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Thermal and mechanical properties of sustainable lightweight strain hardening geopolymer composites

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ABSTRACT

The thermal and mechanical properties of sustainable lightweight engineered geopolymer composites (EGCs), exhibiting strain-hardening behavior under uniaxial tension, are reported in this study. Fly ash-based geopolymer was used as complete replacement of cement binder to significantly increase the environmental sustainability of the composite compared to the engineered cementitious composite (ECC). Additionally, three types of lightweight aggregates including expanded perlite, microscopic hollow ceramic spheres and expanded recycled glass were used as complete replacement of micro-silica sand to reduce density and thermal conductivity of the composite. The influences of the type of aggregates on the fresh and hardened properties of the composite including matrix workability, density, compressive strength, thermal conductivity and uniaxial tensile performance were experimentally evaluated. The results indicated that the density and compressive strength of all EGCs developed in this study, even the EGC containing normal weight micro-silica sand, were less than 1833 kg/m^3 and more than 43.4 MPa, respectively, meeting the density and compressive strength requirements for structural lightweight concrete. Replacing normal weight micro-silica sand with lightweight aggregates reduced the compressive and tensile strengths of the EGCs by a maximum of 24% and 32%, respectively. However, the tensile ductility of the EGCs containing lightweight aggregates was comparable to that of the EGC containing micro-silica sand. In addition, the thermal conductivity of the EGCs containing lightweight aggregates were significantly (38–49%) lower than that of the EGC containing normal weight micro-silica sand, resulting in an end-product that is greener, lighter, and provides better thermal insulation than ECC.

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1. Introduction

In the construction industry, the use of lightweight concrete (with a density less than 1850 kg/m^3 [1]) instead of normal weight concrete (2400 kg/m^3) is favorable as it offers several advantages such as reduction in dead loads and section dimensions, enhanced thermal insulation, savings in steel reinforcement, ease of handling and transportation, and lower overall cost [2]. However, one of the major disadvantages of lightweight concrete is greater brittleness and lower fracture toughness compared to normal weight concrete of similar compressive strength [2,3]. For instance, Hengst and Tressler [4] reported that the fracture energy of lightweight foam concrete was significantly lower than that of normal weight concrete. According to Zhang and Gjvorv [5], the tensile to compressive strength ratio of high strength lightweight concrete was lower than that of high strength normal weight concrete. This is attributed to the use of lightweight aggregates, which are usually weaker than the cement matrix, which makes them susceptible to cracking [3]. In past studies, different fibers have been introduced in the mixture design of lightweight concrete to enhance its tensile and flexural strengths, and the flexural toughness. However, these fiber-reinforced lightweight concretes, similar to conventional fiber-reinforced concrete, exhibit tension softening behavior [6,7]. Thus, although the lower density of lightweight concrete promotes its application as an alternative to normal weight concrete, the low tensile ductility and fracture toughness hinder the widespread structural applications of lightweight concrete in the construction industry.

Engineered cementitious composite (ECC) is a special class of high performance fiber reinforced cementitious composites (HPFRCCs) which exhibits strain hardening behavior under tension with very high tensile ductility [8]. The average density, compressive and tensile strengths, and tensile strain capacity of typical PVA-ECC mix 45 (M45) are about 2077 kg/m^3, 52.6 MPa, 6 MPa and 2.7%, respectively, at the age of 28 days [9]. Thus, the tensile ductility of typical ECC M45 is several hundred times the ductility of conventional concrete in tension. Several studies have been conducted to investigate the application of ECC in shear elements subjected to cyclic loading, in mechanical fuse elements in beam-column connections, in shear wall retrofitting of reinforced concrete (RC) buildings, in RC beams as durable cover for rebar corrosion control, and in general concrete structural repair. Other potential applications of ECC are in high-energy absorption structures including short columns, dampers, and connections for hybrid steel/RC structures [10].

Although the density of typical ECC M45 is lower than that of normal weight concrete (2400 kg/m^3), it cannot be considered lightweight according to the definition of ACI Committee 213, which requires the density of concrete at 28 days to be less than 1850 kg/m^3 to qualify as lightweight concrete [1]. Wang and Li [3] attempted to develop lightweight ECCs using four lightweight fillers including expanded perlite, hollow glass bubbles, polymeric microform, and air bubbles produced by air entrainment admixture. In that study, it was found that hollow glass bubbles were effective for lowering the density and improving the fiber dispersion and mechanical properties of ECC [3]. The average density, compressive and tensile strengths, and tensile strain capacity of 1450 kg/m^3, 41.7 MPa, 4.31 MPa and 4.24%, respectively, were reported for the lightweight ECC made by hollow glass bubbles with a mean size of 30 μm [3]. However, such lightweight ECC uses high amount of cement and high temperature-processed hollow glass bubbles [3], which results in high embodied energy and carbon footprint [11], lowering the environmental sustainability of the composite. Therefore, it is necessary to develop green and sustainable lightweight ECCs with significantly lower environmental footprints.

This study evaluates the mechanical and thermal properties of green lightweight engineered geopolymer composites (EGCs) incorporating fly ash-based geopolymer as complete replacement of ordinary Portland cement (OPC) and three types of lightweight aggregates including expanded perlite, microscopic hollow ceramic spheres and expanded recycled glass as complete replacement of micro-silica sand, to achieve the following three objectives: (1) to significantly reduce the environmental footprint, (2) to decrease the density of the composite, and (3) to reduce the thermal conductivity of the composite. These objectives need to be achieved while maintaining good workability of fresh matrix and reasonable strength. A series of experiments including workability of the fresh matrix, density, compression, thermal conductivity and uniaxial tension tests were conducted as detailed in the following sections to characterize the thermal and mechanical properties of the developed green lightweight EGCs.

Among the ingredients of ECC M45, cement is a major contributor to the environmental impact accounting for 48.2% and 81.6% of total embodied energy and CO_2 emissions, respectively [12]. Several studies have focused on replacing cement in ECC M45 with industrial wastes. For instance, normal weight green ECCs have been developed by partial replacement of cement with fly ash [9], slag [13] and iron ore tailings (IOTs) [12].

Recently, Huang et al. [11] attempted to achieve the properties of lightweight and material greenness in ECC, simultaneously. In that study, green lightweight ECCs (GLECCs) were produced using IOTs, fly ash, and fly ash cenosphere as aggregates, mineral admixture, and lightweight filler, respectively [11]. The density, compressive and tensile strengths, and tensile strain capacity in the range of 1649–1820 kg/m^3, 25.0–47.6 MPa, 4.8–5.9 MPa and 3.3–4.3%, respectively, were reported for the developed GLECCs at the age of 28 days, depending on the contents of IOTs, fly ash, and fly ash cenosphere [11]. In this study, lightweight EGC is developed, which is even more environmentally sustainable than the previously developed GLECCs, as the ordinary Portland cement (OPC) binder in ECC is completely replaced by fly ash-based geopolymer binder in EGC.

Fly ash-based geopolymer is a cement-less binder that provides a highly sustainable alternative to OPC [14]. The term geopolymer was firstly introduced by Davidovits [15] as a class of largely X-ray amorphous aluminosilicate binder materials [16]. Geopolymers can be synthesized at ambient or elevated temperature by alkali activation of industrial by-products such as fly ash and slag, which are rich in silica and alumina, or materials of geological origin such as metakaolin [14,17,18]. Previous studies reported that manufacture of fly ash-based