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DURABILITY OF HIGH PERFORMANCE CONCRETE (HPC) SUBJECT TO FIRE TEMPERATURE IMPACT

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In the recent years a tendency for design of increasingly slender structures with the use of high performance concrete has been observed. Moreover, the use of high performance concrete in tunnel structures, subject to high loads with possibility of extreme loads occurrence such as fire, has an increasing significance.

Presented studies aimed at improving high performance concrete properties in high temperature conditions (close to fire conditions) by aeration process, and determining high temperature impact on the concretes features related to their durability.

In this paper it has been proven that it is possible to obtain high performance concretes resistant to high temperatures, and additionally that modification of the concrete mix with aerating additive does not result in deterioration of concrete properties when subject to water impact in various form.

Keywords: durability, high performance concrete, fire conditions, fibre reinforced concrete, aerated concrete

1. INTRODUCTION

Among commonly applied building materials (wood, steel, concrete) concrete is characterized by the best fire resistance. It is non-inflammable material and acts as a barrier preventing from the spread of fire. The concrete exposed to high temperature does not produce any toxic gases or smoke. However, concrete exposure to temperature close to fire conditions results in many physical

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processes occurring in its structure, as well as chemical reactions, leading to irreversible changes in concrete's structure, significantly deteriorating its properties or completely destroying the material. Phenomena occurring in concrete subject to high temperature have been extensively described in [1-13]. It is difficult to clearly define the influence of high temperature on the concrete's properties [14], as there are no standards for such type of studies.

Durability of concrete in the structure depends on several factors. In PN-EN 206 [15] standard obtaining a durable concrete is related to the design according to exposure class. It is important to properly choose components of the concrete (qualitatively and quantitatively) and properly form concrete microstructure (determination of composition, proper dosage, mixing, transport, arrangement, thickening, maintaining). After fulfilling the above mentioned recommendations it can be presumed that in case of proper use of structure (according to its original purpose) durability of the structure is ensured (in most cases for a minimum period of 50 years).

In case of design of structures subject to fire conditions according to PN-EN 1992-1-2 (Eurocode 2) standard [14] ensuring structure durability is a more complex task. In Eurocode there are two following records on how to improve concrete resistance to fire and reduce risk of thermal spalling:

- Use of scattered reinforcement in a form of polypropylene fibres. In elevated temperatures fibres undergo degradation leaving channels in concrete's structure, which enable vapour transportation created as an effect of thermal impact inside the concrete. It results in decrease of vapour pressure in concrete's pores [10] and prevents exceeding local tensile strength.
- Application of reinforcing bar with mesh size equal or lower than 50x50 mm, made of wires with diameter above 2 mm (although in [16] it was found that use of metal reinforcement bars made of wire with diameter below 2 mm with addition of polypropylene fibres in concrete mix allowed to effectively prevent spalling phenomenon, as well as kept compressive strength of concrete exposed to high temperatures at level of 90% according to standard curve comparing to its strength before exposition to temperatures close to fire conditions).

In the literature also other methods for improving concrete resistance to high temperatures can be found.

- Aeration of concrete (aeration concept as a method for improvement of concrete resistance to high temperatures appeared in relation with significantly lower strength drops of light concretes subject to thermal loads than normal concrete)

- Use of mineral additives and selection of proper aggregate (use of mineral additives in concrete composition in a form of granulated blast furnace slag and fly ash reflects to better properties in high temperature conditions [13]). Use of silica fume also results in improved mechanical properties of concrete [16,17], however application of this additive in amount higher than 5% relative to cement mass, causes real risk of thermal spalling occurrence [16,13]).

The objective of the studies was to evaluate the influence of modification of concrete with aerating additive and polypropylene microfibers on high performance concretes exposed to high temperatures. The studies also aimed at determining if the use of above mentioned technological treatments would result in improvement of resistance of high performance concretes to high temperatures.

2. STUDY SUBJECT AND SCOPE

The study subjects were three types of concretes: Concrete mix 1 - high performance concrete aerated (HPC aerated), Concrete mix 2 - high performance concrete with addition of polypropylene fibres (HPC fibre reinforced concrete) and Concrete mix 3 - high performance concrete comparative (HPC comparative). All concretes were made based on the fixed recipe, where water/cement ratio was constant and equal to w/c=0.30 and crushed basalt aggregate with grain size of 2-16 mm with fixed percentage content of fractions was used.

Reaching S3 concrete mix consistence by applying liquidizing additive (superplasticizer) was assumed. In concrete mix 1 (HPC aerated) the assumed aeration level was between 4-5% by applying aerating additive. In concrete mix 2 (HPC fibre reinforced concrete) a scattered reinforcement in a form of polypropylene fibres was used. Studies of hardened concrete were conducted on unheated specimens, comparative specimens (at 20°C), as well as on air cooled specimens pre-heated to 300°C, 450°C and 600°C.

The scope of concrete mix studies included evaluation of the following properties: consistence, bulk density, air content. Scope of studies of hardened concrete included evaluation of the following properties: compressive strength, absorptivity, water under pressure penetration depth, frost resistance. Through the whole period of studies evaluation of specimens surface and potential changes of the specimens subject to high temperatures was performed. The following were verified: occurrence of thermal spalling phenomenon, extent to which specimen was scratched, and occurrence of change of colour of concrete exposed to high temperature.

