Mechanical Properties and Microstructural Investigation of Ultra-High Performance Glass Powder Concrete

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http://dx.doi.org/10.5755/j01.sace.14.1.14478

JSACE 1/14

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Received 2016/03/04

Accepted after revision 2016/04/15

Additive of glass powder was successfully utilized in ultra-high performance concrete (UHPC) mixture. During experiment was found, that glass powder can be used instead of silica fume (SF), without decrease of mechanical properties and microstructure can be significantly increased. In experiment 100 % of quartz powder was substituted by glass powder. Quantitative and qualitative XRD analysis revealed, that glass powder improves hydration of Portland cement and in such way additional compressive strength up to 40 MPa can be gained. Designed mixtures were blended with laboratory mixer Eirich R02T and later with industrial mixer HPGM 1125. In new UHPC mixture was incorporated different amount of steel fibres. Flexural strength was increased about 5 times from 6.7 MPa to 36.2 MPa.

KEYWORDS: UHPC, glass powder, XRD analysis.

Introduction

Advances in concrete technology have led to develop a new type of cementitious composites: self-compacting concrete, self-healing concrete, 3D printing concrete, ultra-high performance concrete and etc. (Nguyen *et al*, 2014). In this article we going to focus on ultra-higher performance concrete. UHPC with the very low water-to-cement ratio (W/C) demonstrates excellent workability, advanced mechanical and durability properties (Yu *et al* 2014). These and other properties mainly depends on particle size distribution, packing density, optimal W/C ratio. So deeper literature review is needed to properly understand the material.

Tavakoli and Heidari (2013) conducted microstructural investigations with scanning electron microscope (SEM) micrographs and pinpointed, that UHPC differs a lot from the conventional concrete. Author thinks, that concrete mixture with silica fume and low water to binder ratio leads to a very dense and homogenous structure. Thus porosity and permeability to fluids can be decreased. Author also denotes that composition with silica fume decreases amount and size of potlandite (CH) crystals. Mainly due to positive effect of pozzolanic reaction. Due to pozzolanic reaction CH crystals are consumed and addition calcium silicate hydrates (CSH) are formed. Thus compressive strength increased further and other mechanical properties can be improved. Alawode *et al* (2011) during experiment, noticed that concrete with high W/C ratio tends to create large CH crystals, those large crystals serve as weak transition link between coarse aggregates, and thus during compressive strength tends to decrease.

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Journal of Sustainable Architecture and Civil Engineering
Vol. 1 / No. 14 / 2016
pp. 5-11
DOI 10.5755/j01.sace.14.1.14478

Saccani and Bignozzi (2010) noticed that silica fume not the only one pozzolanic material which has positive effect on cementitious material structure. Authors confirmed, that glass powder also has positive effect. During the experiment they noticed, that alkali silica reaction can appear when particle size ranges from 0.075 mm to 2.00 mm. However if glass powder is milled to powder, pozzolanic reaction instead of alkali silica reaction can occur. Du and Tan (2013) also noticed positive effect of glass powder on cement hydration, however founded that powder of clear glass makes about 9 time higher expansion comparing to brown glass. Increased expansion was explained due to reduced amount of Cr_2O_3. Wang and Huang (2010) during experiment founded that LCD glass can increase compressive strength almost about 2 times from 40 MPa to 75 MPa. Lin *et al.* (2008) made also similar experiments. Author used ^{29}Si MAS NMR methods and noticed that glass powder in cement system can drastically increase amount of CSH. Kou and Xing (2012) in his research founded that glass powder has positive effect on cement hydration, however glass powder decreases early strength of concrete. Author also denotes that reactivity of glass powder comparing to silica fume is very slow. Karakurt and Topçu (2011) suggested that combination with ground granulated blast-furnace slag, natural zeolite and fly ashes has positive effect when ternary system with alkalis activated. Created binder is highly resistant to sulphate environment. Shafaatian *et al.* (2013) during experiment used crushed glass with particle size from 150 μm to 4.75 mm and noticed that ASR gel occurs only in cracks between large particles of crushed glass. Schwarz and Neithalath (2008) created a model in which described when glass powder tends to create alkali silica reaction and when acts as pozzolanic material.

The main aim of this article using qualitative and quantitative XRD analysis, mercury porosimetry and other test methods to find out how combination of glass powder and micro steel fibers affects the compressive strength of UHPC.

