ARCHIVES OF CIVIL ENGINEERING, LVI, 1, 2010

DOI: 10.2478/v.10169-010-0003-z

THE IMPACT OF THE AMOUNT AND LENGTH OF FIBRILLATED POLYPROPYLENE FIBRES ON THE PROPERTIES OF HPC EXPOSED TO HIGH TEMPERATURE

I. HAGER[1], T. TRACZ[2]

This paper presents the results of research on high performance concretes (HPC) modified by the addition of polypropylene fibres (PP fibres). The scope of the research was the measurement of the residual transport properties of heated and recooled concretes: gas permeability and surface water absorption. Seven types of concrete modified with fibrillated PP fibres were tested. Three lengths: 6, 12 and 19 mm and three amounts of fibres: 0, 0.9 and 1.8 kg/m^3 were used. The research programme was designed to determine which length of fibres, used in which minimum amount, will, after the fibres melt, permit the development of a connected network and pathway for gases and liquids.

Key words: high performance concretes, high temperature, spalling, PP fibres, gas permeability.

1. INTRODUCTION

The behaviour of high performance concrete (HPC) exposed to high temperature can prove a major limitation on the use of such concrete in the construction industry. HPC exposed to high temperature can be prone to explosive spalling, which could result in the exposure of steel reinforcement. This would create a vulnerability in the load-bearing capacity and stability of the structural element.

According to various sources (BAZANT [1], HERTZ [2], KALIFA *et al.* [3]), the explosive behaviour of concrete is a combination of two phenomena occurring simultaneously in heated concrete: a thermo-mechanical effect and a hydro-thermal effect. The temperature increases the pressure of the gas and liquid contained in the material's pores, accompanied by rapid moisture vaporization within the surface area of the heated concrete (hydro-thermal effect). Additionally, the difference of thermal strains in layers of concrete with different temperature (thermo-mechanical effect) becomes apparent in the heated material, and the accumulated energy is released violently, resulting in the so-called explosive spalling. These two effects together cause unfavourable stresses in

---

[1] Ph.D., Institute of Building Materials and Structures, Cracow University of Technology, Poland, e-mail: ihager@pk.edu.pl

[2] Ph.D., Institute of Building Materials and Structures, Cracow University of Technology, Poland, e-mail: ttracz@pk.edu.pl

concrete. In situations where the stress exceeds the ultimate tensile strength of concrete and an explosive spalling can occur. As numerous tests have shown (Kalifa *et al.* [4], Nishida *et al.* [5], Hoff *et al.* [6]), polypropylene fibres improve the stability of high performance concrete exposed to high temperature. At temperature close to 170°C the fibres melt. The melted polypropylene is partly absorbed by the cement matrix [4], creating a network of open pores, which increases permeability, and consequently reduces the internal pressure in heated concrete. However, the exact mechanism by which PP fibres work is still not fully explained. In the research conducted by Kalifa *et al.* [4], an increase was observed in the micro-cracking of heated concrete with PP fibres compared to concretes without fibres. This suggested that the presence of fibres in the cement matrix may be considered as a discontinuity that favours the initiation and development of micro cracks during heating, contributing to an increase in concrete permeability. Moreover, it has been pointed out that while melting, polypropylene undergoes a transition from the crystalline to the amorphous phase (polypropylene density decreases from 910 kg/m^3 to 850 kg/m^3), which causes its volume increase by approximately 7% (Pasquini [7]).

The results presented here are a continuation of the research carried out by the authors and described in Hager and Tracz [8]. In that study, the properties of two types of concrete were compared: concrete without fibres and concrete with an addition of PP fibres amounting to 1.8 kg/m^3. The results obtained suggested that the addition of PP fibres was effective and had the desired impact causing a considerable increase in concrete permeability after melting. The increase in the transport properties of the concrete was confirmed by measurements of its surface absorption, which demonstrated that the capillary porosity of concrete with fibres when heated to 160÷200°C was higher than that one of concrete without fibres.

The results presented in this article provide a summary of the results of an extensive research program described partially in Hager and Tracz [9, 10]. The aim of the research was to establish the optimum amount and length of PP fibres allowing to obtain an effective porous network and thus the reduction of pore pressure during heating. From the technical point of view, the use of polypropylene fibres in quantities amounting to 0.1÷0.2% of concrete volume is an effective way of limiting the occurrence of spalling in HPC; however, there are no reports that would clearly indicate the optimum fibre length. According to the percolation model presented by Bentz [11], given a fixed amount of fibre, long fibres should be more efficient.

