ULTRA HIGH PERFORMANCE CONCRETE HARDENING UNDER PRESSURE

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ABSTRACT

In this study effect of pressure application to a fresh concrete right after casting and during the first 24 hours of hardening has been examined. Ordinary concrete can be defined as a porous media with high capillary porosity, especially in the aggregate–hydrated cement paste transition zone. The aim of pressure application is to maximally eliminate pores, to remove excess capillary water, and to improve density of the concrete matrix By the pressure application it is possible to considerably reduce an amount of pores (>20 nm), to make concrete matrix denser and significantly increase its compressive strength. In this study concrete was cast in a specially designed cylindrical mould with an option to apply pressure. Pressure of 0 – 50 MPa has been applied. Cylindrical samples with a diameter of 50 mm and a diameter to height ratio 1:2 have been prepared. The concrete mix, incorporating silica fume and nanosilica particles has been prepared.

Keywords: High performance concrete, pressure application, compressive strength

INTRODUCTION

Ultra high performance concrete (UHPC) is a modern building material with superior properties such as high compressive strength, high modulus of elasticity, low permeability, excellent durability and high fluidity. All these properties can be achieved taking into account some basic principles and processing methods, that can be listed as follows: (i) minimising defect occurrence in concrete matrix and obtaining maximum density by optimizing particle size distribution (ii) minimising water/cement ratio by using high range water reducing admixtures which are compatible with the cement (iii) using pozzolanic materials such as silica fume to fill voids between larger particles, improve rheological properties and enhance secondary calcium silicate hydrate formation (iv) incorporation of steel fibers to prevent brittle failure and polypropylene fibers to increase UHPC fire resistance (Aitcin, 1998; Jain, 2003; Khurana, 1998; Khayat et al., 1996; Richard et al., 1996)

In 1994 Richard and Cheyrezy (Richard et al., 1994) produced reactive powder concrete (RPC) with compressive strength of 800 MPa. RPC is a type of UHPC which is characterized by very fine particles, no coarse aggregate is present. Production technology includes pressure application and heat treatment.

First demonstrations of UHPC outside laboratory were in footbridges. These structures appeared in the end of 1990ties. Some of the most well-known examples are in Sherbrook (1997), Seoul (2002) and Kassel (2007) (Tang, 2004*;* Fehling et al., 2004). First two road bridges using UHPC with a compressive strength more than 170 MPa were built in France in 2001 (Bourg-lès-Valence bypass) (Hajar et al., 2004). Initially structures were designed basing on the experimental data of particular concrete as there were no building codes for UHPC present. However, first guidelines for UHPC appeared in 2002 in France.

UHPC is one of the most promising types of concrete in 21st century. Although efforts in developing the UHPC started in the last century, it is most probable that 21st century will benefit more from UHPC technology and more slender and aesthetical structures will be designed by architects who have acquired knowledge about UHPC. One of the factors of wider UHPC application will also be cost reduction as technology will be improved. There are already examples of commercially available UHPC that is used in the construction industry today. One such example is Ductal®. The Ductal® technology was developed by the combined efforts of three companies, Lafarge, the construction materials manufacturer, Bouygues, contractor in civil and structural engineering and Rhodia, chemical materials manufacturer (Acker et al., 2004) .

The aim of this study is to investigate influence of different pressure applied during sample hardening process. Concrete mix composition with compressive strength of approximately 100 MPa was selected as basic mix. Pressure has been applied right after casting in order to improve concrete properties, mechanical strength of prepared samples was compared. By pressing concrete in the fresh state, most of entrapped air and excess capillary water can be eliminated, pore diameters reduced and some chemical adverse effects coming with cement hydration, for example autogenous shrinkage, eliminated. Distance between particles determines most of the concrete properties, eliminating of voids and reducing pore diameters would result in enhancement of concrete performance (Neville, 1995; Freyssinet, 1936).

As the macroscopic properties of UHPC are related to its microstructure - porosity, pore-size distribution as well as morphology of hydration products, concrete has been observed using scanning electron microscope (SEM) and very few pores with diameters >50nm have been found. Ultra high performance concrete border of 150 MPa has been reached by 50 MPa pressure application.

MATERIALS AND METHODS

The materials used in this study were commercially available raw materials, cementitious materials and admixtures. UHPC is characterised by very high content of high performance cement and silica fume. In this study concrete mix has been designed to reach approximately 100 MPa without pressure application at the age of 28 days and by pressure application right after casting make concrete matrix denser to achieve UHPC compressive strength border (150 MPa) at the age of 28 days.