3. STUDY MATERIALS AND THEIR CHARACTERISTICS

In order to prepare concrete mix the Portland cement CEM I 42,5R was used. Before initiation of studies the cement was analysed according to the requirements of PN-EN 197-1 standard: 2012E [18]. In all concrete mixes as a fine aggregate sand from Vistula river was used, while as a coarse aggregate - basalt chippings with fraction of 2/8 and 8/16 mm. Sand point at level of 37% was taken, while aggregate fraction lower than 8 mm accounted for 65%. Aggregate grain-size distribution curve was entered between limit curves creating area of good grain-size according to PN/B/06250 [19]. In order to prepare concrete mix a tap water was used, fulfilling requirements of PN-EN 1008:2004P standard [20]. To achieve assumed level of consistency of concrete mix (S3-tested with slump test method), a superplasticizer based on modified polycarboxylates was applied. Assumed aeration level of concrete mix was 4-5% (HPC aerated). The above mentioned level of free air spaces in concrete mix was obtained with the use of liquid aerating additive.

In concrete mix 2 (HPC fibre reinforced concrete) 1,5 kg/m3 of fibres was used. Parameters of microfibers (table 1) were compliant with PN-EN 14889-2 standard [22].

Table 1. Basic information on microfibers

Characteristics	**Technical data of fibres**
Density, [dm^3]	0,91
Length, [mm]	12
Diameter, [μm]	18
Tensile strength, [MPa]	557
Flexibility modulus, [MPa]	4148
Melting temperature, [°C]	160
Fibres application details	
Recommended dosage	600÷900 g / 1 m^3 concrete

Flammable properties of applied fibres were studied using the following research methods:

- ignition temperature determination method according to PN-69/C-89022 [23],
- heat of combustion determination method according to PN-EN ISO 1716:2010 [24],
- thermogravimetric method according to PN-EN ISO 11358:2004-09 [25],

Average ignition temperature value of applied fibers was 406°C. Heat of combustion of fibres was 42,4109 [kJ/g].

Thermogravimetric measurements were conducted with the use of dynamic method, registering change in specimen mass as a function of temperature at constant heating rate of 10°C/min. During studies nitrogen was used as both propellant and research atmosphere gas. The obtained measurement result is illustrated in a form of thermogravimetric curve and differential thermogravimetric curve (fig.1). SEM images of studied fibres are shown in figure 2.

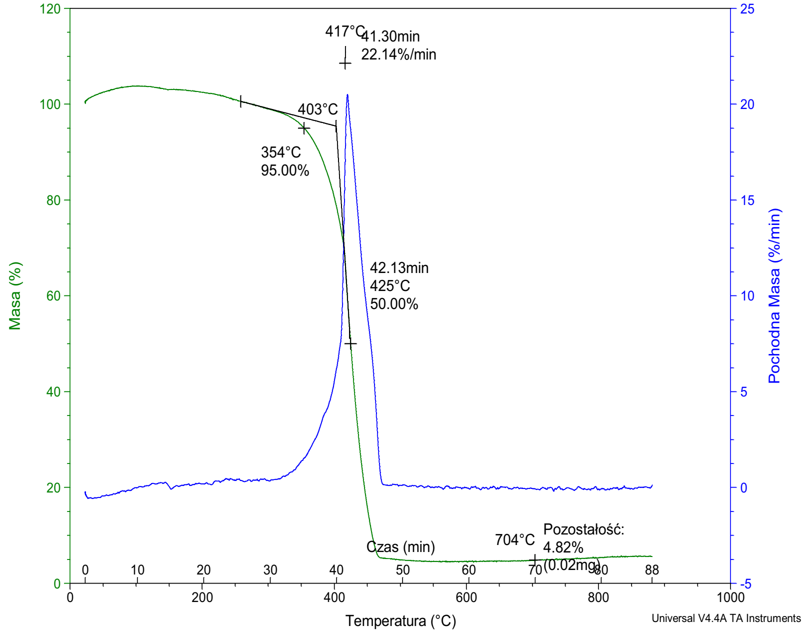


Figure 1. TG curve and derivative of mass change in temperature obtained during thermogravimetric analysis of fibres in nitrogen atmosphere at heating rate of 10°C/min – own studies

Table 2. Thermogravimetric analysis results of fibres in nitrogen atmosphere at heating rate of 10°C/min – own studies

Specified parameters	**Determined values**
Pyrolysis starting temperature [°C]	403
Temperature of 5% of mass loss [°C]	354
Temperature of 50% of mass loss [°C]	425
Pyrolysis end temperature [°C]	704
Temperature of max mass loss speed [°C]	417
Mass of residue [%]	4.82

