JSACE 1/10

Influence of Water to Cement Ratio with Different Amount of Binder on Properties of Ultra-High Performance Concrete

Received 2014/06/30

Accepted after revision 2015/01/05

Influence of Water to Cement Ratio with Different Amount of Binder on Properties of Ultra-High Performance Concrete

Evaldas Šerelis*, Vitoldas Vaitkevičius, Vidas Kerševičius

Kaunas University of Technology, Faculty of Civil Engineering and Architecture
Studentu st. 48, LT-51367 Kaunas, Lithuania

Mariangela Deligia

Università degli studi di Cagliari, Dipartimento di Ingegneria Civile, Ambientale e Architettura

*Corresponding author: **evaldas.serelis@ktu.lt**

crossref http://dx.doi.org/10.5755/j01.sace.10.1.7166

Four different compositions of ultra-high performance concrete (UHPC) have been created for this study, while W/C ratio varied from 0.25 to 0.33. Amount of cement, quartz sand and super plasticizer has been maintained constant (at 735 kg/m^3, 962 kg/m^3 and 36.76 l respectively). Glass powder and silica fume were used as binder. Optimal fineness of glass powder was selected by Chapelle test. In this study different combinations of silica fume, glass powder and quartz powder as microfiller were used. Compressive strength up to 160 MPa was obtained. The main aim of experiment was to create relationships between w/c ratio and compressive strength and to find optimal composition of UHPC. Test methods such as: slump, dynamic viscosity, density, and compressive strength were used. In experiment glass powder was successfully utilized in UHPC.

Keywords: compressive strength, dynamic viscosity, slump, UHPC, W/C ratio.

Introduction

Advances in the science of concrete materials have led to the development of a new class of cementitious composites, namely ultra-high performance concrete (UHPC). The mechanical and durability properties of UHPC make it an ideal candidate for use in various construction elements (Graybeal *et al.* 2011). UHPC has very good workability with very low water to cement ratio (W/C≤0.30). High compressive strength and workability comes from excellent homogeneity and packing density (Orange *et al.* 1999; Ma *et al.* 2003). However packing density and workability are closely related. In order to optimize the mixture with desired characteristics, it is important to find optimal w/c ratio.

According to Ma *et al.* 2003, W/C ratio and workability of self-compacting concrete has very strong correlation. Lower W/C ratio reduces voids between particles and thus packing density can be increased. Increased packing density has positive effect on reduced porosity in cement matrix. Similar conclusion has been made by Long *et al.* 2002. He analysed the compactness of binary

ktu 1922

Journal of Sustainable Architecture and Civil Engineering
Vol. 1 / No. 10 / 2015
pp. 78-86
DOI 10.5755/j01.sace.10.1.7166

and ternary compound pastes containing silica fume (SF), pulverized granulated blast furnace slag (PS) and pulverized fly ash (PFA). He stated that SF is more effective in improving the packing density of cement matrix, because silica fume has positive effect on interfiling spaces between larger particles. Sobolev *et al.* 2004 proposed a new method to design and optimize concrete mixture. In experiment he replaced part of cement by various mineral addictive's. According to research workability of UHPC can be modified by different amount of super plasticizer (from 5% up to 10% by weight of cement) and by different amount of silica fume (from 5 % up to 25 % by weight of cement). However particle size distribution also has important role. Amen *et al.* 2011 studied compressive strength of UHPC development with different amount of silica fume. He founded that silica fume has positive effect on early and later compressive strength of concrete. Moghadam *et al.* 2012 founded that with decreased W/C ratio most of mechanical properties will improve and porosity will decrease. The similar findings were made by Rahmani *et al.* 2012. He also noticed that with decreased W/C ratio also increased resistance to abrasion can be observed.

Microstructural investigations conducted by Reda *et al.* 1999 with SEM micrographs, pointed out the reason why UHPC differs from conventional concrete. In fact, it is believed that the mixture containing SF and silica flour (a pulverized quartz of a uniform size <75 μm) together with the low W/B ratio leads to a very dense and homogeneous microstructure, with a very low porosity, which impede the formation of the large crystals of CH (that, in fact, are generally absent in UHPC). It has been noticed in some specimens that a relatively high content of silica fume, together with the inclusion of silica flour and the elevated temperature curing regime, created an effective pozzolanic environment which consumed most of the weak CH crystals produced during hydration. These crystals were converted in to strong C-S-H, and so excellent mechanical properties occurred. Alawode *et al.* 2011 founded that in the concrete with high W/C ratio, CH crystals tend to grow larger comparing with low W/C ratio mixtures.

