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Micromechanics-based investigation of a sustainable ambient temperature cured one-part strain hardening geopolymer composite

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HIGHLIGHTS

- A sustainable ambient temperature cured "dry-mix" geopolymer composite is developed.
- The developed geopolymer composite exhibited comparable performance to SHCC M45.
- High tensile strength (4.6 MPa) and very high tensile ductility (4.2%) were achieved.
- The developed geopolymer composite offers 76% less carbon emissions than SHCC M45.
- The developed geopolymer composite offers 36% less embodied energy than SHCC M45.

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ABSTRACT

Geopolymer composite research is aimed to make sustainable alternatives to Portland cement-based composites. However, the two main obstacles for commercialization are the use of large quantities of user-hostile liquid activators and heat curing. This study is aimed to overcome these obstacles by developing an ambient temperature cured "one-part" strain hardening geopolymer composite (SHGC). The developed composite as a "dry mix" uses a small amount of solid activator and eliminates the necessity for heat curing. The quantitative influences of curing condition and type of slag on the composite tensile performance were evaluated. The developed composite demonstrated strong strain hardening behavior comparable to typical strain hardening cementitious composite (SHCC) with high tensile strength of 4.6 MPa and very high tensile strain capacity of 4.2%. A micromechanics-based investigation was performed to explain the experimentally observed macroscopic high tensile ductility of the developed composite. The investigation involved determination of the matrix fracture properties and the fiber-matrix interface properties using fracture toughness tests and single-fiber pullout tests, respectively. The crack-bridging relation of the developed composite, computed via a micromechanics-based model, satisfied the necessary strength and energy-based conditions of steady-state flat crack propagation, which result in sequential development of multiple cracking. The material sustainability evaluation verified that the developed ambient temperature cured one-part SHGC is a promising sustainable alternative to typical SHCC offering 76% less carbon emissions and 36% less energy consumption. This research presents the rational basis for design of such cement-less composites with both high tensile ductility and high material sustainability.

1. Introduction

Strain hardening cementitious composite (SHCC) such as engineered cementitious composite (ECC) represents a unique class of cement-based material exhibiting strain hardening subject to direct tension [1,2]. Based on micromechanics-based design principles, SHCC possesses extraordinary tensile strain capacity, several hundred times that of conventional concrete, with the incorporation of small volume fraction of randomly oriented short fibers [3]. However, there are generally high amount of cement in the mix proportion of SHCC, which results in high autogenous shrinkage, heat of hydration, and cost. In addition, cement manufacturing is considered as an energy intensive industry. The associated

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increase in the CO_2 emission as well as embodied energy apparently compromise sustainability performance of SHCC [4,5].

To resolve this issue, researchers have partially replaced ordinary Portland cement (OPC) in the typical SHCC mix design by supplementary cementitious materials (SCMs). Within the last decade several studies have been conducted to partially replace the OPC in the SHCC mixture with high volumes of ground granulated blast-furnace slag (hereafter referred to as slag) and/or fly ash to reduce the cement content in SHCC mixture. This in return reduces the global warming potential resulting from the carbon emissions of the cement industry [4,5]. A more sustainable approach to overcome this issue is to make cement-less SHCCs by replacing the entire OPC content in the SHCC mixture with geopolymer.

Geopolymer is cement-less binder and a promising sustainable and environmentally friendly alternative to OPC binder. Davidovits [6] was initially introduced the term geopolymer. Geopolymers can be manufactured by alkali activation of metakaolin (a material with geological origin), or fly ash and slag (industrial by-products, which are rich in silica and alumina). Previous studies reported that 60% less energy is needed to manufacture fly ash-based geopolymer compared to the production of OPC [7]. In addition, in comparison to OPC, synthesis of fly ash-based geopolymer results in at least 80% less carbon emissions to the atmosphere [8].

Recently, Ohno and Li [9] established the viability of developing a cement-less strain hardening geopolymer composite (SHGC). In that study, the entire OPC binder in typical SHCC mix proportion was replaced with the fly ash-based geopolymer binder. The compressive and tensile strengths, and tensile strain capacity in the range of 17.4–27.6 MPa, 2.9–3.4 MPa, and 2.7–4.3%, respectively were reported for the developed fly ash-based SHGC [9]. The authors of this paper set out to further build on this formulation and improve the formulation in a number of ways. The identified areas for improvements were compressive and uniaxial tensile strengths. The authors also identified the 14 M sodium hydroxide (NaOH) solution used by Ohno and Li [9] as a potential area where improvement can be made. Ohno and Li [9] used NaOH solution composed of NaOH pellet (59% w/w) and tab water (41% w/w) resulting a very high concentration of more than 14.0 M for their fly ash-based SHGC mixture design. One advantage of reducing the concentration of NaOH solution is that it increases the safety in handling large quantities. Significantly enhanced compressive and tensile strengths, and tensile strain capacity of up to 63.7 MPa, 4.7 MPa, and 4.3% respectively were reported for the fly ash-based SHGC made of a low concentration NaOH solution (8.0 M, 28.6% w/w) and sodium silicate (Na_2SiO_3) solution with a SiO_2/Na_2O ratio of 2.0 (71.4% w/w) [10,11].