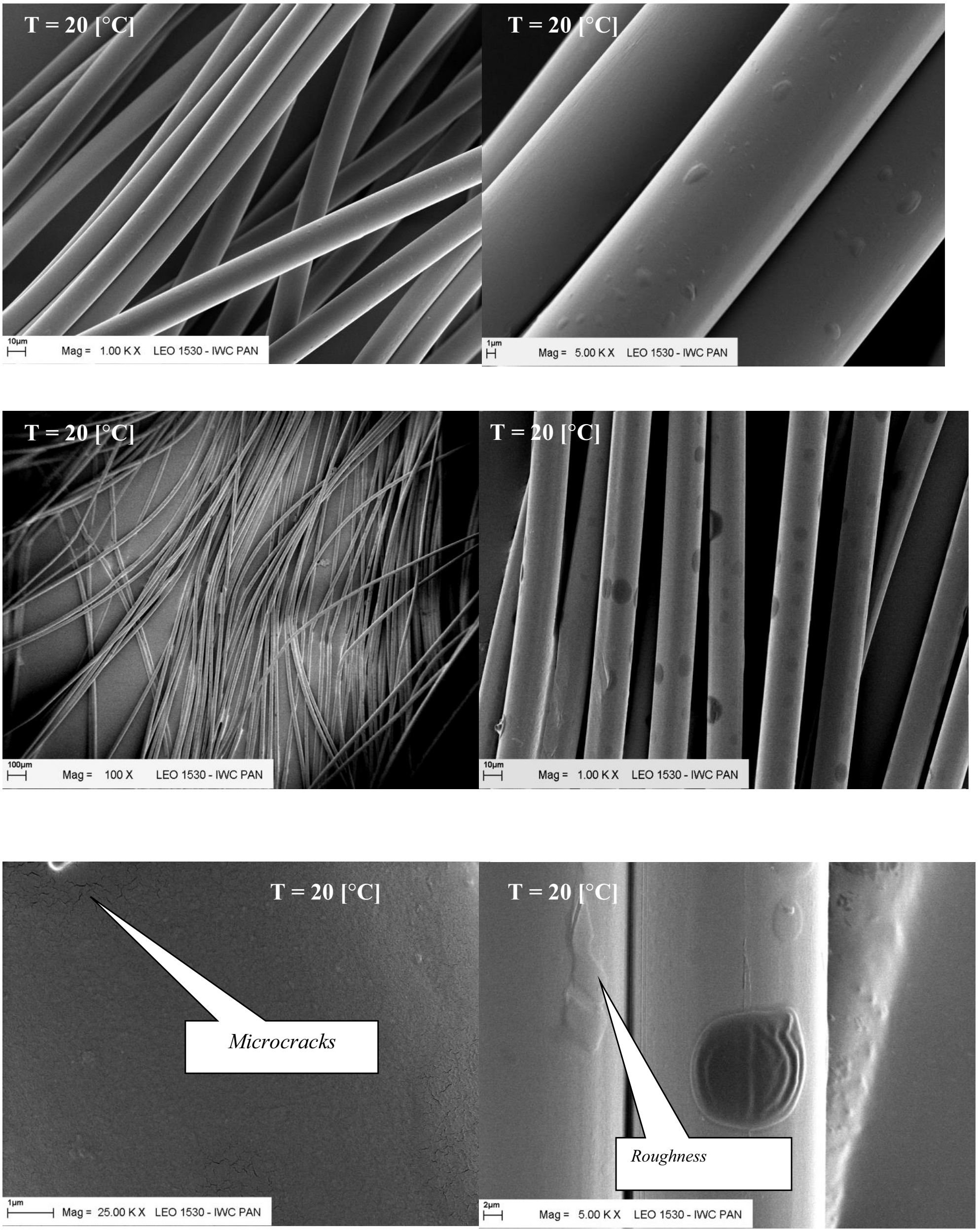


Figure 2. SEM images of studied fibres

3.1. COURSE OF EXPERIMENTAL STUDIES

Compositions of concrete mixes are given in table 3.

Table 3. Composition of concrete mix per 1m3 of concrete

Components	Determination of composition		
	HPC aerated	HPC fibre reinforced concrete	HPC comparative
CEM I 42,5R concrete, [kg]	450	450	450
Water, [kg]	135	135	135
Sand 0/2, [kg]	732	732	732
Basalt 2/8, [kg]	568	568	568
Basalt 8/16, [kg]	695	695	695
Superplasticizer, [% m.c.]	1.75	2.33	1.75
Aerating additive, [% m.c.]	0.2	-	-
Polypropylene fibres, [kg]	-	1.5	-
w/c	0.30	0.30	0.30

3.2. THERMAL LOADS PROCEDURE

All concrete specimens subject to heating during the course of studies after reaching age of 28 days were moved from climate chamber to laboratory dryers for 7 days and drayed at 105°C. Next, in the "witness" specimens intended for temperature control inside the element - holes for thermocouples were drilled.

Heating was carried out at the research stand, including main components such as medium temperature chamber furnace PK 1100/5 type and PC equipped with appropriate software for control and recording of temperature during heating of specimens. Heating process took place as per "standard" curve ISO 834 [26] and PN-EN 1991-1-2 [14]. Every time the increase of temperature in the specimens was registered in 3 measuring points (fig. 3).

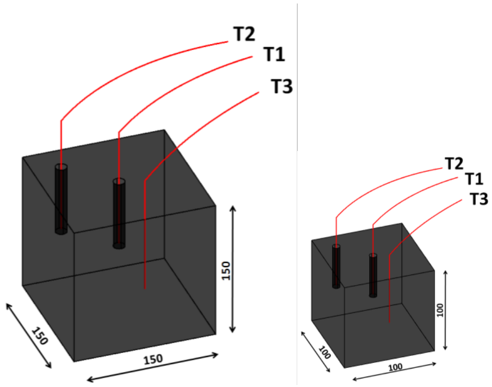


Figure 3. Scheme of thermocouples arrangement in all "wittness"specimens

4. Study results and analysis

Results of concrete mix and hardened concrete properties are shown in table 4.

