EFFECT OF THERMAL TREATMENT ON PROPERTIES OF HIGH STRENGTH CONCRETE

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ABSTRACT

High Performance Concrete (HPC) and Ultra-High Performance Concrete (UHPC) are modern building materials with advanced mechanical properties and durability compared with traditional concrete. Increasing of their mechanical properties allows reducing cross section of construction element. As a result, less raw materials are consumed.

Obtaining of concrete with high mechanical strength is related to a low W/C ratio, superplastificators and use of specific mixing and hardening technologies. One of the factors that influence properties of concrete is thermal treatment during hardening process. For traditional concrete steam treatment is used, but in the case of specific modern materials like HPC and UHPC increasing of mechanical properties can be achieved with the thermal treatment at temperature over 100°C.

The effect of thermal treatment on concrete compressive strength was investigated on cube-shaped specimens of 5cm. The heat treatment temperature varied from 50°C to 200°C with a 50°C increment. The specimens were heated under the same conditions for each temperature level; speed of increasing the temperature was 2°C per minute, thermal treatment at maximal temperature lasted 4 hours. Thermal treatment and compressive strength tests were carried out on the 3rd and 28th days. Tests were performed with specimens cooled down slowly to room temperature after heating.

Additional tests were made for water absorption and permeability, including SEM analysis comparing concrete specimens with and without specific thermal treatment applied.

The results showed that, despite the possible dehydration, compressive strength of thermally treated HPC specimens has improved. Maximal compressive strength was achieved for specimens thermally treated at 200°C. Compressive strength of non-heated specimens was about 80 MPa (on 3rd day) and 130 MPa (on 28th day), and thermally treated specimens showed a strength about 155 MPa (on 3rd and 28th day).

Results for SEM, water absorption and permeability, compressive strength of specimens at different thermal treatment conditions are summarized it this paper.

Key words: High strength concrete, HPC, thermal treatment, permeability of HPC

INTRODUCTION

Construction sector is one of the biggest industries having an enormous impact on the economic development. 4.6 trillion USD were spent in the world in this sector, in 2011 (Crosthwaite, 2012). Concrete is the most widely used construction material in the world with an annual use of cement estimated to constitute 3.86 billion tons in 2012 (For Construction Pros.com, 2011). The cement production industry generates up to 5% of the total amount of CO_2 emissions (Flower et al, 2007).

Considering the huge amount of concrete used in the world, qualitative changes in the material and its production process could have a significant impact on global economic development and the total amount of CO_2 emissions. Improvement of mechanical properties of concrete would allow the size of constructions to be reduced and less concrete would be necessary decreasing the amount of raw materials used.

Introduction of high strength concrete (with a compressive strength more than 100 MPa) in particular construction elements of civil engineering would give an economic benefit. Dimensions of columns often used in high-rise buildings could be decreased therefore increasing the total useful floor area. Without changing dimensions of columns it is possible to reduce the amount of necessary reinforcement in columns. Here is the economic benefit – while high strength concrete might be more expensive than an equal amount of traditional concrete, the total costs can be lower due to improved concrete properties. Increased modulus of elasticity of high strength concrete increases stiffness of high-rise buildings and reduces deformations due to wind load. Design of parking facilities improves as well if the supporting columns are smaller.

According to the results of the recent research, it is possible to reduce by 50% the amount of gases causing the greenhouse effect in the production of building materials by using high strength concrete (Habert et al, 2012). Consequently, not only the economic benefit can be observed, but sustainable development is encouraged as well.

Obtaining of concrete with high mechanical strength is related to a low W/C ratio, superplastificators and use of specific mixing and hardening technologies. One of the factors that influence properties of concrete is thermal treatment during the hardening process. For traditional concrete, steam treatment is used, but in the case of specific modern materials like HPC and UHPC increasing of mechanical properties can be achieved with thermal treatment at a temperature of over 100°C

Concrete is non-flammable and is considered to be a fire-proof material, thus is is used in constructions with increased requirements for fire safety, for example, firewalls and fire-proof sections in buildings (Mehta et al, 2006). Thermal treatment is used in the process of concrete curing as well in order to obtain a higher early age strength. For example, this method is widely used for the production cycle optimisation in the production of precast concrete elements. Several researches regarding the impact of thermal treatment on concrete properties and its application time and application period have been performed since 1950. Research results have been included in various design norms and guidelines. However, the research object usually has been traditional concrete with a compressive strength of 15-30 MPa. As the use of high strength concrete and the research on its properties has expanded during the last years, there are well-founded suspicions that the performance of high strength concrete under thermal treatment is not characterised precisely in design norms.