Table 1

Concrete mix composition

Material	Quantity, kg/m^3
Cement CEM I 42,5 N	800
Sand 0.3-2.5 mm	510
Sand 0-1.0 mm	480
Ground quartz sand	200
Silica fume	100
Nanosilica	20
Superplasticizer	20
Water	200

Relatively high amount of ordinary type CEM I 42.5 N portlandcement was used. The amount of silica fume and nanosilica was 12.5% and 2.5% of cement mass respectively. Both silicas were made by Elkem (Norway). Polycarboxilate based superplasticizer has been used. The W/C ratio was 0.25. Basic concrete mix has been designed in order to provide 28 day compressive strength in the range of 100 MPa. Mix composition is given in the Table 1.

Particle size distribution

To produce UHPC, well grading of materials is essential. Particle size distribution curve of selected mix is given in Figure 1.
Optimal packing of available materials for the mix was obtained via computer programm EMMA by Elkem materials. To determine particle packing down to nano-scale, modified Andreassen particle packing model was employed (curve parameters q=0.25, D_{max} = 2.5 mm and D_{min} = 0.0001 mm was selected).

Mixing procedure

The mixing procedure of materials was the following: all dry materials were mixed till a homogenous mixture formed (approximately for 1.5 min). Then water and superplasticizer was added in two steps. During the first step approximately 70% of water was added. During the second step the rest of the water and the full amount of superplasticizer were added. Total mixing time was approximately 6 minutes. Mix with the cone slump of class S2 has been obtained after finishing mixing.

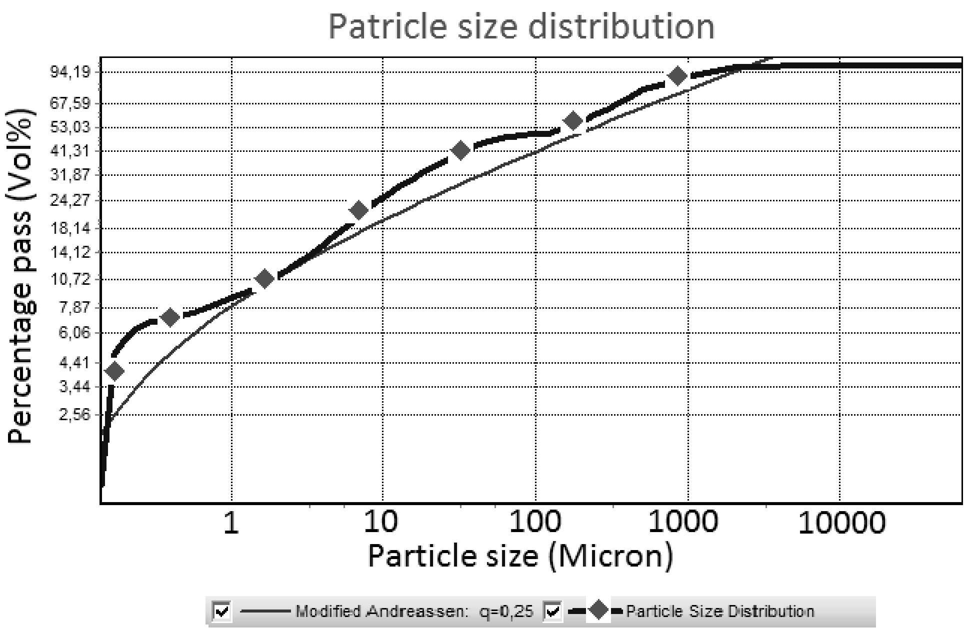

Figure 1. Particle size distribution of the selected concrete mix.

Experimental setup

Special cylindrical mould with inner diameter of 50 mm and varying height was designed and produced for this study. The mould consisted of 3 high precision details: central cylinder and two pistons closing cylinder from both ends. Pressure was applied by a manual hydraulic press. Pressure readings were taken from the manometer installed on the press. The experimental setup for pressure application is shown in Figure 2.

Figure 2. Experimental setup for pressure application to the specimens.

Right after casting pressure was applied to the concrete and retained for 24 hours.
Cylindrical specimens with a diameter 50 mm and height 100 mm were prepared. Pressures of magnitude 0, 10, 20, 30, 40 and 50 MPa were applied to the specimens during initial hardening in order to remove the entrapped air and excess water. After 24 hours the specimens were demoulded and cured in the water at the temperature of 20 ˚C until the age of 28 days was reached. At the age of 28 days compressive strength was determined.