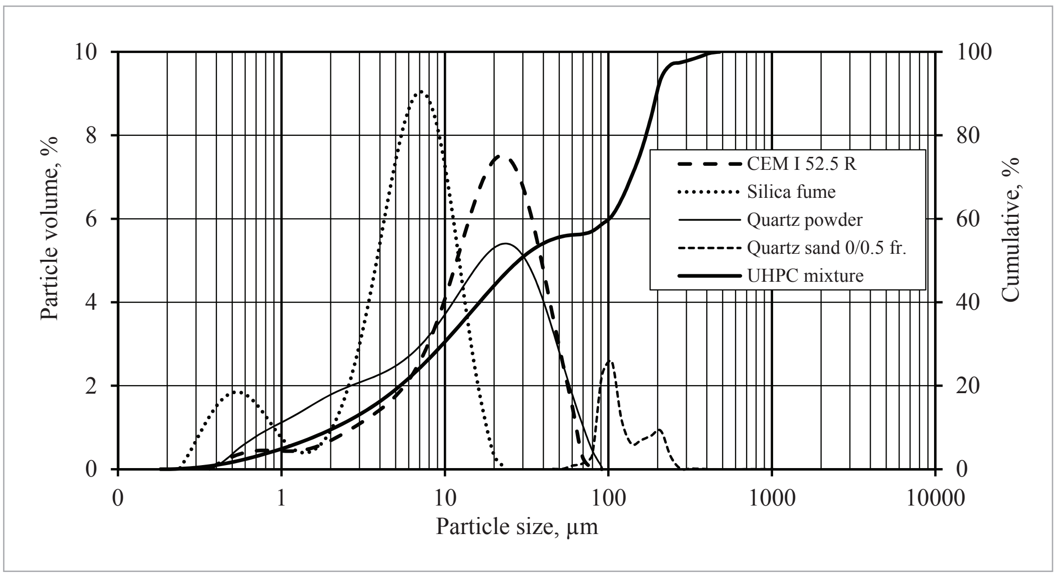
Used materials

Cement. The main properties of CEM I 52.5 R cement: the paste of normal consistency – 28.5%; specific surface (by Blaine) – 4840 cm^2/kg; the setting time (initial/final) is 110/210 min; the compressive strength (after 2/28 days) – 32.3/63.1 MPa; the soundness (by Le Chatelier) – 1.0 mm. The mineral composition: C_3S – 68.70; C_2S – 8.70; C_3A – 0.20; C_4AF – 15.90. The particle size distribution is shown in Fig. 1.

Silica fume (SF). Main properties of silica fume: bulk density – 400 kg/m^3; density – 2532 kg/m^3; pH – 5.3. The particle size distribution is also shown in Fig. 1.

Fig. 1

Particle size distribution of silica fume, Portland cement, quartz powder, 0/0.5 fr. quartz sand and UHPC mixture



Quartz powder (QP). The main properties of quartz powder: the bulk density is 900 kg/m^3; the density - 2671 kg/m^3; the specific surface (by Blaine) - 3450 cm^2/g; the average particle size – 18.12 μm. The particle size distribution is shown in **Fig. 1.**

Glass powder (GP). The main properties of glass powder: specific surface (by Blaine) – 3350 cm^2/g; density - 2528 kg/m^3; the average particle size - 25.80 μm.

Quartz sand (QS). The main properties of quartz sand: fraction - 0/0.5; specific surface (by Blaine) numerical value is 91 cm^2/g; density – 2650 kg/m^3.

Chemical admixture. superplasticizer (SP) based on polycarboxylic ether (PCE) polymers with the following main properties: appearance – dark brown liquid; specific gravity (20 ºC) – 1.08 ± 0.02 g/cm^3; pH value – 7.0 ± 1; the viscosity – 128 ± 30 Pa·s; has 65.0% alkali content and 60.1% chloride content.

Micro steel fibres. The main properties of the fibres: the length - 13 mm, the diameter – 0.30 mm and the tensile strength - 1000 MPa.

Methods

Glass powder preparation. In experiment recycled glass crushed from various bottle were used. Crushing was made in two steps: in first step bottles were crushed with jaw crusher to an average particle size of 0.3-0.8 cm, and later with vibratory disc mill coarse aggregates of glass were milled to powder. The rotation speed of vibratory disc mill was 750–940 rpm.