The objective of this research was to assess the impact of temperature to which concrete is heated on concrete properties affecting its ability to allow liquid and gas transport. The research included the determination of such properties as gas permeability, surface water absorption and microporosity for several types of concrete before and after heating. These properties are the most relevant to the quantitative assessment of the effectiveness of polypropylene fibres as an additional limiting of the occurrence of spalling in HPC. Moreover, the impact of heating temperature on changes in the compressive strength of samples heated to temperature of 600°C was also assessed.

2. MATERIALS AND PREPARATION OF SPECIMENS

The study was carried out using concretes made from basalt aggregate and CEM I 52.5R cement. The quantitative and qualitative composition of all high-performance examined concretes was the same, with the exception of the amounts and lengths of the polypropylene fibres used. Fibrillated polypropylene fibres with lengths of 6, 12 and 19 mm, and in amounts of 0, 0.9 and 1.8 kg/m^3 were used for the the research. According to the figures quoted by the manufacturer, the melting temperature for the fibres was 163°C, and their flash point was 360°C. Moreover, the density of fibrillated fibers used in this study was 910 kg/m^3.

Cylindrical specimens of 150 mm in diameter and 50 mm high were used for gas permeability and surface water absorption measurements. These specimens were cut out from 150/300 mm standard cylinders. Compressive strength was determined by using 100 mm cubic specimens. All specimens were formed and cured in compliance with the PN-EN 12390-2 standard, and the tests were conducted after 90 days of curing. Detailed compositions of the concretes that were prepared, together with their designations, are shown in Table 1.

Table 1

Mix designs of HPC with and without PP fibres.
Składy betonów BWW bez włókien z włóknami PP

Type of component / Concrete labels	Unit	B100	B100/0.9/6	B100/1.8/6	B100/0.9/12	B100/1.8/12	B100/0.9/19	B100/1.8/19
Cement CEM I 52,5	kg/m^3	490						
Water	kg/m^3	145						
Sand 0/2 mm	kg/m^3	611						
Basalt aggregates 2/8 mm	kg/m^3	712						
Basalt aggregates 8/16 mm	kg/m^3	712						
Fibrilated PP fibres:								
length 6 mm	kg/m^3	–	0.9	1.8	–	–	–	–
length 12 mm	kg/m^3	–	–	–	0.9	1.8	–	–
length 19 mm	kg/m^3	–	–	–	–	–	0.9	1.8
Plasticizer	% mc	0.9						
Superplasticizer	% mc	1.0 ÷ 2.0						
Complementary data								
Water-cement ratio	–	0.30						
Cement paste content	dm^3/m^3	≈ 310						
Mortar content	dm^3/m^3	514						

3. MEASUREMENT RESULTS AND ANALYSIS

Concrete samples were heated in a Nabertherm LH30/13 furnace at a constant rate of 1°C/min. The heating rate was selected in accordance with the RILEM recommendations [14] aimed at limiting thermal stresses due to the thermal gradient in concrete specimen. After the target temperature was reached, the specimens were heated for further two hours in order to stabilise the temperature over their entire cross-section. The next stage was the free cooling of specimens in the furnace to the room temperature. Therefore, all the properties established were residual. This procedure was applied to all the samples examined.

3.1. PERMEABILITY

Gas (nitrogen) permeability was determined by using the RILEM-Cembureau method using the device shown in Fig. 1 and Fig. 2.

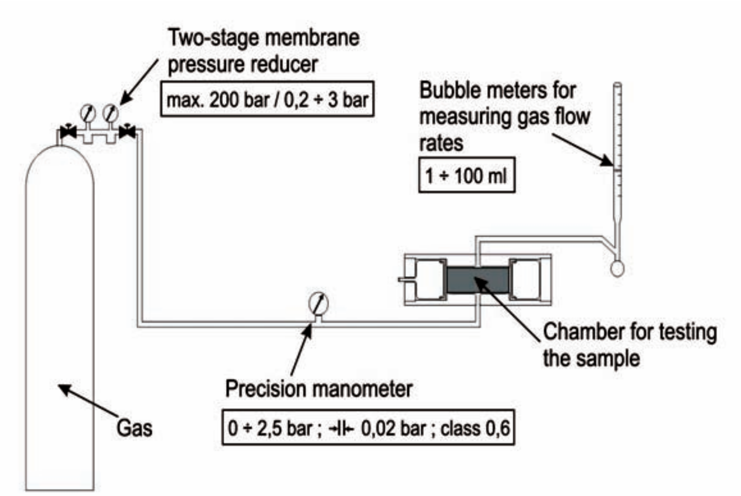


Fig. 1. Scheme of the set up for testing the permeability (RILEM-Cembureau method).
Rys. 1. Schemat budowy urządzenia do pomiaru przepuszczalności (metodą RILEM-Cembureau)