The effect of recycled glass powder (GP) on the slump and compressive strength in ultra-high performance fibre reinforced concrete (UHPFRC) has been studied by Kou *et al.* 2012. In this experiment the cement was partially replaced by the glass powder and the amount of silica fume was kept constant. The results revealed that glass powder reduced the flow ability of fresh UHPFRC. As a matter of fact, the workability of concrete decreased with an increase in amount of glass powder. It has been also founded out that, by replacing cement with GP, the 7 days-compressive tend to decrease, while the later compressive strength (after 28 days) tend to increase. Similar conclusions have been made by Khatib *et al.* 2012. He noticed that optimal amount of glass powder is when 10 % of cement is replaced by glass powder, however when substitution degree is above 20 %, the compressive strength tends to decrease. Patil *et al.* 2013 also agrees that addition of GP increases the strength of concrete. His experiments underline that in 7 days glass powder give less strength, this probably due to low hydration process. Abdelalim *et al.* 2008 stated that when W/C ratio varies from 0.15 to 0.17 optimal amount of silica fume is between 10 % and 15 % of cement mass. However not all silica reacts chemically with portlandite, some of it remains unreacted and fills empty voids, between larger particles. Tavakoli *et al.* 2013 found that above 15 % of silica fume of cement mass tends to decrease workability of concrete.

According to the literature there are not so many results pointing out how exactly W/C ratio influences mechanical properties of UHPC. How glass powder affects workability and compressive strength of UHPC. Some authors state that glass powder can increase workability and compressive strength of concrete while others think differently. It is not clear which amount of glass powder is optimal in UHPC system. In order to clarify misconception four different composition of ultra-high performance concrete (UHPC) have been created for this study, while W/C ratio varied from 0.25 to 0.33. The main aim of experiment was to create relationships between w/c ratio and compressive strength and to find optimal composition of UHPC. Test methods such as: slump, dynamic viscosity, density, and compressive strength were used.

