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Advanced mechanical properties and frost damage resistance of ultra-high performance fibre reinforced concrete

Vitoldas Vaitkevičius [a,*], Evaldas Šerelis [a], Danutė Vaičiukynienė [a], Vidas Raudonis [b], Žymantas Rudžionis [a]

[a] *Dept. of Building Materials, Kaunas University of Technology, Studentų 48, 51367 Kaunas, Lithuania*
[b] *Dept. of Automation, Kaunas University of Technology, Studentų 48, 51367 Kaunas, Lithuania*

HIGHLIGHTS

- Glass powder decreases porosity of ultra-high performance concrete.
- Glass powder increases hydration process of Portland cement.
- Mixture of ultra-high performance concrete can be prepared with decent technology.
- Addition of micro steel fibres in ultra-high performance concrete do not increase resistance to salt-scaling.

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ABSTRACT

Ultra-high performance concrete (UHPC) mixture with advanced mechanical and durability properties was created using decent mixer. Usually UHPC is made with advanced and sophisticated technology. In experiment UHPC was prepared with high intensity mixer "EIRICH R02", then mixture was modified and prepared in rotating pan mixer "Zyklos ZZ50HE". Rotating pan mixer is similar to mixer which has common concrete plants. Experiment results revealed that UHPC with W/C = 0.30 and advanced mechanical and durability properties can be prepared. In experiment tremendous amount of micro steel fibres (up to 147 kg/m^3) were incorporated in UHPC. Concrete with excellent salt scaling resistance and great mechanical properties was obtained. Compressive strength was increased about 30% from 116 MPa to 150 MPa and flexural strength was increased about 5 times from 6.7 to 36.2 MPa. Salt-scaling resistance at 40 cycles in 3% NaCl solution varied from 0.006 kg/m^2 to 0.197 kg/m^2. There were a few attempts to create UHPC and UHPFRC with decent technology, however, unsuccessfully till now. In the world practice this new material is currently used in the construction of bridges and viaducts.

1. Introduction

Recent advantages in concrete and nanotechnology opened new ways to create a strong and long lasting material with advanced properties. There has been made an extensive effort to improve the strength and durability of concrete, however, ordinary type of concrete (30 MPa) has reached certain limits, which nowadays could not meet all necessary requirements for strength, durability, safety, security and low maintenance. Those factors are important for high rise buildings, high span bridges and many other various products made of concrete [1]. Ultra-high performance concrete (UHPC) can easily meet such properties. UHPC according to the EN 206:2013 standard, has compressive strength over 100 MPa [2]. With proper equipment and appropriate composition, compressive strength can be increased up to 250 MPa. Such concrete could easily meet all needed requirements for strength, durability, safety, serviceability and etc.

UHPC, as well as all materials, has its own advantages and disadvantages. The main disadvantages could be: relatively high price; lack of appropriate standards; very brittle failure; challenging mixing process; high autogenous shrinkage; there is a small amount of a long-term research on how it holds up over time in certain conditions. Deeper research is needed to overcome existing problems of current UHPC preparation methods. These methods require rather expensive materials and relatively advanced technology. According to Aldahdooh et al. typical UHPC mixture has 500 kg/m^3–1000 kg/m^3 of Portland cement and up to 250 kg/m^3 of silica fume [3]. Yu et al. tried to improve particle size distribution and reduce Portland cement amount in UHPC. He founded that

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[*] Corresponding author.

E-mail addresses: vitoldas.vaitkevicius@ktu.lt (V. Vaitkevičius), evaldas.serelis@ktu.lt (E. Šerelis), danute.palubinskaite@ktu.lt (D. Vaičiukynienė), vidas.raudonis@ktu.lt (V. Raudonis), zymantas.rudzionis@ktu.lt (Ž. Rudžionis).

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UHPC with W/C = 0.23 and compressive strength up to 160 MPa can be achieved when Portland cement is reduced down to 612 kg/m^3 [4]. Sabet et al. (2013) proposed the idea, that expensive silica fumes could be replaced with natural zeolite or fly ash [5]. Nazari and Riahi founded that ground granulated blast-furnace slag could be used as partial replacement of Portland cement and silica fume [6]. Yoo et al. did a research of how different amount of fibres affects mechanical and fracture properties of UHPC. The results were that incorporating up to 4% (by volume) of steel fibres have positive effect to reduce brittle failure [7]. Wang et al. (2012) in his research offered a simple approach to overcome sophisticated technology to produce UHPC. He proposed a simple method to increase dosage of superplasticizer and to use coarser microfillers [8]. According to proposed idea, UHPC with W/C = 0.18 and compressive strength up to 175 MPa can be prepared. Maruyama and Teramoto did a research and founded that deleterious autogenous shrinkage in ultra-high performance concrete is critical issue, mainly due to pozzolanic reaction. This phenomenon could occur when silica fume consumes water and reacts with portlandite [9]. In research Zhutovsky and Kovler noticed that internal curing has astonishing effect on deleterious autogenous shrinkage [10]. In order to overcome deleterious autogenous shrinkage, Yoo et al. proposed to use shrinkage reducing admixtures or adequate amount of steel fibres [11]. Similar conclusions were proposed by Soliman and Nehdi [12]. Although UHPC has its own disadvantages, various low cost solutions are presented.