The permeability (k) was determined using following equation Eq. (3.1):

$$k = \frac{2QP_a\eta L}{A(P^2 - P_a^2)} \tag{3.1}$$

where: Q = V/t – the measured gas flow intensity [m^3/s], P – pressure (absolute) [Pa], Pa – atmospheric pressure [1 bar = 10^5Pa], η – viscosity of the gas [Pa·s], A – cross-section area of the specimen [m^2], L – thickness of the specimen [m].

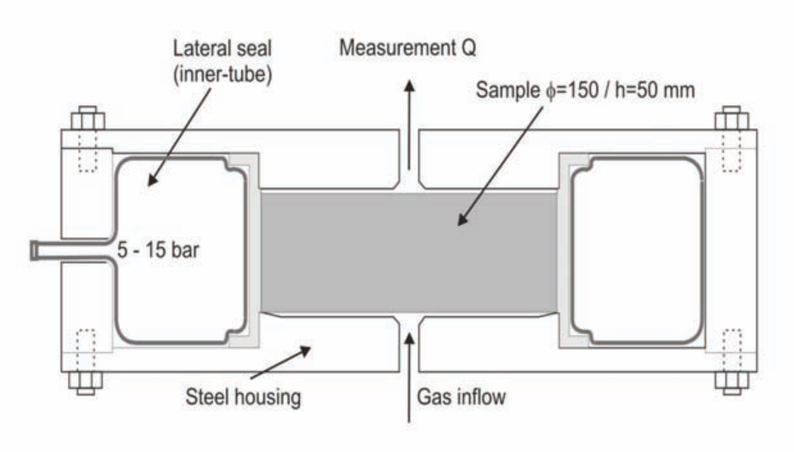
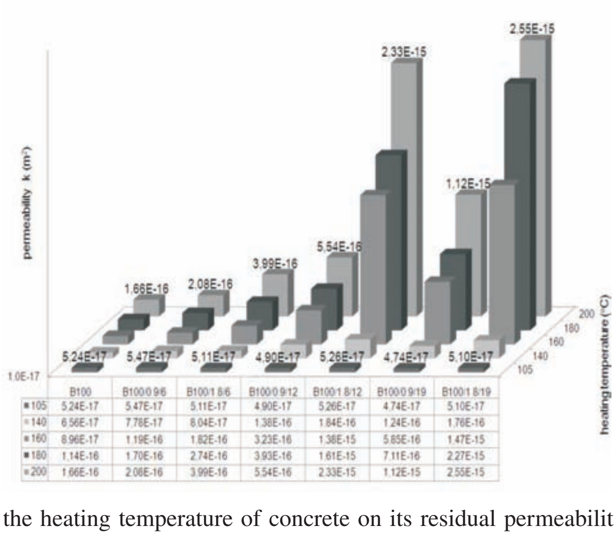


Fig. 2. Detailed scheme of the sample testing chamber
Rys. 2. Szczegółowy schemat budowy komory do badania próbek

Permeability measurements started with the determination of initial permeability for specimens dried to constant mass at temperature of 105°C, according to the guidelines for the method applied described in RILEM Technical Recommendation [12]. Subsequently, the samples were heated to temperature ranging from 140 to 200°C, and their permeability was measured following cooling.