RESULTS AND DISCUSSION

Quite stable pressure value has been kept up during pressure application, only minor corrections in first 20 minutes were necessary. Due to relatively low W/C ratio (0.25), little excess water was observed.

Macroscopic observations

As the macroscopic properties of UHPC are closely related to its microstructure, right after demoulding all specimens were evaluated visually. Macroscopic observations revealed that the samples hardened under higher pressure had significantly less porous structure. If there were clearly visible pores for samples hardened without pressure, completely opposite situation was for samples hardened under 50 MPa pressure, where no pores in macroscopic level could be discovered. Even for the specimens hardened under 10 MPa pressure very few macroscopic defects were noticed (Figure 3).

Figure 3. The specimens prepared by 10 MPa pressure application.

Material density

Densities of the specimens were observed carefully in order to control pressure application process. Theoretically there could be situation that side wall friction between cylinder and piston increases significantly if fine concrete particles are entrapped between the two details and consequently lower pressure is applied to the sample. However, due to the high precision of cylinder and piston details and careful concrete casting such negative situation was not experienced. Measured densities for samples with different pressure levels are shown in Figure 4.
In figure 4 two different regions can be clearly divided pressure 0 -10 MPa and pressure 10 – 50 MPa. Figure 4 show that the most significant increase of density is observed, when pressure is increased from 0 to 10 MPa. In next intervals density increases almost linear, but the increase rate is in average only 7.6% of that observed in first interval. Conclusion can be drawn that for concrete with cone slump class S2, 10 MPa pressure is sufficient to eliminate most of entrapped air and excess water. By increasing pressure above 10 MPa, further micro and nano scale pore diameters are decreased.

Porosity

Porosity percentage of specimens was calculated taking into account material density and spacific gravity of the concrete samples.