Used materials

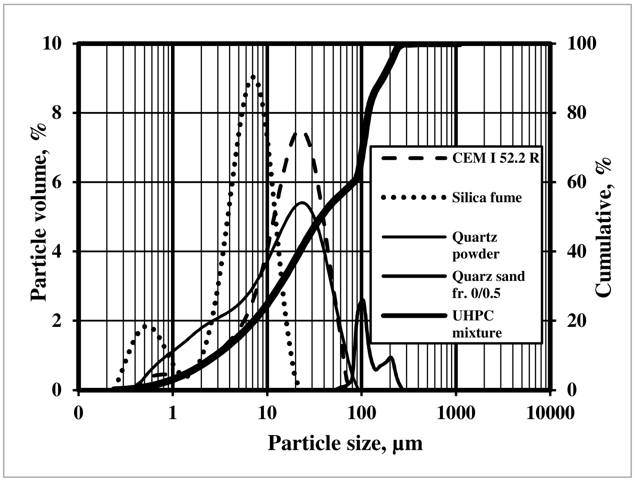


Fig. 1

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

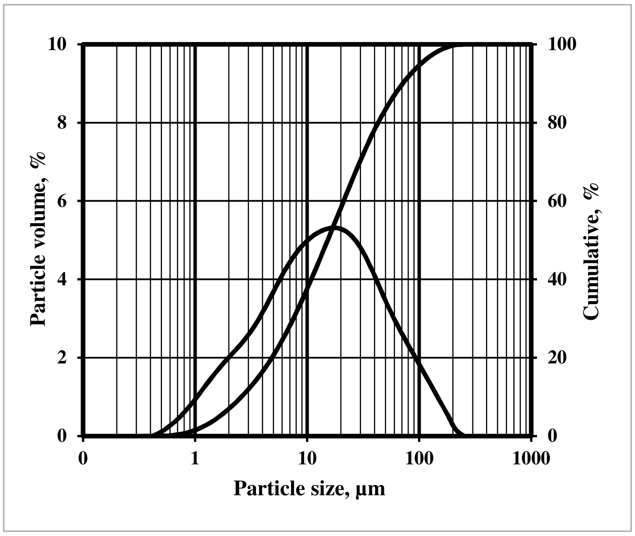


Fig. 2

Particle size distribution of glass powder

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

Silica fume. Silica fume, also known as microsilica (MS) or condensed silica fume is a by-product of the production of silicon metal or ferrosilicon alloys. Main properties: density – 2532 kg/m^3; bulk density – 400 kg/m^3; pH – 5.3. Particle size distribution is shown in Fig. 1.

Quartz powder. In experiment quartz powder was used. Main properties: density 2650 kg/m^3; bulk density – 900 kg/m^3; average particle size – 18.12 µm; specific surface (by Blaine) – 6543 cm^2/g. Particle size distribution is shown in Fig. 2.

Glass powder. In experiment glass powder was made from various colour bottles. Bottles were crushed in ball miller and milled until certain fineness. Main properties: density 2528 kg/m^3; specific surface (by Blaine) – varied from 2119 cm^2/g to 7399 cm^2/g with optimal value of 5240 cm^2/g. Particle size distribution is shown in Fig. 2.

Quartz sand. In experiment quartz sand was used. Main properties: fraction: 0/0.5; density 2650 kg/m^3; specific surface (by Blaine) – 91 cm^2/g.

Chemical admixture. In experiment superplasticizer (SP) was used. SP is based on polycarboxylic ether (PCE) polymers. Main properties: appearance: dark brown liquid, specific gravity (20 °C) – 1.08±0.02 g/cm^3; pH – 7.0±1; viscosity - 128±30 m·Pa; alkali content ≤ 5.0 %, chloride content ≤ 0.1 %.

Methods

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

The pozzolanic activity of glass powder. Pozzolanic activity was assessed by Chapelle test (Khmiri *et all.* 2012). One gram of glass powder is mixed with 1 g of CaO and 200 ml of water. The suspension is boiled for 16 h and the free $Ca(OH)_2$ is determined by means of sucrose extraction and titration with a HCl solution.

Mixing, sample preparation and curing. Fresh concrete mixtures were prepared in modified laboratory mixer (mixing procedure given in Table 1). Main parameters of mixer: max mixing capacity – 3 litre; revolutions per minute - 40 rpm; oscillation frequency – 50 Hz, amplitude – 0.50 mm. Mixtures were prepared from dry aggregates. Cement and aggregates were dosed by weight, water and chemical admixtures were added by volume. Cylinders (d=50 mm, h=50 mm) were formed for the research to determine concrete properties. Homogeneous mixtures were cast in moulds and kept for 24 hours at 20 °C/95 RH (without compaction). After 24 hours some specimens were kept in water and some specimens were thermal treated (3+16+5) for 24 hours in 80 °C water.

Table 1

Mixing procedure of UHPC

Time, sec.	Mixing procedure
60	Homogenization of silica fume, cement, quartz powder, glass powder and quartz sand
30	Addition 100% of water and 50% superplasticizer
60	Homogenization
120	Pause
30	Addition of the remaining superplasticizer
60	Homogenization

Slump and viscosity. Slump was measured according to EN 1015-3:1999 standard (without compaction). Dynamic viscosity was measured by falling ball method (Vaitkevičius *et all.* 2013).

Density and compressive strength. Density and compressive strength was measured from 6 cylinders (d=50 mm; h=50 mm) as average value. Density was measured according to EN 12390-7:2009 standard, compressive strength according to EN 12390-4:2003 standard.

Results

According to the methods described before, four compositions of UHPC with different amounts of binder were created (Table 2). Silica fume and glass powder were used as binder. Water to cement ratio (W/C) in all compositions varied from 0.25 to 0.32. QP/GP0-SiO_2/GP0 is as reference composition, without any pozzolanic material; QP/GP0 is standard UHPC composition with silica fume; QP/GP100 when 100 % quartz powder was substituted by glass powder. In QP/GP100SF/GP100 quartz powder and silica fume were substituted by 100 % of glass powder and in SF/GP100 silica fume was substituted by 100 % of glass powder. For investigation slump, dynamic viscosity, density, and compressive strength test methods were used. Main aim of the experiment was to find relationship between W/C and compressive strength. Properties of UHPC were obtained with and without heat treatment.