	B100	B100/0.9/6	B100/1.8/6	B100/0.9/12	B100/1.8/12	B100/0.9/19	B100/1.8/19
■ 105	5.24E-17	5.47E-17	5.11E-17	4.90E-17	5.26E-17	4.74E-17	5.10E-17
■ 140	6.56E-17	7.78E-17	8.04E-17	1.38E-16	1.84E-16	1.24E-16	1.76E-16
■ 160	8.96E-17	1.19E-16	1.82E-16	3.23E-16	1.38E-15	5.85E-16	1.47E-15
■ 180	1.14E-16	1.70E-16	2.74E-16	3.93E-16	1.61E-15	7.11E-16	2.27E-15
■ 200	1.66E-16	2.08E-16	3.99E-16	5.54E-16	2.33E-15	1.12E-15	2.55E-15

Fig. 3. Influence of the heating temperature of concrete on its residual permeability. Each value is the average results of three measurements.
Rys. 3. Wpływ temperatury wygrzewania na resztkowe wartości przepuszczalności. Każda wartość to średnia z trzech pomiarów

In Fig. 3 results of permeability measurements for seven concretes are shown. Each measurement series comprised three samples.

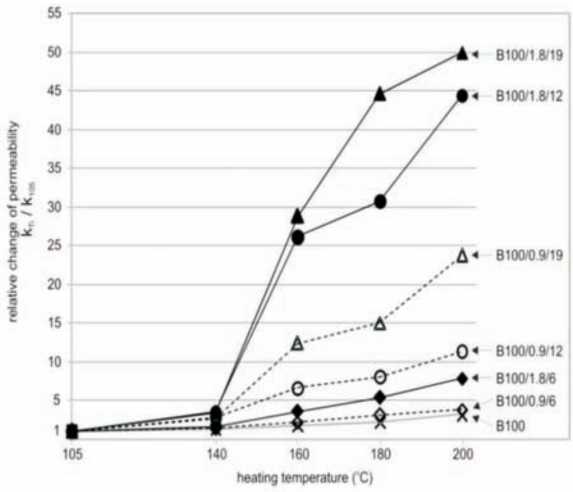


Fig. 4. Relative change in average HPC permeability with and without polypropylene fibres added depending on heating temperature.
Rys. 4. Względna zmiana średnich wartości przepuszczalności betonów BWW bez i z dodatkiem włókien polipropylenowych, w zależności od temperatury wygrzewania

The results of measurements presented in Fig. 4 show the ratio of permeability of concrete after heating to its permeability before heating (initial permeability).

An increase in heating temperature caused residual permeability increase. For concrete without fibres (B100) and concrete with a small addition of short fibres (B100/0.9/6), this increase was relatively small. At 160°C, a significant increase in residual permeability started, and at the same time considerable differences with respect to its value started to emerge.

An addition of 12 mm and 19 mm long fibres had a very large impact on the increase of concrete permeability after heating. An addition of 0.9 kg/m^3 of 12 mm long fibres (B100/0.9/12) caused a 12-fold increase in permeability after heating to 200°C compared to the initial value. When the amount of these fibres was doubled to 1.8 kg/m^3, a 45-fold increase in permeability was recorded. While analysing the results of measurement, the immense impact of 12 mm fibre dosage was observed. For 19 mm long fibres, even higher permeability was recorded, but the impact of dosage was not as significant as for 12 mm long ones.

3.2. SURFACE WATER ABSORPTION

Changes in surface water absorption in g/cm^2 over time were measured for cylindrical specimens heated to 140, 160, 180 and 200°C following permeability measurements.

The increase in specimen mass was recorded at intervals of 60 seconds and with an accuracy of ±0.01 g. During the measurements, one specimen surface was in permanent contact with water. Irrespective of the amount of water absorbed by the specimens tested, the water level remained constant during the measurement, i.e. for 72 hours. The measurement set-up is shown in Fig. 5.

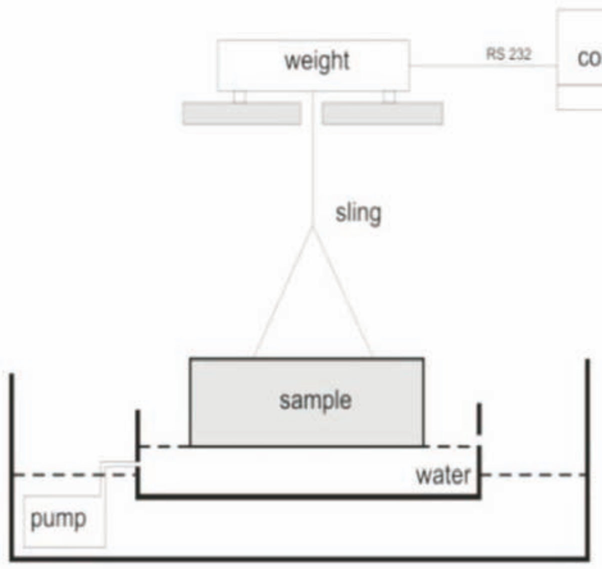


Fig. 5. System for measuring surface water absorbability.
Rys. 5. Stanowisko do pomiaru nasiąkliwości powierzchniowej