The main advantages of ultra-high performance concrete are mechanical strength, durability and workability. Oertel et al. (2014) investigated different types of amorphous silica on hydration in UHPC. During investigation it was noticed, that amorphous silica, such as silica fume, stroeber particles or pyrogenic silica are needed in order to achieve compressive strength over 100 MPa [13]. Yoo et al. investigated effect of micro steel fibres on ultra-high performance concrete and founded that up to 4% (by volume) of micro steel fibres have no significant effect on compressive strength, however, flexural strength can be reached up to 46 MPa [14]. Máca et al. stated that UHPC with up to 2% (by volume) of steel fibre can have workability almost as good as self-compacting concrete, although further increasing of steel fibres has negative effect on workability [15]. Yaz et al. proposed autoclave curing regime. He founded that UHPC without steel fibres can be created with compressive strength up to 270 MPa and flexural strength up to 30 MPa [16]. According to Yi et al. ultra-high performance concrete has up to 8 times greater resistance to accidental impact of blast damage comparing with normal strength concrete (30 MPa) when different amount of steel fibre is incorporated in composition [17]. Teng et al. created various UHPC compositions when W/C ratio varied from 0.28 to 0.35. He founded that even concrete with W/C = 0.35 and Portland cement of 450 kg/m^3 has extremely low chloride diffusivity [18]. Wang et al. investigated UHPFRC durability on progressive aging. Fibres make concrete more porous, however, 74% of its all porosity is smaller than 4 nm which is located in C-S-H [19]. Tayeh et al. stated that UHPC has up to 20 time higher salt-scaling resistance than normal strength concrete [20]. According to literature review UHPC has excellent mechanical and durability properties comparing with ordinary concrete. Most notable characteristics probably are caused by extremely dense microstructure, low porosity ant stronger C-S-H matrix. Although UHPC has outstanding durability, it is important to examine how it was adapted in filed construction. Probably the world's first engineering structure of UHPC was Sherbrooke footbridge (in 1997, USA) [21]. First industrial application was applied in Civaux power plant (France) during 1997 and 1998 when in extremely corrosive cooling towers steel beam were substituted by UHPC beams [22]. Gaertnerplatzbridge Bridge was built in Kassel (Germany) at 2007 [23]. Although, UHPC is relatively new material and a lot of further research is still needed, according to the literature review and worlds practice, ultra-high performance concrete can tolerate very aggressive environment, static or dynamic loads with negligible deterioration.

Extensive literature review has been made, and it is clear, that UHPC has impressive mechanical and durability properties. The main aim of this research is to create UHPC composition which could be prepared with decent mixer and without usage of advanced technology. New composition was prepared with different amount of micro steel fibres. Main properties in experiment were determined by mercury intrusion porosimetry, XRD analysis, compressive strength, flexural strength and salt-scaling. Proposed composition could be used as innovative material for various elements made of concrete which could be prepared with decent mixer.

2. Used materials

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. Quartz powder was used in the experiment. Main properties: density 2671 kg/m^3; bulk density – 900 kg/m^3; average particle size – 18.12 µm; specific surface (by Blaine) – 4423 cm^2/g. Particle size distribution is shown in Fig. 1.

Glass powder. Glass powder was used in the experiment. Main properties: density 2528 kg/m^3; average particle size – 25.80 µm; specific surface (by Blaine) – 3350 cm^2/g. Particle size distribution is shown in Fig. 2.

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

Chemical admixture. Superplasticizer (SP), based on polycarboxylic ether (PCE) polymers, was used in the experiment. Main properties: appearance: dark brown liquid, specific gravity

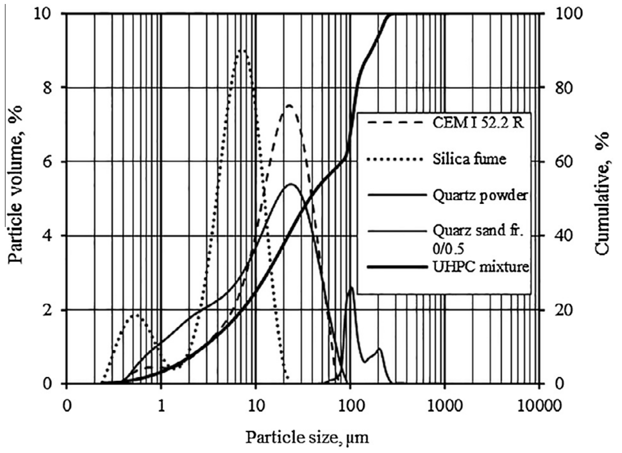

Fig. 1. Particle size distribution of Portland cement, silica fume, quartz powder and 0/0.5 mm fr. quarts sand.