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Sustainable one-part geopolymer foams with glass fines versus sand as aggregates

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HIGHLIGHTS

- Recycled glass fine can be used as an alternative to fine sand in geopolymer foams.
- The paste with glass aggregate is 100 kg/m^3 lighter than that with sand aggregate.
- Less foaming is needed to target low densities for the paste with glass aggregates.
- Geopolymer foams with glass aggregates are 77% stronger at 600 kg/m^3 density.
- Thermal performance of the foams with glass aggregate is better at 600 kg/m^3 density.

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ABSTRACT

The ever increasing demand for high-quality river sand in construction, which poses economic and environmental concerns, highlights the necessity for finding suitable alternatives. Waste glass has a very low impact tolerance, which makes it very easy to grind and use as a fine aggregate in the construction of lightweight building elements. In this study, glass fines are used as a replacement for fine sand in manufacturing geopolymer foams. The thermal and mechanical properties of the two systems with different densities are investigated and compared with a control sample of geopolymer foam with no aggregates. The geopolymer paste with sand aggregates has a density that was approximately 100 kg/m^3 higher than the paste with glass aggregates. The heavier samples with sand aggregates required a higher degree of foaming to drop the density to a similar range, which negatively affects their strength. For a density of 1000 kg/m^3, the geopolymer foams with glass aggregates are 25% stronger than the foams with sand aggregates. The strength improves further by 31% and 77% as the density drops down to 800 kg/m^3 and 600 kg/m^3, respectively. The shape of the bubbles in geopolymer foams with glass aggregates is more regular with less interconnectivity between pores, especially at lower densities. This pore characteristic enhances the insulation capacity of lightweight foams with glass aggregates where thermal conductivity of 0.15 W/mK was achieved in the sample with 600 kg/m^3 density.

1. Introduction

Geopolymer concrete is an environmentally friendly alternative for ordinary Portland cement based concrete [1–3]. Geopolymers are cementitious binders that can be used as an alternative to Portland cement (OPC) in construction applications. The reaction mechanism in geopolymers is different from a cement hydration reaction. The aluminosilicate precursors used for making geopolymers are activated in an alkaline environment, and the main ingredients of geopolymers first dissolve in the bulk solution and then undergo speciation, gelation, reorganization and polymerization until they form a cementitious material that is applicable for construction purposes [4,5]. Contrary to the manufacturing of cement, the production of geopolymer is not energy intensive and consumes minimal natural resources. Geopolymer precursors are usually selected from landfill waste materials such as fly ash [6]. Also, the manufacturing process is conducted at ambient or slightly elevated temperatures. Therefore, geopolymer has significant potential for reducing CO_2 emissions and consumption of natural resources that are associated with the production of traditional OPC concrete [7–9]. Also, if the solid precursors can be sourced locally and cost-effectively, and the activator doses are kept low, geopolymer concrete manufacturing can be very cost effective compared to OPC concrete [1,10].

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Geopolymers have been widely advertised for their attractive properties such as high early strength, excellent fire resistance and high resistance to aggressive chemicals. However, depending on the selection of source materials and the mix design, the properties of geopolymers (e.g. strength and durability) can fall anywhere between low and high [7,11]. It is vital to understand the underlying chemistry of geopolymer formation to design effective mixtures for specific applications. With a high percentage of amorphous silica content, waste glass is considered as a reactive aggregate in concrete manufacturing [12]. In OPC concrete, the reaction of aggregates with alkaline solution in the pores is called an alkali-silica reaction (ASR) [13]. The hydroxyl ions existing in the pore solutions can activate the reactive silica content in aggregates and form unwanted new products in this region. ASR triggers developing cracks in the most vulnerable area of OPC concrete, and is the main durability issue in OPC concrete [13]. However, the ITZ is not as vulnerable in geopolymer concrete as in OPC concrete, and the expansion of geopolymers as a result of ASR is remarkably lower than that of OPC concrete [14,15]. On the other hand, the reaction between the binder and the aggregates in geopolymer concrete may potentially help to achieve better compactness at the ITZ and improve the properties of developing gel in this region by increasing the compactness.

Moreover, compared to natural mineral aggregates (e.g. sand), glass aggregates increase the air content of cementitious mixtures [16]. This could be attractive in foamed concrete applications when the air voids are part of their lightweight structure, meaning that less extent of external foaming would be needed to target similarly low densities when glass is used as aggregate. Foamed concrete is a lightweight concrete with air pockets entrapped in its matrix by different foaming methods. Foam concrete is lightweight which is less labour-intensive. Also, less materials is used in its manufacturing process. Therefore, foam concrete has many advantages in construction such as decreasing the dead load of the buildings, reducing the construction time and costs, improving the housing affordability as well as enhancing thermal and acoustic performance of buildings [17–21]. Similarly, geopolymer foam concretes are the more sustainable option for lightweight construction elements [22–25]. In geopolymer concretes, waste glass has been utilized as the alkali activating agent [26,27], the source material for making geopolymer mortars [28] and the solid component of thermally treated foams [29]. According to our knowledge, there is no research on substituting glass fines with fine sand in geopolymer foam concrete. As a component of foamed concrete, the differences between the properties of glass and sand, their binding characteristics with geopolymers, and their air entraining capacity are very interesting. In this section, the properties of geopolymer foams made with glass fines as aggregates are studied and compared with geopolymer foams made with fine sand. The engineering properties of the foams are studied, and the microstructure of the pores is correlated with the mechanical properties and thermal performance of the two different systems.