The selected measurement results are presented in two sections. In section one, the test results depend on quantity of fibres used, and in section two, the test results depend on their length. In Fig. 6, changes in surface water absorbability in kg/m^2 following heating for concrete specimena without addition of fibres and for concrete specimen with 0.9 and 1.8 kg/m^3 of 12 mm long fibres added are shown.

The curves in Fig. 6 demonstrate significant variation in the magnitude of the increase in surface water absorption of the concretes tested, as a result of heating. Concrete without fibres (B100) exhibits an increase in the value measured during the initial heating phase for a heating temperature of 200°C. A similar trend can be observed for concretes that contain 0.9 kg/m^3 of 12 mm long fibres. For a larger amount of fibres (1.8 kg/m^3), surface water absorption is begin to increase already in temperature exceeding 140°C. This is reflected in the results of the residual permeability measurements presented above. Heating of the B100/1.8/12 concrete to 160°C causes residual permeability increase of more than 25-fold, while for the B100/0.9/12 concrete, only a six-fold increase in the value measured was observed.

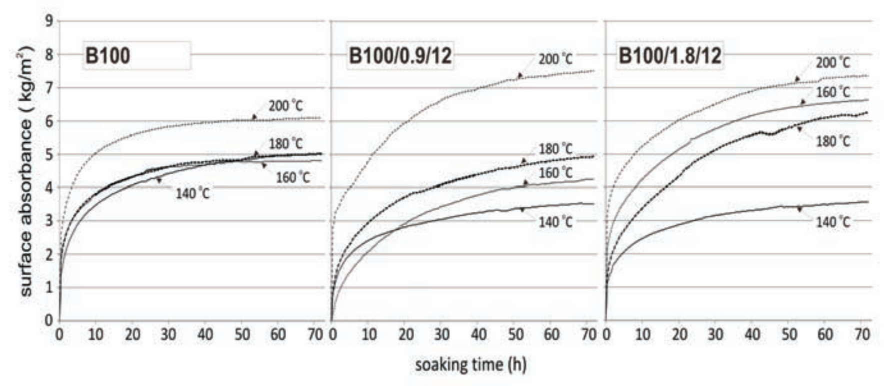


Fig. 6. Changes in the surface water absorbability of HPC without fibres (B100) and with fibres (B100/0.9/12 and B100/1.8/12) caused by heating to 140, 160, 180 and 200°C.
Rys. 6. Przebieg zmian nasiąkliwości powierzchniowej BWW bez włókien (B100) i z włóknami (B100/0.9/12 i B100/1.8/12) wywołany wygrzewaniem do temperatur 140, 160, 180 i 200°C

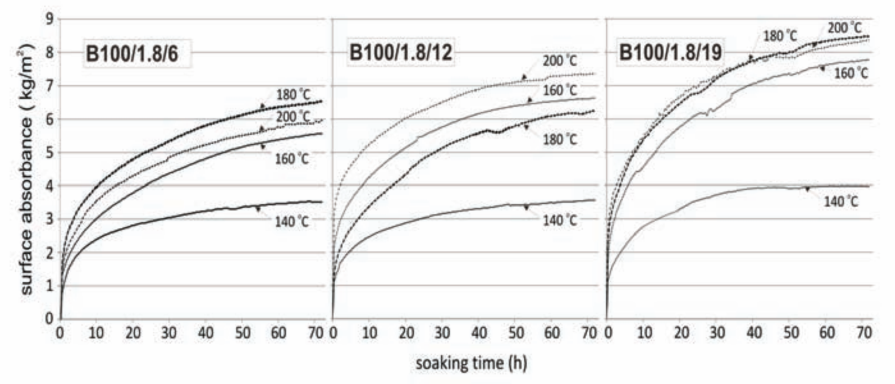


Fig. 7. Changes in the surface water absorbability of HPC with 1.8 kg/m^3 of 6, 12 and 19 mm long fibres caused by heating to 140, 160, 180 and 200°C.
Rys. 7. Przebieg zmian nasiąkliwości powierzchniowej BWW z włóknami w ilości 1.8 kg/m^3 o długościach 6, 12 lub 19 mm wywołany wygrzewaniem do temperatur 140, 160, 180 i 200°C