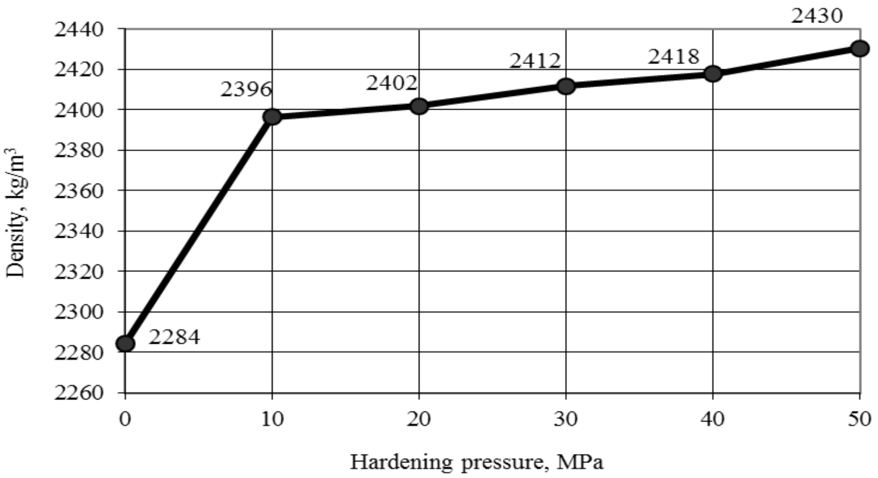

Figure 4. Density of the specimens depending on hardening pressure applied

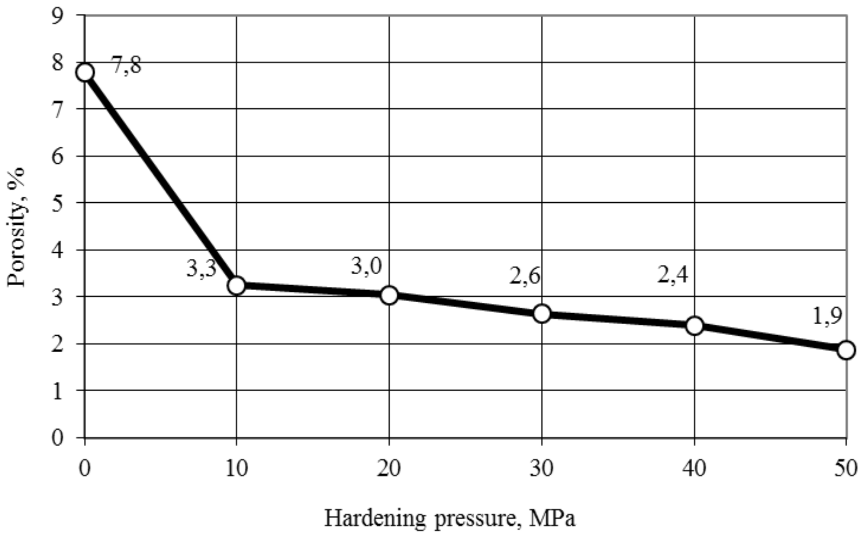

Figure 5. Porosity of the specimens depending on hardening pressure applied

Specific gravity was determined by pycnometer method (the sample was ground befote test) and porosity was calculated using previously obtained sample densities. Results are displayed in Figure 5.

In Figure 5 two different regions can be divided identically as in case of density. By increasing pressure from 0 MPa – 10 MPa, porosity rapidly decreases from 7.8% – 3.3%. By increasing pressure from 10 MPa – 50 MPa porosity decreases with the average rate of 7.8% of that observed in the first interval. Rapid porosity decrease in the first pressure interval can be explained by the fact that calculated porosity results also include macroscopic defects and relatively small pressure is necessary to eliminate macroscopic air voids. However, significantly higher pressure is required to reduce the micro and nano-scale pore size diameters. The lowest porosity value acquired in this study by 50 MPa pressure application was 1.9%.

Compressive strength

Samples without pressure application reached compressive strength of 103.9 MPa. Samples with 50 MPa pressure application reached compressive strength of 153.6 MPa, which corresponds to the strength increase of 48%. Every 1 MPa of pressure applied to sample in the first 24 hours gave in average an extra 1 MPa of compressive strength after 28 day hardening. In the interval of first 10 MPa pressure application this rate was three times higher. This pressure interval may be practically applied in the pre-cast concrete industry, although higher pressure value is technologically difficult to achieve for the real concrete elements. The smaller the distance between concrete particles, the lower porosity, the higher density and higher final compressive strength was reached The compressive strength results are given in the Figure 6.

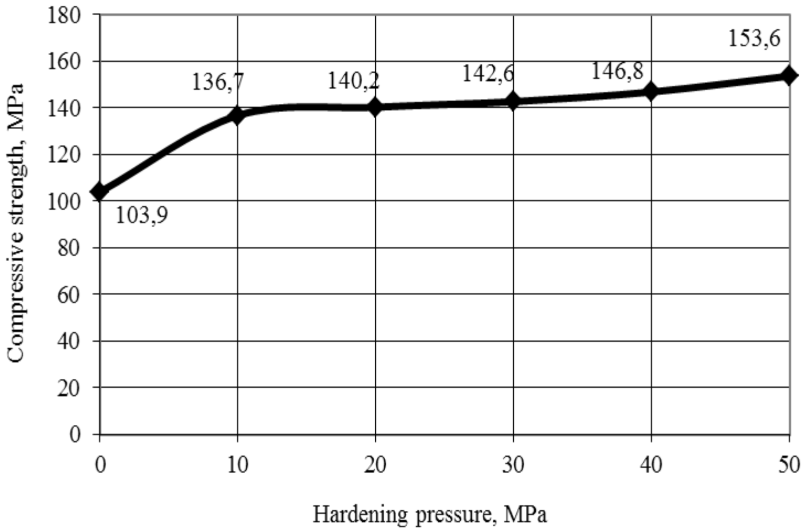

Figure 6. Compressive strength of the specimens depending on hardening pressure applied

Microscopic (SEM) observations

Figure 7 shows destroyed concrete surface at the magnitude of 100 times. The concrete specimens with highest compressive strength (153.6 MPa) were observed by SEM. Samples were taken from the middle of destroyed specimens to observe microstructure of the concrete. Dense concrete matrix and destroyed aggregates are visible in Figure 7. Magnitude of 1000 times (Figure 8) reveals dense structure of calcium silicate hydrates.

Pore diameters were evaluated graphically from SEM micrographs. Very few pores with diameters larger than 200 nm were determined, however, there are some examples of pores with diameter approximatelly 200 nm (Figure 9).

In terms of the different effect of pore size on concrete performance, the pores in concrete can be classified as follows: harmless pores (<20 nm), few-harm pores (20–50 nm), harmful pores (50–200 nm) and multi-harm pores (>200 nm) (Ye, 2001).