Optimal fineness of glass powder

According to Chapelle test (Fig. 3), the pozzolanic reactivity is evaluated on the basis of the amount of $Ca(OH)_2$ consumed during the pozzolanic reaction.

Experiment results indicate that pozzolanicity of glass powder after it oversteps fineness of 5240 cm^2/g tends to increase insignificantly. When fineness of glass powder varies from 2119 cm^2/g to 7399 cm^2/g consumed amount of $Ca(OH)_2$ varies from 465 mg to 652 mg respectively.

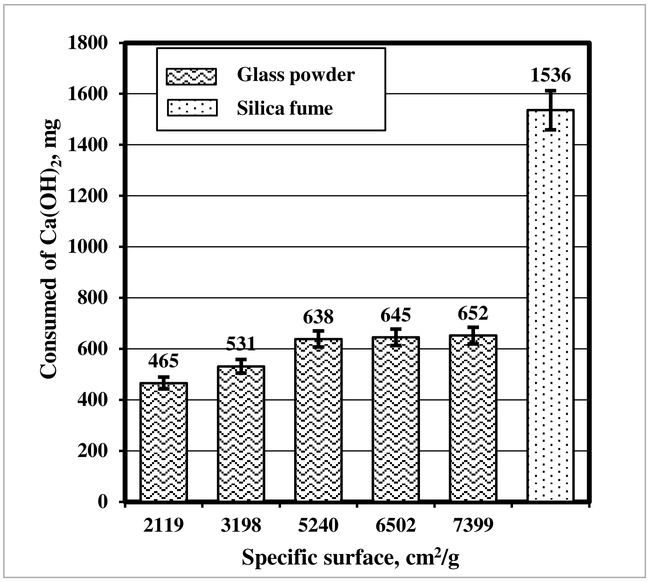


Fig. 3

Results of Chapelle test for glass powder and silica fume

Table 2

Compositions of ultra-high performance concrete

Composition	Water, kg/m^3	Cement, kg/m^3	W/C	Mircro Fillers, kg/m^3			Quartz sand #0/0.5, kg/m3	SP, kg/m^3
				Silica fume	Quartz powder	Glass powder		
QP/GP0 $SiO_2$0/GP0	184	735	0.25	-	511	-	962	36.76
	198		0.27					
	213		0.29					
	228		0.31					
	235		0.32					
QP/GP0	184	735	0.25	99	412	-	962	36.76
	198		0.27					
	213		0.29					
	228		0.31					
	235		0.32					
QP/GP100	184	735	0.25	99	-	412	962	36.76
	198		0.27					
	213		0.29					
	228		0.31					
	235		0.32					
GP/GP100 SiO_2/GP100	184	735	0.25	-	-	511	962	36.76
	198		0.27					
	213		0.29					
	228		0.31					
	235		0.32					