The improved compressive and tensile performance of the fly ash-based SHGC developed by the authors [10,11] and the outstanding environmental advantages of geopolymer promote the application of SHGCs as a sustainable alternative to typical SHCC. However, there are two main obstacles for commercialization and widespread application of the developed fly ash-based SHGC. The first obstacle is the use of corrosive and often viscous liquid activators to manufacture the fly ash-based SHGC. Conventionally, the geopolymer binder is synthesized from a "two-part" mix formulation, including solid aluminosilicate source materials and liquid activators. The most important drawback with regards to the "two-part" mix formulation is that in commercial and mass production of the fly ash-based SHGC, handling large quantities of user-hostile alkaline solutions is difficult. The second obstacle is the necessity for heat curing for the production of the developed fly ash-based SHGC, which hinders its in-situ application.

This study is aimed to overcome the aforementioned obstacles by developing an ambient temperature cured "one-part" SHGC as an alternative to the "traditional" heat cured "two-part" fly ash-based SHGC. Such ambient temperature cured "one-part" SHGC as a "dry mix" uses a small amount of solid activator as alternative to the commonly used alkaline solutions and eliminates the necessity for heat curing.

The objectives of this paper are: (1) to highlight the material design approach for the development of the ambient temperature cured one-part SHGC. It includes the summary of the design principles for synthesizing a suitable ambient temperature cured one-part geopolymer matrix with desirable mechanical properties, moderate setting time and adequate rheology for uniform fiber dispersion, along with the fundamental micromechanics-based conditions for strain hardening behavior, both of which led to the development of the ambient temperature cured one-part SHGC. (2) To evaluate the quantitative influences of curing condition and type of slag on the matrix and composite properties, comprising density, workability, compressive strength and uniaxial tensile performance. (3) To perform a micromechanics-based investigation to explain the experimentally observed macroscopic tensile performance of the composites. The investigation included determination of the matrix fracture properties and fiber-matrix interface properties using fracture toughness tests and single-fiber pullout tests, respectively and computing the crack-bridging relation of the composites via a micromechanics-based model. (4) To compare the material sustainability of the ambient temperature cured one-part SHGC developed in this study with the "traditional" heat cured "two-part" fly ash-based SHGC previously developed by the authors [12], and the typical SHCC mix 45 (M45) [5], using material sustainability indicators (MSIs) [13].

2. Research significance

Material sustainability has not often been a concern in the development of high performance fiber-reinforced cementitious composites (HPFRCCs) as high amount of cement is usually used in the mix proportion of different types of HPFRCCs such as ultra-high performance fiber-reinforced concrete (UHPFRC) [14–16] and typical SHCC [4] compared to the conventional concrete. Within the last decade, several efforts have been made to consider the environmental sustainability aspects in the development of SHCCs through replacing a large amount of OPC by SCMs such as slag [17], fly ash [4,5], and iron ore tailings (IOTs) [18]. The viability of developing fly ash-based SHGCs with remarkable mechanical properties, yet with significantly lower environmental footprints compared to typical SHCC have been established in the recent studies [9–12,19]. Nevertheless, the necessity for heat curing and the use of large quantities of user-hostile liquid activators are the two main obstacles, which hinder the commercialization and broad application of the developed fly ash-based SHGCs as a sustainable alternative to typical SHCC. This study is aimed to overcome these obstacles by developing an ambient temperature cured one-part SHGC, which as a "dry mix" uses a small amount of solid activators and eliminates the requirement of heat curing. The ambient temperature cured one-part SHGC developed in this study is a promising sustainable alternative to typical SHCC. It is expected to promote sustainability of the infrastructures via concurrent improvements of material greenness and infrastructure durability through ultra-high ductility and tight crack width control.

3. Material design approach

3.1. Micromechanics-based conditions for strain hardening behavior

The pseudo strain hardening (PSH) behavior in short fiber-reinforced brittle matrix composites is due to consecutive development of multiple cracking in the matrix. It is essential to have