Table 4. Properties of concrete mix and hardened concrete

		Studies of concrete mix			
Characteristic		HPC aerated	HPC fibre reinforced concrete		HPC comparative
Class of consistence		S3	S3		S3
Density, [kg/m^3]		2570	2530		2600
Air content, [%]		4,2÷4,8	< 2		< 2
		Studies of hardened concrete			
Characteristic	Temperature, [°C]	Age, [days]	HPC aerated	HPC fibre-concrete	HPC comparative
Compressive strength, [MPa]	20	2	52,5	51	54,5
	20	28	76,9	74,7	72,7
	20	90	77,7	80,6	83,5
	20	180	80,4	91,1	97,2
	300	28	85,0	78,4	88,5
	450	28	82,7	74,4	81,8
	600	28	58,0	48,2	59,3
Absorptivity, [%]	20	28	4,49	4,21	4,20
	300	28	3,95	4,34	4,40
	450	28	4,31	4,54	4,41
	600	28	4,97	5,10	5,25
Depth of penetration of water under pressure, [mm]	20	2	3	22	2
	300	9	71	40	9
	450	16	88	35	16
	600	150	150	150	150
Frost resistance F150, [MPa]	20	F150	77,9	77,5	78,5
	20	witness specimen	81,6	82,1	82,7
	300	F150	71,5	77,3	83,8
	300	witness specimen	74,8	74,0	84,1

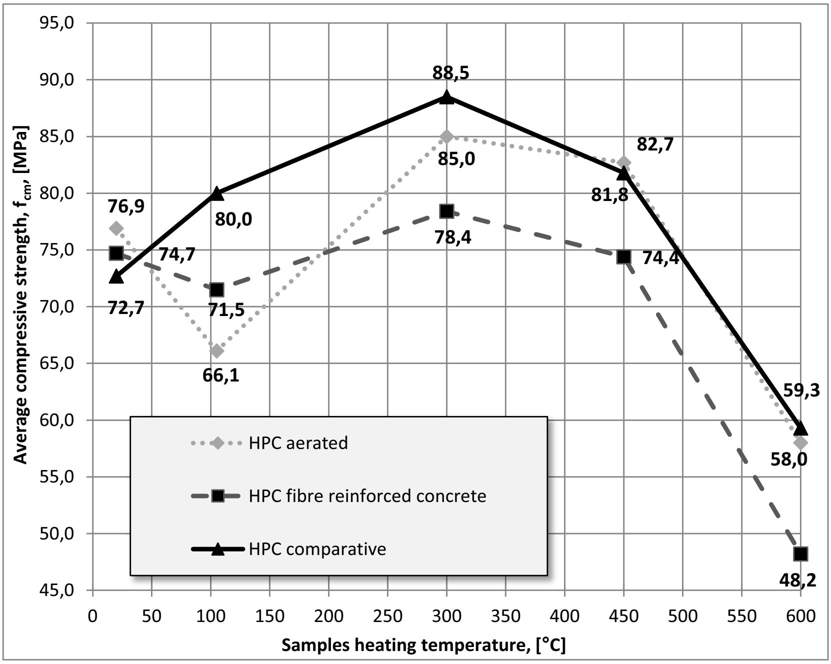


Figure 4. Compressive strength of concrete specimens subject to thermal load

Already at 105°C, temperature at which the specimens were dried5, deterioration of strength properties in concrete with addition of polypropylene fibres (4% drop) and aerated concrete (14% drop) was observed (fig.4). Adverse effect was demonstrated in case of HPC comparative, which compressive strength increased after concrete drying at 105°C (10% increase).

In the studied high performance concretes at 300°C significant changes in strength comparing to results obtained at 105°C were observed. The highest strength increase was obtained for HPC aerated concrete (increase by 29%); while for HPC fibre reinforced concrete and HPC comparative it was 10% and 11%, respectively. At 300°C the highest strength was shown for non-modified concrete (HPC comparative), and the lowest for concrete with addition of polypropylene fibres (HPC fibre reinforced concrete), the differences in strength for the above listed mixes was above 10 MPa in favour of HPC comparative.

Transition between temperature of 300°C and 450°C was beard by HPC aerated, which lost only 3% of its strength at 300°C.The most significant decrease of strength was observed for HPC

[5] F.ex. in case of concrete absorptivity measurement.

comparative (8% drop). The lowest compressive strength at 450°C was found for concrete modified with fibres - HPC fibre reinforced concrete (74,4 MPa), and the highest for aerated concrete (82,7 MPa).

Exposure of concrete to temperature of 600°C resulted in significant loss of strength for all studied concretes. Again, HPC fibre reinforced concrete proved to be the worst, which weakened to the greatest extent (comparing to strength at 450°C - 54%6). The highest resistance to temperature of 600°C showed HPC aerated and HPC comparative, where difference in strength was only 2% and close to 60 MPa, while for HPC fibre reinforced concrete it was lower by 23% from the above mentioned concretes and equal to 48,2 MPa.

All studied concretes were characterized by the strength higher at 300°C than at 20°C. At 450°C this tendency was not visible only for HPC fibre reinforced concrete, for which the strength slightly decreased comparing to the one obtained at 20°C. After exposure to 600°C all concretes had lower strength than at 20°C. For HPC fibre reinforced concrete the highest strength decrease was found (35,5% drop).

Figure 5 shows changes of compressive strength of the studied concretes after exposure to high temperatures comparing to expected strength decreases described in Eurocode 2 [14].