Thermal treatment of concrete is used separately or as a steam-heat treatment with possible high-pressure steam. Treatment at an elevated temperature accelerates cement hydration or reactions of other cementitious materials, therefore resulting in higher early age strength compared to the normal conditions. It is observed that after a 28 day curing period, at a temperature regime +5°C – +46°C the difference between concrete which has been thermally treated or cured under normal conditions becomes less evident as the similar hydration stage is reached after 28 days. It should be noted that according to practical observations the higher thermal treatment temperature results in a lower final strength of concrete, for example, after 180 days (Mehta et al, 2006).

In modern concrete more and more attention is paid to fine mineral additives, for example, microsilica. However, the results of researches on thermal treatment of concrete containing amorfous silica and conclusions regarding the impact of the fine mineral additives are contradictory. For example, M.S.Morsy and others concluded that microsilica additives have a positive impact on the concrete after 28 days of curing at a temperature of up to 400°C (thermally treated for 2 hours), because the compressive strength of treated specimens increased in comparison with the non-treated specimens (Morsy et al, 2010). Ali Behnood and Hasan Ziari in turn argue that the presence of microsilica in concrete do not have a positive contribution to its mechanical properties apart from the higher compressive strength in comparison with concrete without microsilica (Behnood et al, 2008). The compressive strength of concrete increases only slightly compared with the thermal treatment of 100°C and 200°C. Concrete mixes with amorfous silica which were thermally treated at a temperature exceeding 200°C showed more significant strength reduction in comparison with concrete without this additive. It should be noted that the initial strength of concrete in the research of M.S.Morsy and others was up to 50MPa, while in the research of Ali Behnood and Hasan Ziari it ranged from 60-85MPa. The initial strength of concrete is one of the factors having an impact on concrete properties at a high temperature.

MATERIALS AND METHODS

In this research the impact of high temperature regime on high strength concrete was examined. Concrete with the approximate compressive strength of 100 MPa and chemical composition shown in Table 1 was used.

Table 1

Chemical composition of concrete used in research

Components	Amount,kg/m3
Cement CEM I 42,5 N	800
Sand 0,3- 2,5 mm	510
Sand 0-1,0 mm	480
Sand 0-0.3 mm	100
Ground quartz sand	100
Microsilica	100
Nanosilica	20
Superplasticizer	20
Water	200

Thermal treatment of specimens was performed on 3rd and 28th days, while physical and mechanical properties were tested on 4th and 29th days of curing respectively. Compressive strength was also tested on the 58th and 86th days to assess the dynamics of curing without thermal treatment. Thermal treatment was performed applying temperatures of 50, 100, 150 and 200°C, compressive strength, water absorption and water permeability of the specimens were tested as well. Thermal treatment of specimens at temperatures of 250°C and 300°C was performed on the 3rd day as well in order to test the impact of temperature on the concrete at a high temperature, which is close to the temperature of possible concrete destruction under the impact of increased steam pressure.

Technology of the concrete mix preparation consisted of several stages. First all the dry components were mixed in a mixer for approximately 1.5 minutes in order to obtain a homogenous mix. Then nanosilica was added in the form of a water suspension with a ratio of 1:2 (water:nanosilica) according to the mass. Next 2/3 of the necessary water was added followed by 1/3 of water mixed with superplasticizer. The mixing process was continued until a homogenous fluid mix was obtained. The total mixing time was about 6 minutes.

The prepared concrete mix was moulded in respective moulds (steal moulds including 5x5x5 cm cubes for mechanical tests, 4x4x16 cm prisms for water absorption tests and 10x10x10 cm cubes for water permeability tests). Specimens were vibrated on a vibrating table for about 10 seconds.