2. Materials and methods

Fly ash (FA) with the commercial name of Melbourne Ash was purchased from Cement Australia. Granulated blast furnace slag (GBFS) used in this study is supplied from Independent Cement, Australia. Anhydrous sodium metasilicate with a composition of 50.5% wt. Na_2O, 46.2% wt. SiO_2 and 3.3% wt·H_2O is supplied from Redox. The solid activator is used in this study in order to develop one-part mix (just add water) geopolymers similar to cement, and improve the commercial viability of geopolymers [30,31]. Fine sand is usually used in foam concrete applications. The fine sand used in this research has d_{50} of 251 μm. Glass fines (with 70% of particles between 0.4 and 2 mm) were obtained from Alex Fraser. In order to remove the organic pollutants, the glass fines were washed as received and dried at 60 °C for 24 h. A Rocklabs ring mill was then used to mill the glass and reduce its particle size. The particle size of the milled glass was measured using the Malvern Mastersizer 2000 laser-diffraction particle-size analyser, and its d_{50} was measured to be 18 μm. The impact velocity tolerance of glass is known to be much less than that of sand [32]. This characteristic of glass allows it to be grinded to fine particles much easier, which is also very attractive for lightweight concrete applications. The results of X-ray Fluorescence (XRF) analysis of the source materials are presented in Table 1.

Three geopolymer systems were studied, namely a control group, glass group and sand group. The geopolymer system with pure geopolymer paste and no aggregates is called the control group. The control group was synthesized to facilitate the comparison between two mortars. Two mortars (glass group and sand group) were made by mixing 30% wt. of glass or sand as aggregates with 70% wt. of geopolymer dry mix. The mix design of the geopolymer binder consists of 55.4% wt. FA, 36.8% wt. GBFS and 7.8% wt. sodium metasilicate in a dry mix. A consistent water to binder ratio of 0.38 was used for all three systems. Geopolymer dry ingredients were firstly mixed manually for two minutes, and water was gradually added and blended with the dry mix manually for one minute first (to prevent the dry mixture from splashing out during mixing) and then mixed by a Hobart mixer for another five minutes. The resulting paste was used for studying the characteristics of the binding skeleton in geopolymer foams. For mechanical testing, the mixtures were poured into 50 × 50 × 50 mm cubic moulds, and sealed and cured at ambient temperature until the day of testing. For testing the dry shrinkage of geopolymers, specimens with dimensions of 40 × 40 × 160 mm were prepared according to the AS1012.13:2015 standard [33]. After seven days, the specimens were submerged in lime-saturated water, and the samples were dried at 23.3 °C in a chamber with 60% humidity. The shrinkage of the samples at 7, 14, 21, 28 and 56 days was determined by measuring the change in length as a percentage of the initial length.

Fresh geopolymer pastes were also foamed with the mechanical foaming technique in order to study the performance of the porous samples in different densities. Premade foam (with ~100 kg/m^3 density) was used to introduce voids in the binder pastes. A commercial surfactant was diluted with water (1:60 surfactant to water weight ratio) and used as a foaming agent [34]. Foam was then made with the aid of compressed air in a Dema compressed air foam generator. Pre-made foam was added as required to each group of geopolymers in order to target dry densities of 1200, 1000, 800 and 600 kg/m^3. 20% of the required premade foam was initially added to the geopolymer mix to increase the workability of the paste, and the remaining 80% of foam was gently blended in afterwards. The wet foam mixtures were then poured into 50 × 50 × 50 mm cubic moulds, and sealed and cured at ambient temperature until the day of testing.

The Instron 5569A instrument (with a displacement rate of 1nmm per minute) was used for measuring the compressive strength of the foamed samples. For testing the mechanical strength of non-porous geopolymers, an ELE ADRAuto 1500 compression testing machine (with a loading rate of 0.5 kN/s) was used. The reported compressive strength was the average of the three samples. Microscopic images were taken from the cross-section of the porous samples by a Leica M205FA automated microscope to compare the pore characteristics in three groups of geopolymers. The thermal conductivity of the porous samples was measured by a TCi device developed by C-Therm Technologies Ltd. This device measures the thermal conductivity by using the Modified Transient Plane Source (MTPS) method. Details of the