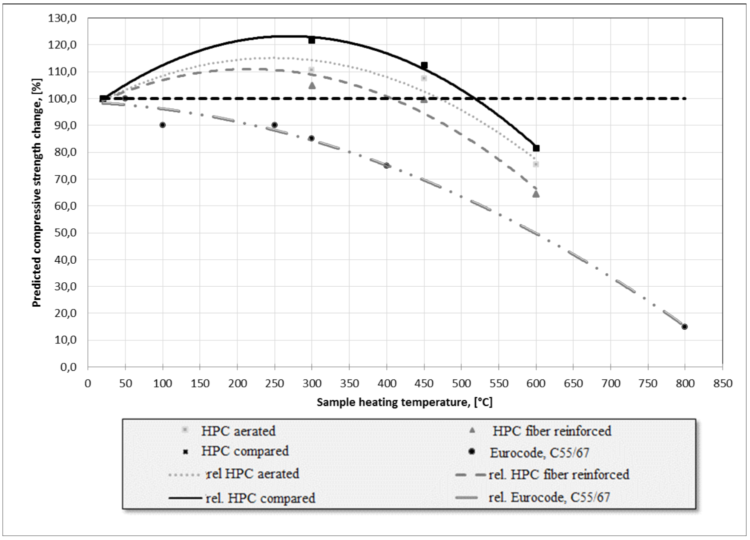


Figure 5. Expected compressive strength changes of the concrete according to Eurocode 2 with included own studies results

[6] In this case as 100% of compressive strength a value obtained after HSC fibre reinforced concrete exposure to 450°C was taken into account.

It can be concluded from figure 5 that according to Eurocode 2 [14], compressive strength of high performance concrete of C55/67 class decreases starting from the moment when concrete is heated to 100°C. According to study results obtained by the authors, concrete strength increases up to exposure temperature of 300°C. After exceeding 300°C it starts to decrease, however up to 450°C it was higher than the one measured in non-exposed specimens. It shows that part of PN-EN 1992-1-2 [14] related to compressive strength of high performance concrete designed for fire conditions is very cautious.

4.1. Evaluation of strength class of the concretes exposed to high temperature

Based on the obtained results for concretes subjected to high temperature, a compressive strength class was evaluated. A control of compressive strength of concrete for each concrete mix was carried out as for the initial production according to PN-EN 206 [15]. After 28 days of maturation and heating of specimens up to 105°C, 300°C, 450°C, 600°C for each concrete mix strength class based on double compliance criterion was evaluated as Eq. (1.1):

$$f_{cm} \geq f_{ck} + 4 \wedge f_{ci_{\min}} \geq f_{ck} - 4 \tag{1.1}$$

Classification of the concrete to the particular strength class is given in table 5.

Table 5. Strength class evaluation of concretes subject to thermal loads

Compressive strength classes															
C100/115															
C90/105															
C80/95															
C70/85															
C60/75			C60/75	C60/75				C60/75					C60/75	C60/75	
C55/67	C55/67					C55/67	C55/67		C55/67		C55/67	C55/67			
C50/60		C50/60								!					
C45/55															C45/55
C40/50		←decrease of 1 strength classe	increase of 1 strength classe →	increase of 1 strength classe →	C40/50			increase of 1 strength classe →					increase of 1 strength classe →	increase of 1 strength classe →	←decrease of 2 classes
C35/45					←decrease of 3										
C30/37										C30/37					
C25/30										↓					

	C20/25															
	C16/20															
	C12/15															
	C8/10															
Temperature, [°C]		**20**	**105**	**300**	**450**	**600**	**20**	**105**	**300**	**450**	**600**	**20**	**105**	**300**	**450**	**600**
Concrete		HPC aerated					HPC fibre reinforced concrete					HPC comparative				

The highest decrease of compressive strength after 600°C for concrete with fibres was observed, which is recommended [according to Eurocode] as the best performing material in elevated temperatures. In case of this concrete a drop of 5 strength classes comparing to class determined after 28 days of specimens maturation at 20°C was demonstrated. At the same conditions HPC aerated indicated decrease of only 3 strength classes.

4.2. CONCRETE ABSORPTIVITY

Among the concrete specimens non-exposed to high temperatures the lowest absorptivity was obtained for HPC comparative (4,20%), and the highest for HPC aerated (4,49%), the opposite situation was observed after heating of specimens to 300°C. It is worth notifying that absorptivity of HPC aerated was significantly lower after exposure to 300°C (3,95%) and 450°C (4,31%) comparing to non-heated comparative specimens and the lowest among all concretes subjected to fire temperatures. Most probably at temperature of 300°C structure of aerated concrete changed improving its tightness.

In HPC fibre reinforced concrete and HPC comparative after heating of specimens to higher temperatures absorptivity was constantly increasing. This tendency was not observed for aerated concrete, which absorptivity at 300°C and 450°C decreased. This phenomenon is illustrated in figure 6.