Specific surface and particle size distribution. The specific surface was measured according to EN 196-6:2010 standard and particle size distribution was measured with *Mastersize 2000* instrument produced by *Malvern Instruments Ltd*.

Mixing, sample preparation and curing. Fresh concrete mixes were prepared with *EIRICH R02* mixer. The mixtures were prepared from dry aggregates. The cement and aggregates were dosed by weight while water and chemical admixtures were added by volume. Cylinders (d = 50 mm, h = 50 mm) were formed for the research in order to determine the properties of concrete. Homogeneous mixes were cast in moulds and stored for 24 h at 20 ºC/95 RH (without compaction). After 24 h, thermal treatment (1 + 18 + 3) was applied and during the remaining time till the end of the 28 day-day period, the specimens were stored under water at 20 ºC.

Table 1

Mixing procedure of ultra-high performance concrete

Time, sec.	Mixing procedure
60	Homogenization of binder and inter materials (silica fume, cement, quartz powder and quartz sand)
30	Addition 100% of water and 50% superplasticizer
60	Homogenization
120	Pause
30	Addition of the remaining superplasticizer
120	Addition of steel fibres and homogenization

Flexural and compressive strength. The flexural and compressive strength test was performed according to EN 12390-5 and EN 12390-4 standards. For flexural 3 specimens (40x40x160 mm) were created, for compressive strength 6 cylinders (d = 50 mm; h = 50 mm) were created.

X-ray diffraction (XRD) analysis. Hardened cement pastes were used for XRD analysis. The XRD measurements were performed with *XRD 3003 TT* diffractometer manufactured by *GE Sensing & Inspection Technologies GmbH* with θ-θ configuration und *CuKa* radiation (λ = 1.54 Å). The angular range was from 5º to 70º 2 Theta with a step width of 0.02º and a measuring time of 6 s/step. For

Table 2

Compositions of ultra-high performance concrete

Constituents	Composition			
	QP/GP0	QP/GP100	QP/GP100SF/GP100	SF/GP100
Water, l	186			
Cement, kg/m^3	735			
W/C	0.25			
Silica fume, kg/m^3	99		-	-
Quarz powder, kg/m^3	412	-		412
Glass powder, kg/m^3	-	391	489	99
Quarz sand 0/0.5, kg/m^3	962			
Superplasticizer, l	30.65			

XRD quantitative phase analysis when using the Rietveld refinement, the samples were mixed with 20 wt. % ZnO (a standard material widely used in XRD analysis) as an internal standard and stored in argon atmosphere until measurement. This allows us to derive the estimation of the amount of non-crystalline phases on the grounds of the Rietveld fitting procedure.

Results and discussion

During experiment four compositions of ultra-high performance concrete were created. Compositions were modified substituting quartz powder to glass powder (Table 2). Reverence composition, which had no glass powder was denoted as QP/GP0. Composition where 100 % of glass powder was substituted to glass powder was denoted as QP/GP100. Composition where silica fume and quarts powder were substituted to glass powder was denoted to QP/GP100SF/GP100 and composition where silica fume was substituted to glass powder was denoted to SF/GP100.

XRD analysis

Fig. 2 illustrates the XRD patterns of the four hardened cement. CH phase was found at *d* equalling 0.3042; 0.2789 and 0.1924 nm. Higher reduction of CH phase was observed in compositions with higher amount of glass powder. Glass powder also had positive effect on reduction of intensities of C_2S and C_3S phases. C_2S was found at the following levels of *d*: 0.2790; 0.2783; 0.2745;