Moulds were covered with a polyethylene film to limit the vaporising of water and left for curing at the room temperature. On the 3rd day of curing specimens were demoulded. Part of the specimens was placed in the water to continue curing process, while the rest of them were thermally treated.

Temperatures of 50, 100, 150, 200, 250, 300°C were used in this research. The thermal treatment cycle consisted of heating phase when increasing of the temperature was 2°C per minute, thermal treatment at maximal temperature phase, which lasted for 4 hours and cooling down phase when the specimens were left to cool down to the room temperature (Fig. 1).

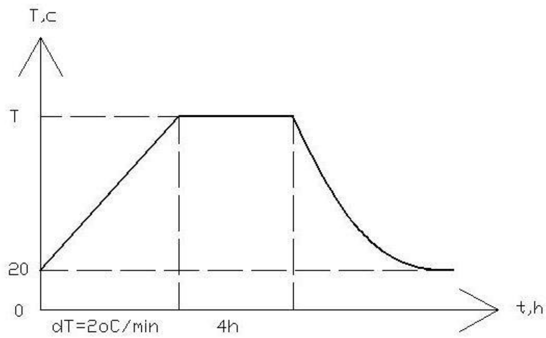

Figure 1. Furnace operating mode,
Where T – temperature, °C;
t – time, hours

Compressive strength of the specimens after the application of various temperatures was tested in this research depending on the time of thermal treatment and testing time. Labelling of specimens:

- Thermal treatment was applied on the 3rd day, compressive strength tested on the 4th day of curing. Labelling 3/4 (thermal treatment day/testing day);
- Thermal treatment was applied on the 3rd day, compressive strength tested on the 29th day of curing. Labelling: 3/29;
- Thermal treatment was applied on the 28th day, compressive strength tested on the 29th day of curing. Labelling: 28/29.

Specimens without thermal treatment, which were cured in water, were used for reference. Specimens 28/29 were taken out of the water 7 days prior to the thermal treatment and left to dry at room temperature. Specimens 3/29 were immersed in water again after thermal treatment and treated similarly to the 28/29 specimens until the testing of compressive strength.

Dynamics of the reference specimens' compressive strength was tested on the 4th, 29th, 58th and 86th days. Specimens were cured in water at room temperature and taken out of the water 7 days prior to mechanical tests. 5x5x5 cm cubes were used for compressive strength tests.

4x4x16 cm prisms were used for water absorption tests. Water absorption of 3/29 and 28/29 specimens were tested by treating them at temperatures of 50-200°C with 50°C increments.

Water permeability tests were performed with reference specimens and the specimens which were thermally treated at 200°C on the 3rd day and then immersed in water until the 29th day. Specimens were tested on the 31st day according to the standard LVS EN 12390-8:2009 Testing hardened concrete - Part 8: Depth of penetration of water under pressure.

The concrete microstructure was investigated using a scanning electron microscope (SEM) as well as by X-ray analysis of reference specimens without thermal treatment and specimens treated at 200°C for 4 hours.

RESULTS AND DISCUSSION

The obtained compressive strength results are shown in Fig. 2. Growth of compressive strength can be observed with a temperature increase. However, regardless of the maximal compressive strength at the maximal temperature of (153.1 MPa for 28/29 specimens at 200°C) and the following thermal treatment, even this treatment effect decreases with the increase of curing time and temperature.

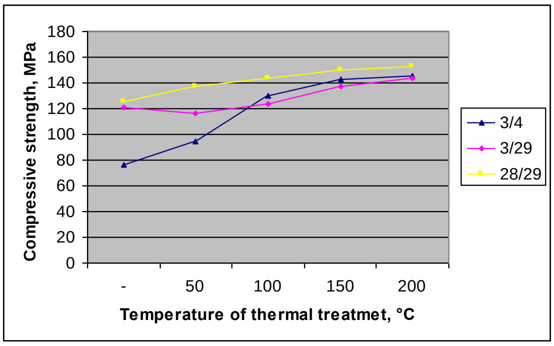

Figure 2. Compressive strength of the specimens

Compressive strength development dynamics of the specimens without thermal treatment was tested, which reached 123 MPa and 139.8 MPa on the 29th and 58th days respectively. It corresponds to 160% and 170% strength activity index compared to the compressive strength on the 4th day (76.8 MPa). Up to 29 days compressive strength increased rapidly, then it slowed down, but did not stop completely, which is typical for concrete mixes with such pozzolanic additives as microsilica and nanosilica. Compressive strength of concrete specimens was 137.9 MPa on 86th day which corresponds to 180% strength activity index