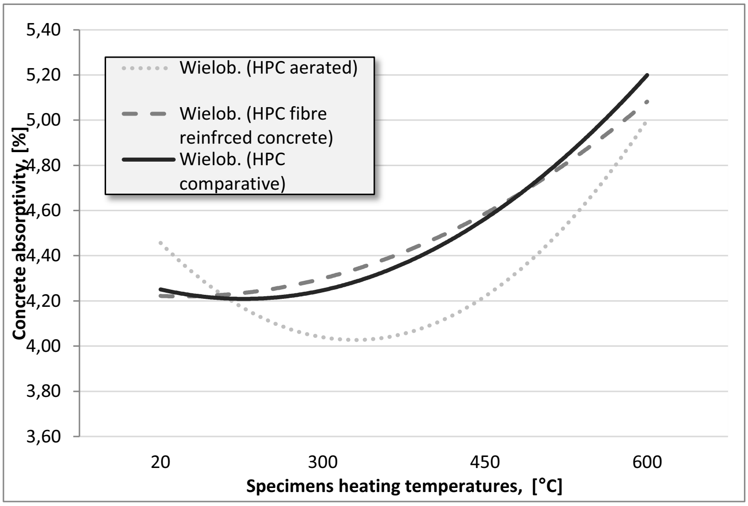


Figure 6. Characteristics of changes in absorptivity of concrete in elevated temperatures

Addition of fibres had no influence on concrete absorptivity after exposure to high temperatures. Trend lines of HPC fibre reinforced concrete and HPC comparative mix overlapped. For aerated concrete when exposed to 300°C and 450°C much lower absorptivity was observed.

After placing specimens in water (air cooled after heating to high temperatures) the "effect of effervescent tablet" was observed, and specimens began to rapidly release air bubbles in direction towards the water table.

Such phenomenon can be associated with opening of external capillary pores, which during heating migrated out the moisture. This could suggest that the absorptivity of concrete after heating to high temperatures would be much higher than it was observed in the reality. The absorptivity of all studied concretes (exposed earlier to 450°C) did not exceed 5%, which was considered as a satisfactory result taking into account that in the similar studies conducted by Egyptians [13] absorptivity was about 8%, and even 9% after exposure to 600°C. The obtained results can be considered as fulfilling the requirements, although in many technical specifications it can be found that absorptivity should not exceed 4%.

After exposure of concrete to 600°C, only absorptivity of aerated concrete did not exceed threshold of 5% and was equal to 4,95%. High absorptivity was obtained for comparative concrete (5,25%), while slightly lower (5,10%) for HPC fibre reinforced concrete.

It should be noticed that in case of HPC comparative, increase of temperature from 300°C to 450°C changed absorptivity result only for 0,01%, while in case of HPC fibre reinforced concrete it was 0,2%.

After impact of elevated temperatures (300°C, 450°C, 600°C) the lowest absorptivity among the studied concretes (and at the same time the best) was obtained for HPC aerated.

4.3. WATER PENETRATION DEPTH

Among the non-exposed concretes the lowest depth of moisture in a result of penetration of water under pressure was observed for HPC aerated concrete (2 mm), similar results were obtained for concrete with fibres (3 mm). Ten times (22 mm) higher depth of moisture for HPC comparative was demonstrated, however such result was very good and confirmed high tightness of all designed concretes. View of specimens after water penetration study is given in figure 7.

Figure 7. Wetted specimens of HPC comparative, non-exposed to high temperatures (own photo)

For HPC fibre reinforced concrete specimens heated earlier to 300°C temperature, a rapid increase of water penetration was observed (change from 3 to 71 mm). It was caused by the fact, that polypropylene fibres which were added to concrete mix after exposure to 300°C were partly degraded, opening the paths for the coming water. The highest resistance to water was found for aerated concrete (change from 2 to 9 mm), also after exposing concrete to 450°C HPC aerated concrete showed best parameters. For HPC comparative after exposure to 300°C and 450°C moisture height of approx. 40 mm was obtained.

Summing up, after impact of 300÷450°C the lowest water penetration depth was obtained for HPC aerated (9÷16 mm) and highest for the concrete with fibres addition (71÷88 mm).

After exposure of concrete to 600°C no resistance of high performance concretes to water under pressure existed. Specimens seeped through after 180 minutes.

During the studies it has been observed that the water migrated mostly through the scratches formed during heating to high temperatures (figure 8).

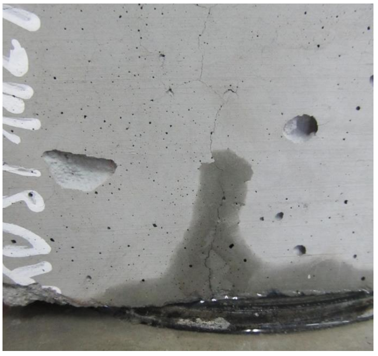


Figure 8. Water migrating through scratches in a specimen subject earlier to high temperature (own photo)

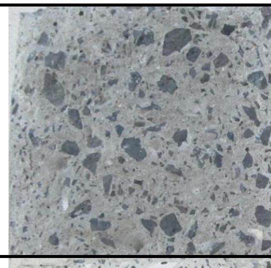
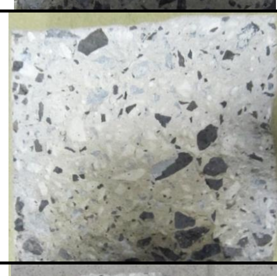
In figure 8 scratch range can be seen, in which the highest moisture was observed. View of fractured concrete specimen exposed earlier to temperature of 600°C is shown in figure 9.

Figure 9. Specimen after water penetration depth study (after 600°C) (own photo)

It should be noticed that the moisture area included all lower part of specimen, which was associated with leaking of the water sideways.