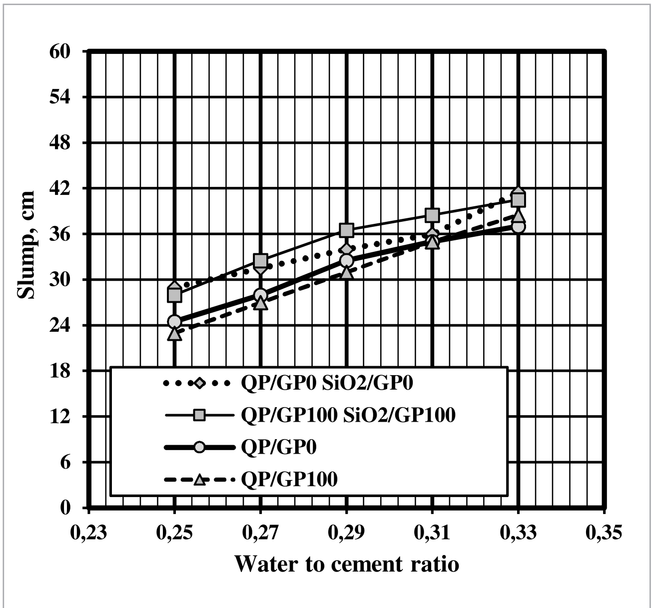


Fig. 4

Relationship between water to cement ratio and slump

Optimal fineness of glass powder according to the consumed amount of $Ca(OH)_2$ is 5240 cm^2/g. The same amount of silica fume consumes 1536 mg of $Ca(OH)_2$ and it is almost 3 times more reactive than glass powder. In Fig. 3 specific surface of silica fume is not presented, because Blaine test method shows inaccurate results. Specific surface of silica fume usually varies from 15000 m^2/kg to 30000 m^2/kg by BET test method.

Slump and dynamic viscosity

As was expected, the increase of W/C ratio resulted in increase of mixture's slump. Regardless if was used or not any pozzolanic material, but slump in all composition was almost the same and varied from 24 cm to 42 cm (Fig. 4). The lowest dynamic viscosity was noticed in composition (GP/GP100 SiO_2/GP100) when 100 % of glass powder and 100 % of silica fume were substituted by glass powder.

When W/C varied from 0.25 to 0.33 dynamic viscosity varied 202 Pa·s to 57 Pa·s respectively with optimal value of 57 Pa·s at W/C=0.27 (Fig. 5). Decreased dynamic viscosity probably could be attributed due to better particle size distribution and due to lower specific surface area of glass powder comparing with quartz powder and silica fume.

Density and compressive strength

As it was expected density in all compositions with and without thermal treatment was very similar and it was about 2400 kg/m^3. The density of UHPC by thermal treatment was not significantly influenced (Fig.6 and Fig.7).

Slightly decreased density probably could be attributed due to higher amount of evaporable water which tends to increase capillary porosity of concrete and thus decrease overall density. It seems that glass powders does not influence overall density of UHPC or the influence it insignificant.

The lowest compressive strength was obtained in composition (QP/GP0 SiO_2/GP0) without heat treatment and without any pozzolanic additive. When W/C varied from 0.25 to 0.33 compressive strength varied from 114 MPa to 94 MPa respectively (Fig. 8).

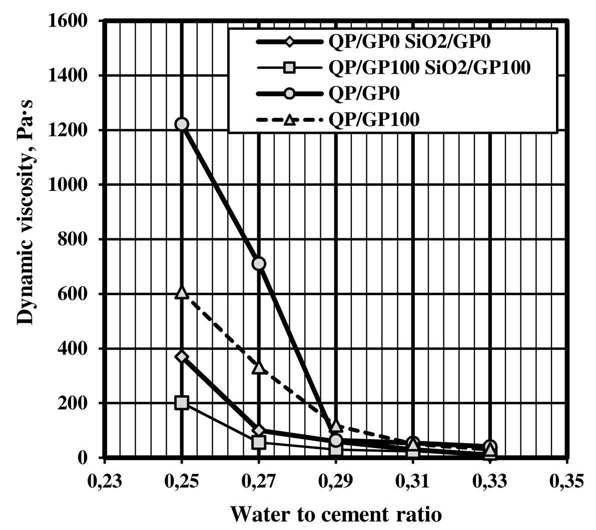


Fig. 5

Relationship between water to cement ratio and dynamic viscosity

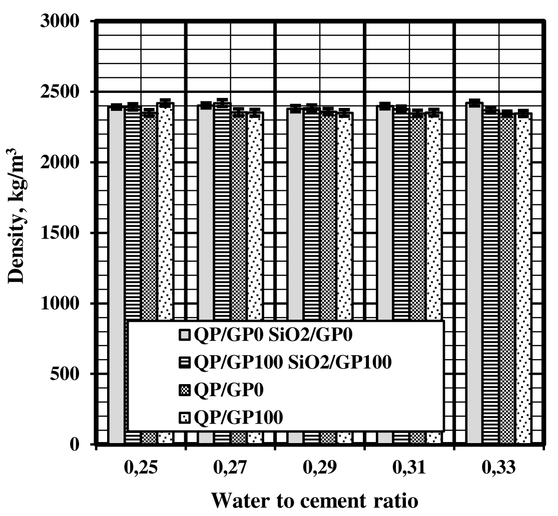


Fig. 6

Relationship between water to cement ratio and density when heat treatment was not applied