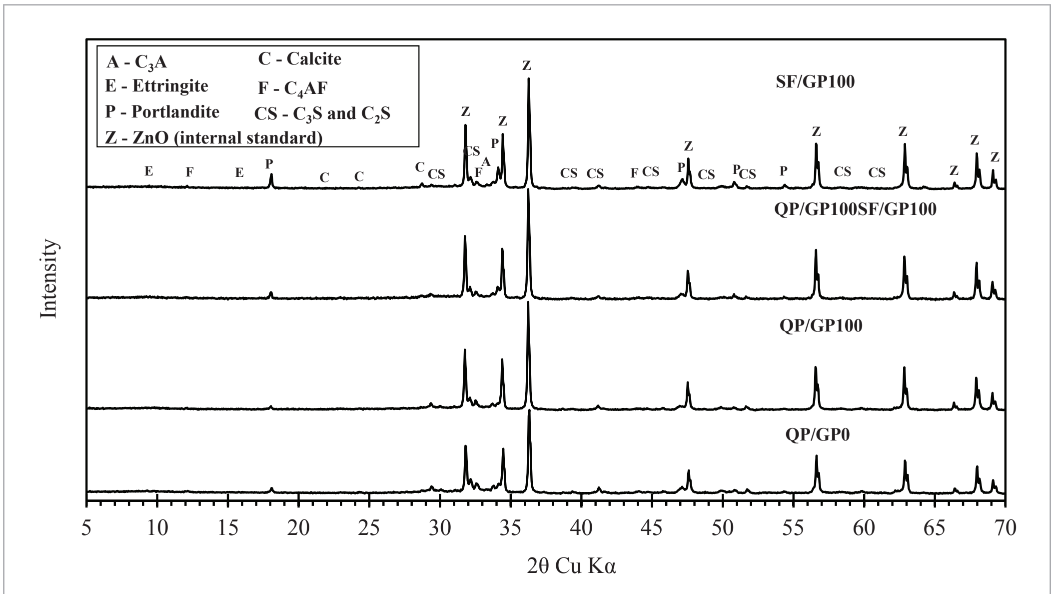


Fig. 2

XRD patterns of hardened cement pastes with different amounts of glass powder

0.2645; 0.2610; 0.2189 nm while C_3S phases were found at *d* equalling 0.3036; 0.2773; 0.2748; 0.2604; 0.2181 nm. Experiment cleared out, that glass powders tends to increase hydration of Portland cement.

Rietvield refinement was additionally applied (Table 2 and Fig. 3). During experiment was noticed, that composition with glass powder reacted more intensively comparing with composition which had no glass powder. However with combination of silica fume and glass powder reaction increased even further. Decreased amounts of C_2S, C_3S, CH phases denotes, that glass powder increased hydration process of cement, and also acted as pozzolanic material. So additional amount of CSH phases is formed. This has positive effect on mechanical properties of UHPC.

XRD qualitative and quantitative analysis revealed, that glass powder has positive effect on cement hydration. Further research showed, that compressive strength can be increased up to 40 MPa from 182 MPa to 221 MPa (Fig. 4) when silica fume and quartz powder were substituted to glass powder. Thus expensive silica fume can be eliminated. During the experiment was noticed, has silica fume is more reactive pozzolanic material compering with glass powder, however with glass powder better economic and ecological effect can be achieved.

Mechanical properties after mix with industrial mixer

During the research, it was unexpectedly observed that whenever glass powder was incorporated in UHPC composition, with the substitution up to 100% of quartz powder the compressive strength increased about 40 MPa from 182 MPa (Fig.4) (GP/GP0) to 221 MPa (GP/GP100). Such enormous compressive strength could be obtained in each plant manufacturing concrete as long as it is equipped with advanced and sophisticated technology; however most producers unfortunately cannot afford such equipment. In order to prepare UHPC with standard mixers, the concrete particle size distribution was modified according to Yu *et al.* (2010) recommendations and the water-to-cement ratio was increased up to 0.30.

