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The effect of glass powder on the microstructure of ultra high performance concrete

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HIGHLIGHTS

- Dissolution of glass powder will make more dense structure of UHPC.
- Glass powder will additional increases compressive strength more than 30 MPa.
- Glass powder is a good contender for silica fume.
- Pozzolanic reaction is not primary beneficial property of glass powder.
- Purposed new hydration mechanism of the glass powder in Portland cement.

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ABSTRACT

Glass powder prepared of various types of recycled bottles was used in ultra-high performance concrete (UHPC). Experimental investigation of glass powder as complete replacement for quartz powder and silica fume showed that UHPC with improved micro-structural and compressive strength properties can be prepared. Glass powder milled to micro-scale undergoes low pozzolanic reaction and acts as catalyst accelerating the dissolution of clinker phases and forms low basicity calcium silicate hydrate (C–S–H). These reactions give positive effect on mechanical and microstructural properties of UHPC. Microstructural investigation was made by mercury intrusion porosimetry (MIP), X-ray diffraction (XRD) analysis and by ^{29}Si MAS NMR analysis. Experimental results revealed that additional compressive strength of 40 MPa can be gained with combination of glass powder and silica fume.

1. Introduction

Glass is a solid material which generally consists of non-crystalline silica, sodium oxide, calcium oxide and other components [1–3]. The chemical composition mainly depends on the raw materials used and differs slightly for each glass type. The most common soda-lime glasses consist of ⩾70% amorphous SiO_2, ⩾12% Na_2O and ⩾5% CaO [4–6]. Being amorphous and containing relatively large quantities of silicon, glass should be an excellent pozzolanic material for concrete industry. Thus when glass is finely grounded to powder, in theory, it could be used as partial cement replacement. However glass powder has very high amount of Na_2O which could initiate alkali–silica reaction. Therefore glass powder can be characterized by a few controversial facts: it has enough amorphous SiO_2 to be considered as pozzolanic material; available CaO can react with water and amorphous SiO_2 forming low basicity C–S–H. Glass also has a very high amount of Na_2O which is a source for alkali silica reaction. These truths are highly debated between various scientists; however it is not entirely clear how glass can affect microstructure of concrete with its high amount of alkalis. Most researchers denote three main factors which contribute to alkali silica reaction: sufficient amount of alkalis, reactive aggregate and sufficient amount of water [7–9]. However the following factors also have significant influence: water to cement ratio, permeability to moisture, solubility of alkalis, size of aggregates and type of concrete. The amount of Na_2O_{eq} is limited to 0.80% according to the EN 206:2013 standard [10]. Yet, there are plenty of cases where this limit is overstepped without deleterious effect on concrete. In order to understand how glass powder affects microstructure and properties of ultra-high performance concrete it is necessary to do a deeper research.

Corinaldesi et al. investigated the microstructure of mortars with 30–70% replacement of fine sand with particle size up to 100 μm varying w/c from 0.56 to 1.00. Compressive strength