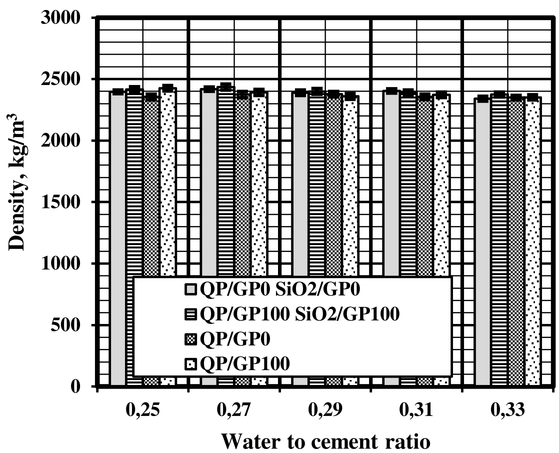


Fig.7

Relationship between water to cement ratio and density when heat treatment (3+16+5) for 24 hours in 80 °C was applied

Fig. 8

Relationship between water to cement ratio and compressive strength when heat treatment was not applied

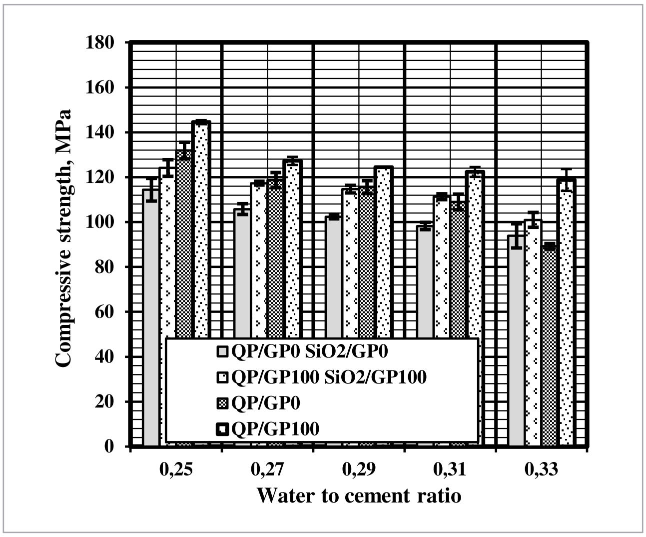
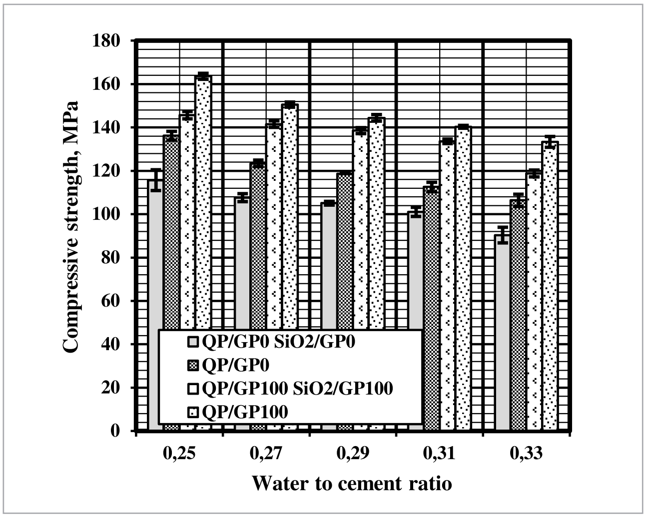


Fig. 9

Relationship between water to cement ratio and compressive strength when heat treatment (3+16+5) for 24 hours in 80 °C was applied



The highest compressive strength was noticed in composition (QP/GP100) with silica fume and when 100 % of quartz powder was substituted by glass powder. When W/C varied from 0.25 to 0.33 compressive strength varied from 145 MPa to 119 MPa respectively. After thermal treatment compressive strength increased even more (Fig. 9).