As the tests carried out show, it is not only the quantity of PP fibres added that has an influence on the surface water absorption of heated concretes, but also their length. In general, as the length of the fibres used increases, changes in concrete surface water absorption become more pronounced. It is probable that 19 mm long fibres added to concretes heated to 160°C or higher create a continuous network of interconnected capillary pores, which affects the magnitude of surface water absorption increase during the first few hours of soaking.

3.3. Porosity

In order to explain the changes observed in properties affecting the ability of heated concrete to transport gas and water, tests were carried out to determine the microporosity distribution in mortars extracted from the HPCs tested. Concretes with additions of 0.9 kg/m^3 of 6 mm long fibres and 1.8 kg/m^3 of 19 mm long fibres were selected for testing. Measurements concerned the microporosity of concretes before heating and after heating to 180°C.

Measurement results are presented in Fig. 8.

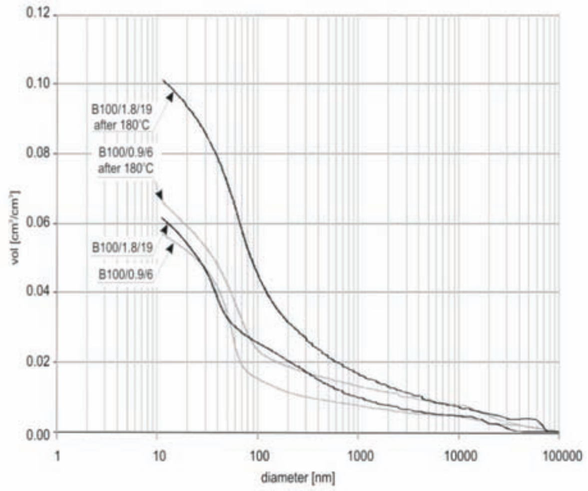


Fig. 8. Distributions of concrete mortar sample porosities determined using the mercury porosimetry method.

Rys. 8. Rozkłady porowatości próbek zaprawy z betonów wyznaczone metodą porozymetrii rtęciowej

Before heating, very similar porosity distributions were observed for the HPC mortars with differing additions of PP fibres. After heating to 180°C, the overall porosity of B100/0.9/6 concrete mortar rose from 0.058 to 0.068 cm^3/cm^3, while for the B100/1.8/19 concrete, the increase was from 0.061 to 0.101 cm^3/cm^3. The change observed did not result from the additional porosity caused by the melting of polypropylene fibres. The result of the increase in the micro-cracking of heated concretes with fibres, described by Kalifa *et al.* [4] was most probable here.

3.4. Residual Compressive Strength

Compressive strength and its change as a function of temperature was determined by using 100 mm cubic specimens. Two specimens of each concrete type were heated up to 120, 160, 200, 250, 400 and 600°C, and their compressive strengths were tested after cooling.

Residual compressive strength and strength results for unheated specimens are presented in Fig. 9.a. In Fig. 9.b, relative changes in residual compressive strength are shown.

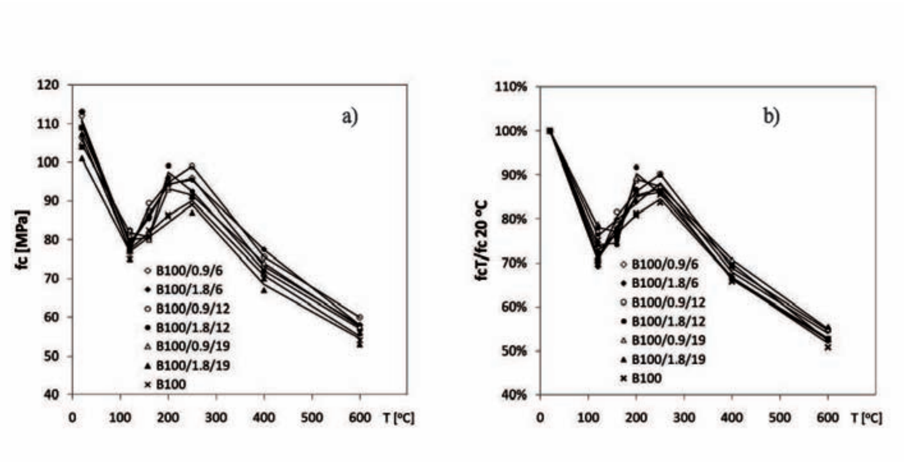


Fig. 9. Heating temperature impact on absolute and relative changes in residual compressive strength.
Rys. 9. Wpływ temperatury wygrzewania na bezwzględną i względną zmianę resztkowej wytrzymałości na ściskanie