Loss of tightness of high performance concretes subject to temperature of 600°C results from degradation of C-S-H gel bonds. Specimens in macro scale do not show large damages (they are characterized by relatively high compressive strength and low absorptivity), however their microstructure shows high degradation degree (Table 6).

Table 6. Comparison of specimens fracture with regards to exposure temperature of the concrete (own photos)

Section of specimen non-exposed to high temperature - **20°C**	
Section of specimen exposed to high temperature - **300°C**	
Section of specimen exposed to high temperature - **450°C**	
Section of specimen exposed to high temperature - **600°C**	

Photos in table 6 show change in specimens fracture characteristic. In the photo of specimen exposed to 600°C only trace amounts of fractured coarse aggregate can be seen and only in the central part of the specimen, where the highest temperature remained for the shortest time. Observed changes were typical for all studied concretes. Based on the above observations it can be concluded that after exposure to high temperatures degradation of C-S-H occurred, which caused that slurry became much less resistant comparing to coarse aggregate.

It can be concluded that determination of penetration depth of water under pressure in the concretes subject to earlier exposure to high temperature should be lead based on the slightly modified research procedure. Authors believe that side surfaces of the specimens should be isolated with resin (as in case of water resistance according to wg PN/B/06250 [19]), in a way that direction of the water flow is forced upwards. It would prevent sideway leaking of the water from the studied specimens, causing concerns about the test correctness (concerning specimens heated to 600°C).

4.4. Frost resistance

After 150 cycles of frosting and defrosting specimens which were exposed to high temperatures showed significantly lower spread of results than specimens heated to 300°C. The difference between compressive strength of witnesses in particular concrete mixes and strength of frozen specimens (F150) was only 1%, and strength of frozen specimens was lower in average for about 5% comparing to witness specimens.

It can indicate that in case of concretes designed for frost resistance, aeration process had no significant effect on one of the mixes, but a very low w/c ratio in all compositions equal to 0,30. Perhaps improvement of frost resistance of HPC aerated comparing to HPC fibre reinforced concrete and HPC comparative could be noticed when all compositions would be subject to higher number of frosting and defrosting cycles (e.g. F300 or even higher).

Slightly larger differences between compressive strength of "witness" specimens and frozen specimens were noticed on the cubes subject to temperature of 300°C. In the aerated concrete the observed decrease of strength of frozen specimens was 4,4%, while for comparative concrete only 0,4%. Opposite tendency was shown for concrete with fibres, for which the increase of specimens strength was obtained, the specimens were first subjected to thermal load (300°C), and next subjected to 150 cycles of frosting and defrosting, comparing to witness specimens (only thermal load of 300°C and afterwards kept in water). The observed strength increase was 4,4%. In none of the studied concretes compressive strength of specimens subjected to 150 frosting and defrosting cycles did not drop below permissible 20% with regards to strength of "witness" specimens. Difference in strength was in a range of +4,4% to -5,5%.

In the specimens no cracks have been noticed. Summarizing, all studied high performance concretes obtained frost resistance degree of F150. Both at normal temperature (20°C), as well as after exposure to high temperature (300°C), none of the concretes experienced any frost damages, compressive strength did not fall below 20%, no mass drop below 5% was noticed, and specimens had no cracks. Total weight loss of concrete was less than 0.8%.

5. SUMMARY AND CONCLUSION

Conducted research program allowed to confirm suitability of aerated HPC concretes for engineering structures exposed to high temperatures and at the same time it indicated necessity of further studies on this type of concretes, as an alternative for concrete with addition of polypropylene fibres, except for extreme design in this case at extreme loads such as temperatures close to fire conditions.

The following conclusion have been formulated:

1. Exposure of concrete to high temperatures (105°C ÷ 600°C) has an influence on compressive strength of high performance concretes.
    - Temperature of 105°C results in decrease of strength of aerated concrete of 14% and 4% for concrete with fibres with regards to its strength at 20°C, and in case of comparative concrete strength increase of about 10%.
    - Temperature of 300°C causes strength increase of aerated concrete of 10,5%, 5% for fibre reinforced concrete, 21,7% for comparative concrete, comparing to its strength at 20°C.
    - Temperature of 450°C results in strength increase of aerated concrete of 7,5%, 12,5% for comparative concrete, and strength drop of 0,4% for fibre reinforced concrete, comparing to its strength at 20°C.
    - Temperature of 600°C results in strength decrease of aerated concrete of 24,6%, 35,5% for fibre reinforced concrete, and 18,4% for comparative concrete, comparing to its strength at 20°C.
    - The worst results have been obtained at temperature of 600°C for the concrete with addition of polypropylene fibres (drop of 5 strength classes comparing to result after 28 days of maturation).