Very good results were noticed in composition (QP/GP100SiO_2GP100) where 100 % of quartz powder and 100 % of silica fume were substituted by glass powder. When heat treatment was not applied in composition QP/GP100SiO2GP100 compressive strength varied from 124 MPa (W/C=0.25) to 101 MPa (W/C=0.33) and it is similar as in ordinary UHPC composition (QP/GP0) without glass powder. However after heat treatment in composition (QP/GP100SiO_2GP100) where 100% of quartz powder and 100 % of silica fume were substituted to glass powder, compressive strength greatly increased. In experiment was noticed, that glass powder could be properly incorporated in UHPC without any loss of compressive strength and thus overall price of concrete can be decreased.

Article analyses very important problem, how properly dispose waste glass. Milled glass can be successfully utilised in UHPC and used instead of silica fume or quartz powder. An eliminated expensive material has great benefit in reducing cost of UHPC. Such experiment is novelty in Lithuania and until now it has not done at all.

Conclusions

Extensive experiment was carried out to create optimal composition of UHPC when different amount of glass powder in the mixture were incorporated. The following conclusions can be derived from the present investigation:

1. Optimal fineness of glass powder according to the consumed amount of $Ca(OH)_2$ is 5240 cm^2/g. Further reducing the fineness of glass powder is not optimal.
2. The best compressive strength (164 MPa) results were obtained in mixture with silica fume and when 100 % of quartz powder was substituted by glass powder.

3 Optimum composition with lowest amount of expensive materials and with compressive strength of 146 MPa were obtained in mixture where 100 % of silica fumes and 100 % of quartz powders were substituted by glass powder.

Acknowledgment

This work has been supported by the European Social Fundwithin the project "Development and application of innovative research methods and solutions for traffic structures, vehicles and their flows", project code VP1-3.1-ŠMM-08-K-01-020.

References

Abdelalim, A.; Ramadan, M.; Bahaa, T.; Halawa, W. 2008. Performance of Reactive Powder Concrete produced using local materials, *HBRC Journal* Vol. 4 No. 3, 66-78. DOI: no

Alawode, O.; Dip, P.; G.; Idowu, O.; I. 2011. Effects of Water-Cement Ratios on the Compressive Strength and Workability of Concrete and Lateritic Concrete Mixes, *The Pacific Journal of Science and Technology*, Volume 2, number 2, 99-105. DOIL no

Dillshad, K.; Amen, H. 2011. Degree of Hydration and Strength Development of Low Water-to-Cement Ratios in Silica Fume Cement System, *IJ-CEE-IJENS*, pages 10-16. DOI: no

EN 1015-3:1999/A2:2006. Methods of test for mortar for masonry - Part 3: Determination of consistence of fresh mortar (by flow table).

EN 12390-4:2000. Testing hardened concrete - Part 4: Compressive strength - Specification for testing machines.

EN 12390-7:2009. Testing hardened concrete - Part 7: Density of hardened concrete.

EN 196-6:2010. Methods of testing cement - Part 6: Determination of fineness.

Graybeal, B. 2011. Ultra High Performance Concrete, *TECHNOTE, HRDI-40*, 202-493-3122, 1-8. DOI:no

Khatib, J.; M.; Negim, E.; M.; Sohl, H.; S.; Chileshe, N. 2012. Glass Powder Utilisation in Concrete Production, *European Journal of Applied Sciences,* 4 (4), 173-176. http://dx.doi.org/10.5829/idosi.ejas.2012.4.4.1102

Khmiri, A.; Samet, B.; Chaabouni M. 2012. ASSESSEMENT OF THE WASTE GLASS POWDER POZZOLANIC ACTIVITY BY DIFFERENT METHODS, *IJRRAS*, 10(2), 322-328. DOI:no

Kou, S.; C.; Xing, F. 2012. The Effect of Recycled Glass Powder and Reject Fly Ash on the Mechanical Properties of Fibre-Reinforced Ultrahigh Performance Concrete, *Hindawi Publishing Corporation, Advances in Materials Science and Engineering*, 1-8. http://dx.doi.org/10.1155/2012/263243

Long, G.; Wang, X.; Xie, Y. 2002. Very-high-performance concrete with ultrafine powders, *Cement and Concrete Research*, 32, 601–605. Very-high-performance concrete with ultrafine powders http://dx.doi.org/10.1016/S0008-8846(01)00732-3