It can be noted that as a result of heating up to 120°C, the relative compressive strength decreases by about 25%, most probably due to the presence of humidity gradient in concrete specimens. As heating continued, the evaporation of free water from the material progress was observed and a partial restoration of strength (160, 200, 250°C), which was related to the reduction of humidity gradients in a specimen. The influence of water movement during heating, and thus the presence of humidity gradient, on compressive strength was clearly shown by testing dried concrete specimen where absence of strength reduction in 120°C was observed. (Hager [13]. Further heating led to steady decrease in strength caused, *inter alia*, by the dehydration of the CSH gel, portlandite decomposition and the destruction of the contact zone due to the different thermal expansion coefficients of cement paste and aggregate.

On the basis of the compressive strength test results shown above, it may be concluded that this property does not vary considerably for the seven compositions of concretes tested. The results obtained for unheated and heated concrete specimen without fibres do not differ significantly from the results obtained for concretes with 0.9 kg/m^3 and 1.8 kg/m^3 of PP fibres added.

4. CONCLUSIONS

The following conclusions may be proposed on the basis of the measurements presented above:

- Both the amount and length of polypropylene fibres added has an influence on the magnitude of changes in residual permeability caused by HPC heating.
- The greatest increase in the residual permeability of heated concretes could be observed in specimens in which 1.8 kg/m^3 of 12 or 19 mm long fibres were added.
- Permeability measurements using the RILEM-Cembureau method are very useful when evaluating the effectiveness of adding polypropylene fibres which, after melting, enables water vapour to be evacuated from heated concrete and its pressure to be reduced.
- The addition of polypropylene fibres to HPCs heated up to temperature ranging from 160 to 200^{o}C affects the capillary porosity of the cement matrix, which is confirmed by measurements of changes in surface water absorption over time.
- Microporosity measurements indicate a significant increase in the quantity of pores with diameters of less than 1 μm in concrete with fibres (B100/1.8/19) heated to 180^{o}C. The change observed does not stem from the additional porosity caused by melting polypropylene fibres, but is rather the result of an increase in the micro-cracking of heated concrete with PP fibres.
- Compressive strength determined as a function of temperature indicates that, for tested concretes, the presence of fibres and their length do not affect this property significantly.
- The presented research results confirm the need for further tests aimed at proving the beneficial effect of PP fibres on reducing spalling in real HPC elements during fires.

References

1. Z. P. Bazant, *Analysis of pore pressure, thermal stresses and fracture in rapidly heated concrete*, Int. Workshop on fire performance of high strength concrete, February 1997, NIST Maryland, pp. 13-14.
2. K. Hertz, *Limits of Spalling of Fire Exposed Concrete*, Fire Safety Journal, **38**, pp 103-116, 2003.
3. P. Kalifa, F.D. Menneteau, D. Quenard, *Spalling and pore pressure in HPC at high temperature*, Cement and Concrete Research, August 2000, pp 1915-1927.
4. P. Kalifa, G. Chéné, C. Gallé, *High-temperature behaviour of HPC with polypropylene fibers: From spalling to microstructure*, Cement and Concrete Research, **31**, 10, October 2001, pp. 1487-1499.
5. A. Nishida, N. Yamazaki, H. Inoue, U. Schneider, U. Diederichs, *Study on the properties of high strength concrete with short polypropylene fibre for spalling resistance*, Concrete Under Severe Conditions Environment and Loading, Vol. 2. 1995.
6. A. Hoff, A. Bilodeau, V.M. Malhorta, Elevated Temperature, Effects on HSC, Residual Strength, Concrete International, pp. 41-47, 2000.
7. N. Pasquini, *Polypropylene handbook, 2nd Edition*, Hanser Publishers, Munich, 2005.
8. I. Hager, T. Tracz, *Influence of high temperature on selected properties of high performance concrete modified with the addition of polypropylene fibres*, Cement Lime Concrete, January / February 2009, nr 1, p. 3.