    - The results of compressive strength studies do not confirm assumptions of the forecast on the strength decrease of high performance concretes as described in PN-EN 1992-2 standard, indicating very cautious approach to high performance concretes "behaviour" at elevated temperatures in the discussed standard.
2. High temperature has an influence on absorptivity of high performance concretes.
    - At elevated temperatures (300°C, 450°C, 600°C) the lowest (thereby the best) absorptivity (<5%) among the studied concretes has been demonstrated for aerated concrete.
    - The aerated concrete has had the lowest absorptivity after exposure to 300°C and 450°C than at temperature of 20°C.
    - After inserting specimens into water (pre-heated to high temperatures) air bubbles have been released from the specimens in the direction towards the water table.
    - High temperature has an influence on the penetration depth of water under pressure in high performance concretes.
    - After heating of specimens to 300°C a rapid increase of water penetration depth has been observed (change from 3 mm to 71 mm).
    - After heating of specimens to 300°C and 450°C the highest tightness for has been obtained for aerated concrete (average amount of moisture was only 9 mm and 16 mm, respectively).
    - None of the studied concretes exposed to temperature of 600°C has proved to be waterproof and shown complete dampness.
    - Evaluation of penetration depth of water under pressure of concretes exposed to high temperatures should be conducted on the sealed specimens, e.g. resin on the specimen sides.
3. High temperature (300°C) has an insignificant impact on high performance concrete frost resistance.
    - All studied concretes have reached frost resistance degree of F150.
    - Significant differences in specimens damage process have been observed.
    - Non-exposed concrete has shown a cohesive - adhesive damage process.
    - Concrete subject to high temperature has demonstrated only cohesive damages within the slurry of cement.
    - After exposure of concrete to high temperatures, C-S-H gel bonds have been destroyed, resulting in decrease of slurry resistance comparing to coarse aggregate.

REFERENCES

1. Hager I., Tracz T., Wpływ wysokiej temperatury na wybrane właściwości betonu wysokowartościowego z dodatkiem włókien polipropylenowych, Cement Wapno Beton, 1/2009;
2. Hager I., Metody oceny stanu betonu w konstrukcji po pożarze, Cement Wapno Beton, 4/2009;
3. Gawin D., Procesy degradacji mikrostruktury kompozytów cementowych w wysokiej temperaturze, Studia z zakresu inżynierii nr 69, Warszawa, 2010;
4. Omer A., Effects of elevated temperatures on properties of concrete, Fire Safety Journal, 42/2007;
5. Kalifa P., Chéné G., Gallé C., High-temperature behaviour of HPC with polypropylene fibres From spalling to microstructure, Cement and Concrete Research, 31/2001;
6. Metin H., The effects of high temperature on compressive and flexural strengths of ordinary and high performance concrete, Fire Safety Journal, 41/2006;
7. Gawin D., Majorana C. E., Schreßer B. A., Numerical analysis of hydro-thermal behaviour and damage of concrete at high temperature, Mechanics Of Cohesive-Frictional Materials, 4/1999;
8. Kowalski R., Mechanical properties of concrete subjected to high temperature, Architecture Civil Engineering Environment, 2/2010;
9. Erdakov P., Khokhryachkin D., Impact of fire on the stability of tunnels, Lulea University of Technology, 2005;
10. Han C., Hwang Y., Yang S., Gowripalan N., Performance of spalling resistance of high performance concrete with polypropylene fibre contents and lateral confinement, Cement and Concrete Research 35/2005;
11. Kalifa P., Menneteau F. D., Ouenard D., Spalling and pore pressure in HPC at high temperatures, Cement and Concrete Research 30/2000;
12. Tanacan L., Yasa Y., Arpacıoglu U., Effect of high temperature and cooling conditions on aerated concrete properties, Construction and Building Materials, 23/2009;
13. Saad M., Abo-El-Enein, Hanna G. B., Kotkata M. F., Effect of temperature on physical and mechanical properties of concrete containing silica fume, Cement and Concrete Research, 5/1996;
14. PN-EN 1992-1-2:2008P: Projektowanie konstrukcji z betonu - Część 1-2: Reguły ogólne - Projektowanie z uwagi na warunki pożarowe;
15. PN-EN 206:2014-04 Beton Wymagania, właściwości, produkcja i zgodność;
16. Poon C-S., Azhar S., Anson M., Wong Y-L., Comparison of the strength and durability performace of normal- and high-strength pozzolanic concretes at elevated temperatures, Cement and Concrete Research 31/2001;
17. Ling T-C., Poon C-S., Kou S-C., Influence of recycled glass content and curing conditions on the properties of sel-compacting concrete after exposure to elevated temperatures, Cement and Concrete Composites, 34/2012;
18. PN-EN 197-1:2012P Cement - Część 1: Skład, wymagania i kryteria zgodności dotyczące cementów powszechnego użytku;
19. PN-88/B-06250 Beton zwykły;
20. PN-EN 1008: 2004P Woda zarobowa do betonu - Specyfikacja pobierania próbek, badanie i ocena przydatności wody zarobowej do betonu, w tym wody odzyskanej z procesów produkcji betonu;
21. PN-EN 934-2+A1: 2012E Domieszki do betonu, zaprawy i zaczynu - Część 2: Domieszki do betonu - Definicje, wymagania, zgodność, oznakowanie i etykietowanie;
22. PN-EN 14889-2: 2007P Włókna do betonu - Część 2: Włókna polimerowe - Definicje, wymagania i zgodność;
23. PN-69/C-89022 Tworzywa sztuczne - Oznaczanie temperatury zapalenia
24. PN-EN ISO 1716:2010; Badania reakcji na ogień wyrobów - Określanie ciepła spalania brutto (wartości kalorycznej)
25. PN-EN ISO 11358-1:2014-09; Tworzywa sztuczne -- Termograwimetria (TG) polimerów - Część 1: Zasady ogólne
26. ISO 834-12:2012 Fire resistance tests - Elements of building construction - Part 12: Specific requirements for separating elements evaluated on less than full scale furnaces.

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