] Tsimbrovska M., Kalifa P., Quenard D. and Dai¨an, J.F., “High performance concrete at elevated temperature: permeability and microstructure”, *Transactions of the 14th Int. Conf. on Structural Mechanics in Reactor Technology*, Lyon (France), 475-482, 1997.

[5] Felicetti R., Lo Monte F. and Pimienta P., “The influence of pore pressure on the apparent tensile strength of concrete”, *Proceedings of the 7th International Conference on Structures in Fire – SIF’12*, June 6-8, 2012, Zurich (Switzerland), 589-598, 2012.

[6] Felicetti R. and Lo Monte F., “Concrete Spalling: Interaction between Tensile Behavior and Pore Pressure during Heating”, *Proc. of the 3rd Int. W. on Concrete Spalling due to Fire Exposure*, September 25-27, Paris (France), DOI: 10.1051/matecconf/20130603001, 2013.

[7] Rossino C., Lo Monte F., Cangiano S., Felicetti R. and Gambarova P.G., “Concrete Spalling Sensitivity versus Microstructure: Preliminary Results on the Effect of Polypropylene Fibers”, *Proc. of the 3rd Int. W. on Concrete Spalling due to Fire Exposure*, September 25-27, Paris (France), DOI: 10.1051/matecconf/20130602002, 2013.

[8] Lo Monte F., *Reinforced Concrete in Fire: from Materials Behaviour to Spalling Sensitivity and Structural Modelling*, PhD Thesis, (Supervisors: Gambarova P.G. and Felicetti R.), Politecnico di Milano, Milan (Italy), 2014.

[9] Goto S. and Roy D.M., “The Effect of W/C Ratio and Curing Temperature on the Permeability of Hardened Cement Paste”, *Cem. and Conc. Research*, 11 (4), 575-580, 1981.

[10] Mehta P.K. and Manmohan D., “Pore Size Distribution and Permeability of Hardened Cement Pastes”, *Proc. of the 7th Int. Congress on the Chemistry of Cement*, Paris (France), V.III, pp.VII-1-5, 1980.