Treating ¾ specimens at temperature 300°C for 4 hours the critical value of the steam pressure for the chosen composition was reached and the specimens exploded during the thermal treatment which could be expected.

Compressive strength of 3/4 specimens after treatment at temperature 250°C was 177.7 MPa, which corresponds to 231% of specimens without thermal treatment 3/4 (76.8 MPa).Water absorption results are given in Table 2.

Table 2

Water absorption results of specimens

		day of treatment	
		3	28
temperature of treatment	50	2.8%	3.0%
	100	2.9%	3.0%
	150	2.9%	3.0%
	200	2.9%	3.0%

The overall trend is that specimens thermally treated on the 3rd day have lower water absorption. However, taking into account the dispersion of results and close mean values, it is not possible to draw apparent conclusions about the impact of thermal treatment on water absorption.

Depth of penetration of water under pressure was not observed for the specimens without thermal treatment by splitting the specimens. For the specimens treated at 200°C it was 3 mm. It indicates the presence of cracks in the upper layers of concrete which have appeared as a result of thermal treatment and encouraged water penetration in contradistinction to the dense structure of specimens without thermal treatment. The map of cracking of specimens is shown in Fig. 3.

High density of concrete is regarded as a factor encouraging the spalling in the top layer of concrete because it limits moisture migration and heat transfer processes in the concrete significantly.

Observing the microstructure of specimens under the SEM, formations shown in Fig. 4 were found. They were present in the specimens treated at 200°C and are similar to aluminium silicate hydrate. These formations were not present in the specimens without thermal treatment. Taking into account the shape of formations, they possibly might weaken concrete structure and encourage the complete or partial destruction of concrete under the impact of increased steam pressure or spalling in the top layer of concrete.

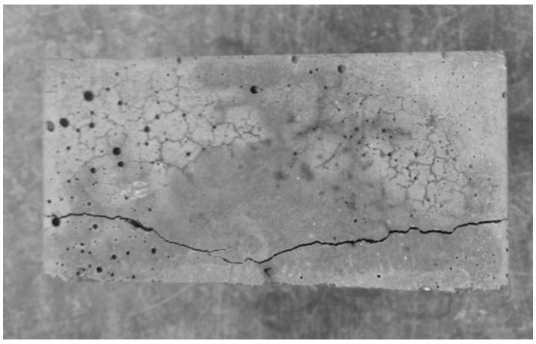

Figure 3. Map of cracking of concrete specimens after thermal treatment at 200°C

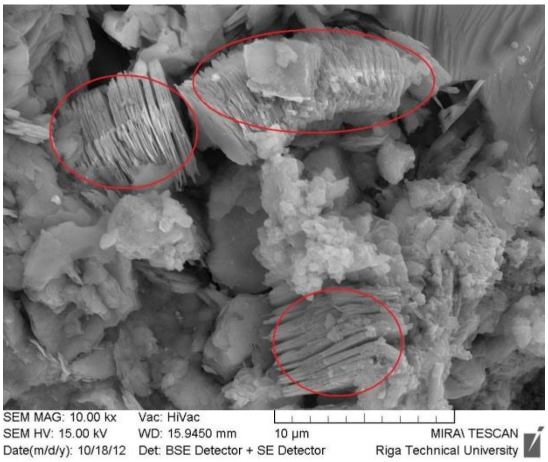

Figure 4. SEM image of the concrete specimen theramlly treated at 200°C

By comparing the results obtained with the RDX method of specimens without thermal treatment (Fig. 5) and specimens treated at 200°C (Fig. 6), in addition to quartz (Q), larnite (L) and plagioclase (P), calcite (C) can be observed which is not present in specimens without thermal treatment.