9. I. HAGER, T. TRACZ, *The impact of the amount and length of fibrillated polypropylene fibres on the properties of HPC exposed to high temperature*, Proc. Int. Symp. "Brittle Matrix Composites 9", eds. A.M.Brandt, J. Olek and I.H. Marshall, Warsaw, October 2009, p. 63-69.
10. I. HAGER, T. TRACZ, *Residual transport properties of heated HPC modified with polypropylene fibres*, Proceedings of 1st International RILEM Workshop on Concrete Spalling Due to Fire Exposure, ed. F. Dehn, E.A.B. Koenders, 3 - 5 September 2009, Leipzig, Germany, pp. 221-228.
11. D.P. BENTZ, *Fibers, percolation, and spalling of high performance concrete*, ACI Journal 97 (3)(2000) pp. 351-359.
12. RILEM Technical Recommendation: Tests for gas permeability of concrete, TC 116-PCD: Permeability of concrete as criterion of its durability, Materials and Structures, Vol. 32, April 1999, 174-179.
13. I. HAGER (GAWĘSKA), *Comportement à haute température des bétons à haute performance – évolution des principales propriétés mécaniques*, Praca doktorska, Ecole Nationale des Ponts et Chaussées, listopad 2004, 172 pp.
14. RILEM TC 129-MHT : Compressive strength for service and accident conditions, Materials and Structures, **28**, pp 410-414, 1995.

WPŁYW ILOŚCI I DŁUGOŚCI FIBRYLOWANYCH WŁÓKIEN POLIPROPYLENOWYCH NA WŁAŚCIWOŚCI HPC PODDANEGO DZIAŁANIU WYSOKIEJ TEMPERATURY

Streszczenie

Zachowanie się betonów wysokowartościowych (BWW) w warunkach działania wysokiej temperatury może stanowić poważne ograniczenie ich stosowania w budownictwie. BWW poddane działaniu wysokich temperatur, jakie wystepują np. podczas pożaru, mogą wykazywać skłonność do eksplozyjnego zachowania się (ang. spalling) prowadzącego do odsłonięcia stali zbrojeniowej. Eksplozyjne zachowanie się może stanowić poważne zagrożenie dla nośności elementu żelbetowego. Jak pokazały liczne badania stosowanie włókien polipropylenowych (PP) ogranicza wystąpienie tego zjawiska. W temperaturze około 170 °C włókna topią się. Stopiony polipropylen jest częściowo wchłaniany przez matrycę cementową, tworząc sieć porów otwartych wpływających na zwiększenie przepuszczalności, a w konsekwencji powodując zmniejszenie ciśnienia pary wodnej w ogrzewanym betonie. Jednak dokładny mechanizm działania włókien polipropylenowych nie jest jeszcze w pełni wyjaśniony. Z technicznego punktu widzenia, zastosowanie włókien polipropylenowych w ilości 0,1÷0,2% objętości betonu stanowi skuteczne rozwiązanie ograniczające wystąpienie eksplozyjnego zachowania się w betonach wysokowartościowych, jednak brak jest doniesień jednoznacznie wskazujących jakiej długości włókna są najefektywniejsze.

Celem prowadzonych badań była ocena wpływu temperatury wygrzewania na cechy materiału związane z jego zdolnością transportową dla cieczy i gazów. Badano siedem BWW modyfikowanych dodatkiem fibrylowanych włókien polipropylenowych o długościach 6, 12 i 19 mm. Stosowano dodatek włókien w ilości 0, 0,9 i 1,8 kg/m^3. Zakres badań obejmował oznaczenie takich cech jak: przepuszczalność dla gazu, nasiąkliwość powierzchniowa oraz mikroporowatość wybranych betonów przed i po wygrzewaniu. Cechy te są najbardziej odpowiednie do ilościowej oceny efektywności stosowania włókien polipropylenowych jako dodatku ograniczającego występowanie spallingu w betonach BWW. Ponadto w badaniach dokonano oceny wpływu temperatury wygrzewania na przebieg zmian resztkowych wartości wytrzymałości na ściskania próbek wygrzewanych do temperatury 600°C.

Remarks on the paper should be
sent to the Editorial Office
no later than June 30, 2010

Received December 02, 2009
revised version
March 05, 2010