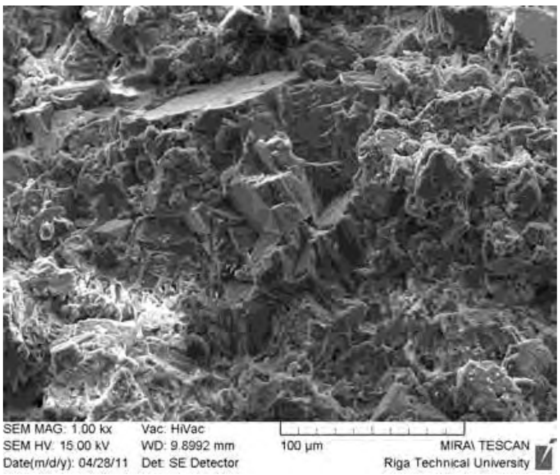

Figure 8. Concrete at the magnitude of 1000 times

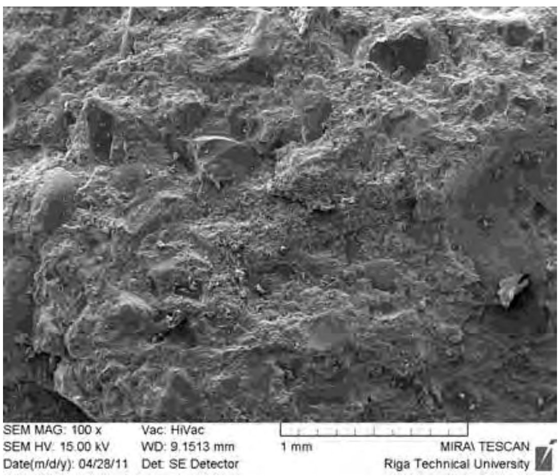

Figure 7. Concrete at the magnitude of 100 times

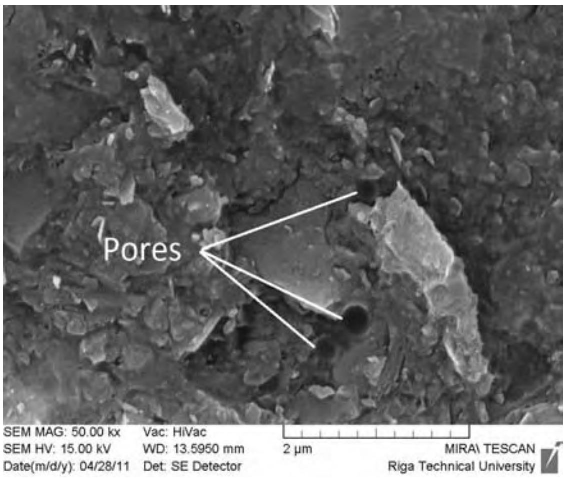

Figure 9. Concrete at the magnitude of 50 000 times

CONCLUSIONS

Pressure of 10, 20, 30, 40 and 50 MPa was applied to the concrete specimens during initial hardening (24 hours) in order to improve physical and mechanical properties of the materials. Compressive strength, density and microstructure were investigated. Following conclusions can be drawn from this study.

Applying pressure in concrete initial hardening phase it is possible to achieve UHPC compressive strength border (150 MPa) for the concrete mixes, which normally at the age of 28 days achieve only 100 MPa.

The greatest gain in concrete performance characteristics was observed by applying pressure at the rate of 10 MPa (strength increase in 31.5 %). By increasing pressure further to 50 MPa slower enhancement of the concrete properties was noticed. Due to 50 MPa pressure application density of samples increased from 2284 kg/m^3 to 2430 kg/m^3, porosity decreased from 7,8% to 1,9%, excess capillary water was removed. Significant gain of compressive strength of 48% (103,9 to 153,6 MPa) was observed for samples pressed with 50 MPa.

Pressure application during the concrete setting can be used in precast element fabrication. For real concrete elements pressure up to 10 MPa may be practically applied in pre-cast plants, higher pressure technologically is difficult to achieve. Results of this study indicate that even relatively small pressure gives significant positive effect in enhancement of concrete properties. Influence of pre-set pressure in range of 0 – 10 MPa must be investigated in future in details.

Summarizing the results it can be concluded, that pressure is an effective instrument to achieve high mechanical strength and high performance characteristics of concrete.

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