Ma, J.; Dietz, J.; Dehn, F. 2003. Ultra high performance self-compacting concrete, *book: International RILEM Symposium on Self-Compacting Concrete*, 136 – 142. DOI:no

Moghadam, H.; A.; Khoshbin, O.; A. 2012. Effect of Water- Cement Ratio (w/c) on Mechanical Properties of Self-Compacting Concrete (Case Study), *World Academy of Science, Engineering and Technology* 65, 458-461. DOI:no

Orange, G.; Acker, P.; Dugat, J. 1999. Damage Resistance and Micromechanical Analysis Of Ultra High Performance Concrete, *High Performance Fiber Reinforced Cement Composities (HPFRCC 3),* 101-112. DOI:no

Patil, D.; M.; Sangle, K.; K. 2013. Experimental investigation of waste glass powder as partial replacement of cement in concrete, *International Journal of Advanced Technology in Civil Engineering*, ISSN: 2231 –5721, Volume-2, Issue-1, 112-117. DOI:no

Rahmani, K.; Shamsai, A.; Saghafian, B.; Peroti, S. 2012. Effect of Water and Cement Ratio on Compressive Strength and Abrasion of Microsilica Concrete, *Middle-East Journal of Scientific Research* 12(8), 1056-1061. http://dx.doi.org/10.5829/idosi.mejsr.2012.12.8.3333

Reda, M.; M.; Shrive, N.; G.; Gillott, J.; E. 1999. Microstructural investigation of innovative UHPC, Cement and Concrete Research 29, 323-329. http://dx.doi.org/10.1016/S0008-8846(98)00225-7 http://dx.doi.org/10.1016/S0008-8846(98)00225-7

Sobolev, K. 2004. The development of a new method for the proportioning of high-performance concrete mixtures, *Cement & Concrete Composites*, 26, 901-907. The development of a new method for the proportioning of high-performance concrete mixtures http://dx.doi.org/10.1016/j.cemconcomp.2003.09.002

Tavakoli, D.; Heidari, A. 2013. Properties of concrete incorporating silica fume and nano-SiO2, *Indian Journal of Science and Technology*, volume 6, issues 1, 108-112. DOI:no

Vaitkevičius, V.; Šerelis, E.; Lygutaitė, R. 2013. Production Waste of Granite Rubble Utilisation in Ultra High Performance Concrete, *Journal Of Sustainable Architecture And Civil Engineering, Darnioji Architektūra IR STATYBA*, No. 2(3), 54-60. http://dx.doi.org/10.5755/j01.sace.2.3.3873

About the authors

EVALDAS ŠERELIS

P.h.D. student

Kaunas University of Technology, Faculty of Civil Engineering and Architecture, Department of Building Materials

Main research area
Ultra-high performance concrete

Address
Studentų st. 48,
LT-3031 Kaunas,
Lithuania
E-mail:
evaldas.serelis@ktu.lt

MARIANGELA DELIGIA

Master student

Università degli studi di Cagliari, Dipartimento di Ingegneria Civile, Ambientale e Architettura; Erasmus Student at Kaunas University of Technology, Faculty of Civil Engineering and Architecture, Department of Building Materials

Main research area
Ultra-high performance concrete

Address
Università degli studi di Cagliari, Dipartimento di Ingegneria Civile, Ambientale e Architettura. Via Marengo, 3 – 09123 Cagliari, Italy
E-mail:
mary.deligia@hotmail.it

VITOLDAS VAITKEVIČIUS

Professor

Kaunas University of Technology, Faculty of Civil Engineering and Architecture, Department of Building Materials

Main research area
Ultra-high performance concrete, high strength concrete, secondary raw materials, concrete additives.

Address
Studentų st. 48,
LT-3031 Kaunas,
Lithuania
E-mail:
vitoldas.vaitkevicius@ktu.lt

VIDAS KERŠEVIČIUS

Dr.

Kaunas University of Technology, Faculty of Civil Engineering and Architecture, Department of Building Materials

Main research area
Ultra-high performance concrete, resistance of concrete to frost damage.

Address
Studentų st. 48,
LT-3031 Kaunas,
Lithuania
E-mail:
vidas.kersevicius@ktu.lt