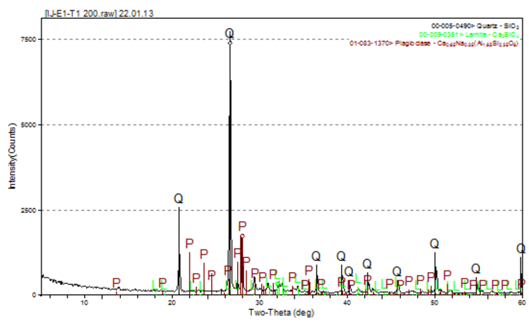

Figure 5. Results of X-ray analysis of specimens without thermal treatment

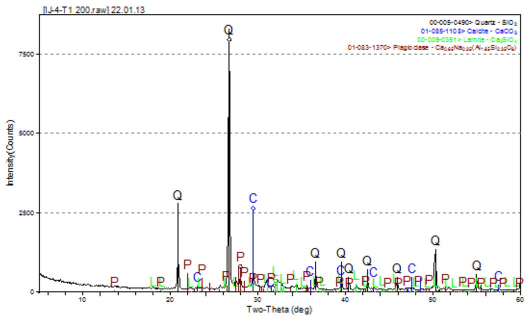

Figure 6. Results of X-ray analysis of specimens treated at 200°C

CONCLUSIONS

Thermal treatment at the temperature up to 250°C increases the compressive strength of concrete, especially in the early curing stage of the high strength concrete (compressive strength of 3/4 specimens without thermal treatment is 76.8 MPa, but it reaches 177.7 MPa or 231% of the compressive strength without thermal treatment after 4 hours of thermal treatment at 250°C);
The treatment temperature exceeding 200°C creates irreversible changes in the structure of high strength concrete and has an impact on its properties, for example, water permeability (water permeability for the specimens after thermal treatment at 200°C grows to 3 mm compared to 0 mm for the specimens without thermal treatment), while the compressive strength may not indicate it (the overall trend is increase of compressive strength according to the Fig. 2);
Using high strength concrete in the production of concrete elements thermal treatment at temperature up to 100°C might be a balanced solution taking into account the shorter period which is necessary to create constructions as well as minimise the negative impact on the concrete properties. Applying this temperature, it is possible to reach the same concrete compressive strength as after 58 days of curing;
Creating constructions from ‚high strength concrete, it is necessary to pay attention to the fact that temperatures exceeding 250°C, for example, in the case of fire, increase the risk of spalling in the top layer of concrete.

ACKNOWLEDGMENT

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REFERENCES

Behnood A., Ziari H. (2008) Effect of silica fume addition and water cement ratio on properties of high-strength concrete after exposure to high temperatures. *Cement & concrete composites*, Vol. 30, Issue 2, p. 106-112.

Crosthwaite D. (2012) World Construction 2012 [online] [accessed on 08.01.2013.]. http://www.davislangdon.com/EME/Research/ResearchFinder/OtherResearchPublications/World-Construction-2012/

Flower D., Sanjayan J. (2007) Green house gas emissions due to concrete manufacture. *The international Journal of life cycle assessment*, Vol. 12, Issue 5, p. 282-288.

For Construction Pros.com (2011) Global Cement Consumption Expected to Reach New Highs [online] [accessed on 08.01.2013.] http://www.forconstructionpros.com/press_release/10366676/global-cement-consumption-expected-to-reach-new-highs

Habert G., Arribe D., Dehove T., Espinasse L., Le Roy R. (2012) Reducing environmental impact by increasing the strength of concrete: quantification of the improvement to concrete bridges. *Journal of Cleaner Production*, Vol. 35, p. 250-262.

Mehta P.K., Monteiro P.J. (2006) *Concrete Microstructure, Properties, and Materials*, 3rd Edition. New York: The McGraw-Hill Companies. 669 p.

Morsy M.S., Alsayed S.H., Aqel M. (2010) Effect of elevated temperature on mechanical properties and microstructure of silica flour concrete. *International journal of civil & environmental engineering*, Vol. 10, Issue 01, p. 1-6.