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increased from 32 MPa to 60 MPa and this effect was attributed to the waste glass [11]. Zerbino et al. was working with mortars and concretes incorporating natural rice husk, varying the water to cement ratio from 0.44 to 0.56. He noticed swelling due to alkali silica reaction when $Na_2O_{eq} \geqslant 5.25$ kg/m^3. However that value mainly depends on capability of moisture transport in cement matrix [12]. Juengera and Ostertag in research used silica fume and sintered silica fume aggregate in concrete and noticed swelling in some specimens. This phenomenon was explained due to an inhomogeneous distribution of silica fume [13]. Saccani and Bignozzi investigated the solubility of various glasses in 1 N NaOH solution. He noticed that lead-silicate glass showed the highest dissolution rate, boro-silicate glass is less soluble comparing with lead-silicate glass and soda-lime glass is the most stable. Also it was observed that lime saturated water Ca^{2+} hinders the dissolution of glass irrespective of the chemical composition. The particles size of glass in the experiment varied from 0.075 mm to 2.00 mm [14]. Du and Tan investigated recycled green, brown and clear glass with particle size up to 0.75 μm and he noticed no deleterious expansions. Clear glass showed higher expansion, green glass showed about 3 times lower expansion than clear glass and brown glass showed about 9 time lower expansion than clear glass. The reduced expansion was attributed to Cr_2O_3 [15]. Wang and Huang used up to 30% of LCD glass with fineness modulus of 3.37 in self-consolidating concrete (W/C = 0.28) and noticed increased flexural strength from 4 MPa to 8 MPa and compressive strength from 40 MPa to 75 MPa. Also decreased permeability and increased resistance to sulphate attack were noticed [16]. Lin et al. used TFT and LCD waste glass with fineness of 370 m^2/kg (by Blaine) in his experiment and noticed a strong increase of C–S–H by ^{29}Si MAS NMR and a strong decrease of $Ca(OH)_2$ by Fourier transformation infrared spectroscopy [17]. Kou and Xing in experiment investigated properties of UHPC with W/B = 0.15 and used glass powder with particle size smaller than 0.0045 mm. He founded that replacement of cement by glass powder is very effective. However glass powder decreases early (7 days) compressive strength of UHPC. Reactivity of glass powder comparing to silica fume was is very low. In order to increase reactivity of glass powder thermal treatment should be applied [18]. Karakurt and Topçu activated ground granulated blast-furnace slag, natural zeolite and fly ashes with alkalis and noticed an improved microstructure of the concrete with an increased resistance to sulphate [19]. Shafaatian et al. noticed that fly ash acts as pH buffer which maintains pore solution's pH between 12.6 and 13.0. Also he found out that when glass powder is incorporated in mortars (W/C = 0.47) ASR gel occurs only between cracks of grounded glass particles. The particle size of the glass powder in the experiment varied from 150 μm to 4.75 mm [20]. Schwarz and Neithalath proposed a model for cement with fly ash and fine glass powder explaining pozzolanic properties of glass powders [21]. Amen noticed a drastically increasing compressive strength and decreasing permeability with porosity, when a cement paste has a water to cement ratio lower than 0.26 [22]. Idir et al. worked with glass powders of various sizes and noticed that the higher expansion can occur when the diameter of glass powder is ⩾1000 μm. However its best pozzolanic performance is obtained when the particle size of the glass powder is between 10 μm and 20 μm [23]. Nassar and Soroushian worked with concrete (W/C varied from 0.38 to 0.50) using waste glass and noticed that glass with particle size of ∼13 μm undergoes a pozzolanic reaction and improves the microstructure of a concrete. In addition a decrease of moisture sorption and chloride permeability was determined. The expansion of concrete specimens varied from 0.006% to 0.016% [24]. Ling et al. used recycled glass with fineness modulus of 3.33 and noticed improved structure and lower porosity of self-compacting concrete after exposure to thermal treatment. He attributed this to the pozzolanic reaction [25]. Ichikawa and Miura created a modified model for alkali silica reaction. The model explained a pessimum amount and a pessimum size effects. According to the model instead of alkali silica reaction pozzolanic reaction could occur, even when excessive amount of reactive aggregates are used [26]. Alkali silica gel could be found during the hydrolysis of reactive amorphous silica, which has similar properties as sodium silicate. Sodium silicate, also known as soluble glass in concrete industry also can sometimes be called water glass [27]. It seems that it is not entirely clear how glass improves or decreases the structure of concrete. However chemical composition, particle size and impurities of the glass powder have the biggest effect on a proper structure formation in concrete. Addition of other pozzolanic materials can suppress or even eliminate deleterious swelling. Although glass has a very high amount of amorphous silica it is not very reactive till it is finely grounded. Alkalis play an important role in cement hydrolysis process however the hydration mechanisms were not fully understood. It seems that when recycled glass is finely grounded in alkali environment it can dissolve and behave as water glass.

Shi experimented with various alkali activators (sodium and potassium hydroxides, silicates, carbonates and sulphates) and found that sodium silicate is the most effective activator [28,29]. Škvára proposed a theory and a model for a new amorphous material known as zeolite or geopolymer (N-A-S-H) which can form in a high alkaline environment when sufficient amount of Al is present [30]. Pacheco-Torgal et al. suggested a new mechanism explaining the geopolymer formation in alkaline solution [31]. Pacheco-Torgal et al. investigated the durability of alkali activated binders and noticed a very high stability in various environments and emphasizes that although sodium silicate is a promising activator however more research is needed [32,33]. García Lodeiro et al. researched C–S–H gel with different addition of alkali and aluminium. He determined by ^{29}Si and ^{27}Al NMR spectroscopy three-dimensional alkaline aluminosilicate gel cross-linking with two-dimensional C–S–H gel [34]. Buchwald et al. and Hilbig and Buchwald besides aluminosilicate network in alkali-activated metakaolin-slag blends founded stable C–S–H phases [35,36]. According to the literature there it is not entirely clear how glass powder affect the structure of UHPC. It looks as if coarse particle of glass (⩾0.20 mm) can initiate a deleterious swelling. However finely grounded glass powder up to 100 μm can act as a pozzolanic material or chemical activator. This phenomenon is not entirely clear. The main aim of this article is to find out how glass powder affects microstructure of UHPC, and by using mercury porosimetry, qualitative and quantitative XRD, by ^{29}Si MAS NMR and compressive test methods to explain the effect of glass powder on microstructure of UHPC. According to the literature review, properly recycled waste glass can not only increase durability and compressive strength of concrete but also can solve some major environmental, energy, and expenses problems by partial replacement of cement.

2. Used materials

2.1. Cement

Portland cement CEM I 52.5 R was used in the experiments. 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. The particle size distribution is shown in Fig. 1.

2.2. 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. The particle size distribution is shown in Fig. 1.