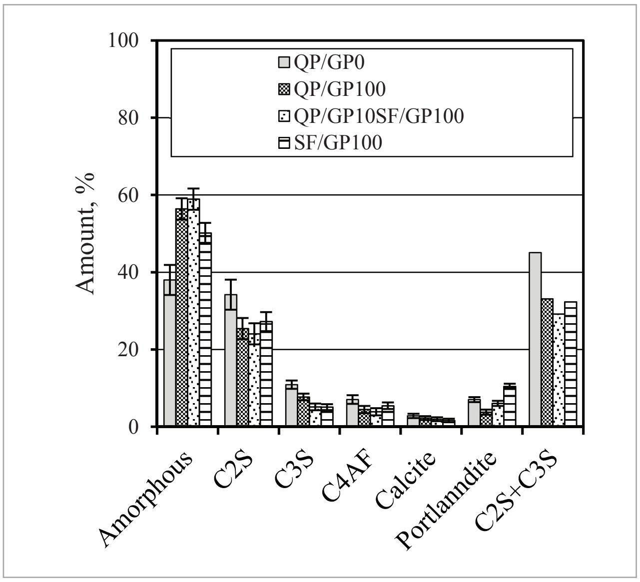


Fig. 3

Mineralogical composition of the binder with different amounts of glass powder

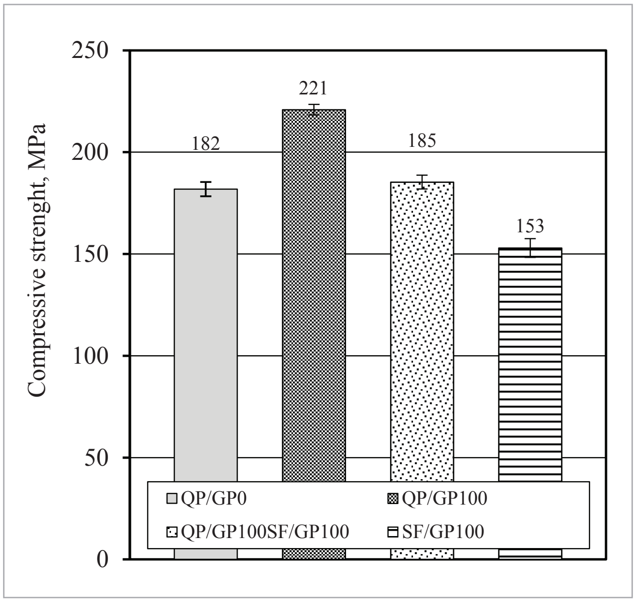
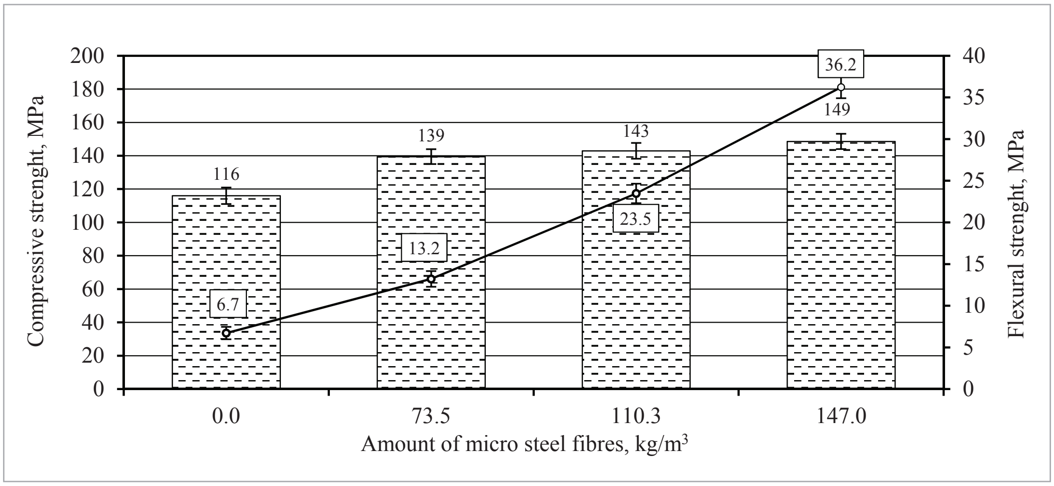


Fig. 4

Compressive strength of UHPC with different amounts of glass powder

Fig. 5
The compressive and flexural strength of UHPC with various amounts of micro steel fibres (W/C=0.30)



Interesting fact was observed, when composition was mixed with industrial mixer (Fig. 5). During experiment we added up to 147 kg/m^3 of micro steel fibres, the compressive strength increased about 30% from 116 MPa (QP/GP0-F0) to 149 MPa (QP/GP0-F147) whereas the flexural strength increased more than 5 times from 6.7 MPa (QP/GP0-F0) to 36.2 MPa (QP/GP0-F147). The experiment results proved that micro steel fibres exert a positive effect on the compressive and flexural strength of UHPC. Created compositions could be used for various elements made of concrete with excellent durability and mechanical properties.

Conclusions

1 Quantitative and qualitative XRD analysis revealed that glass powder increases hydration process of Portland cement. Silica fume is almost 5 times more reactive comparing to glass powder.

2 Silica fume can be completely eliminated from UHPC, and thus economical and ecologic effect can be achieved.

3 The designed concreted mixture is suitable for use in field conditions: high strength beams, slabs, columns and etc.

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