An integrated design method of Engineered Geopolymer Composite

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A B S T R A C T
Strain-hardening ductile fiber-reinforced geopolymer composite, named Engineered Geopolymer Composite (EGC), is a promising material for achieving green and durable civil infrastructure. Despite increasing attentions of the unique material, inefficient trial-and-error approaches are often employed in the material design, which slows the research and development. This paper proposed a new design methodology of EGC that integrates three design techniques: Design of Experiment (DOE), micromechanical modeling, and Material Sustainability Indices (MSI). The mix design of a preliminary version of EGC was optimized to achieve higher compressive strength, maintain high tensile ductility, and enhance the material greenness simultaneously. With the aid of the systematic design process, an optimized EGC with improved compressive strength of 43.1 MPa and high tensile ductility of 4.7% was developed, while achieving 11% less embodied energy and 55% less CO₂ equivalent emissions compared with a standard Engineered Cementitious Composite (ECC). Therefore, the applicability and effectiveness of the proposed design method were successfully demonstrated.

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1. Introduction

Ductile fiber-reinforced geopolymer composites have been recently proposed for green and durable civil infrastructure [1]. In essence, the new material technology combines geopolymer [2–4] and Engineered Cementitious Composite (ECC) [5,6]. Enhanced material greenness is attributed to the geopolymer matrix; it relies on no ordinary portland cement (OPC) but can use industrial byproducts, such as fly ash and slag, for the primary ingredient. Low carbon footprints of cement-free geopolymer concrete have been estimated by many researchers [7–10]. Besides the high material greenness, fiber reinforcement imparts improved durability to the material, as reported in ECC materials [11–13]. Synergistic interaction between fiber and matrix offers the strain-hardening characteristic and high tensile ductility, suppressing inherent brittleness of the geopolymer matrix. Further, when the material is overloaded, damage is distributed as self-controlled multiple microcracks. The tight cracking enables the ductile geopolymer to maintain their mechanical and durability properties even when highly damaged. With these unique properties, a new family of ductile fiber-reinforced geopolymer composites — named Engineered Geopolymer Composite (EGC) — shows great promise as a sustainable construction material. So far, several previous studies have demonstrated the feasibility of ductile geopolymer composites and reported their strain-hardening behavior and multiple-cracking characteristics in tension and flexure [14–17].

While EGC is increasingly gaining attention in the research field, difficulty in the material design slows the research and development. One of the biggest challenges is the large number of design variables. Geopolymer matrix typically involves more design variables than cement matrix, including types of alkaline activators and solid aluminosilicate materials, their mix proportions, curing regimes, etc. Moreover, optimization of fiber and fiber/matrix interface properties is also required for EGC, which further expands the degrees of freedom in the material design. As a result, empirical trial-and-error approaches, which have been often employed in the research field, are inefficient to explore the vast design space.

It should be also noted that EGC design is a multi-response optimization problem. Many prior studies on geopolymer design are only focused on compressive strength. Typically, a series of specimens are prepared by varying several design factors (e.g. type of alkaline activator, activator/fly ash ratio, etc.), and an optimum design that provides the best response (i.e. compressive strength) is determined. This traditional approach, however, is ineffective for EGC development; high tensile ductility and enhanced material greenness are desired properties in EGC optimization, as well as fundamental mechanical properties such as compressive strength. Finding an optimum mix design to simultaneously improve those
multiple responses is time and cost intensive when relying on the conventional trial-and-error approach. To facilitate research and development of EGC materials, more efficient and systematic design methodologies are needed.

This paper proposes a new design methodology for strain-hardening fiber-reinforced geopolymer composites with high tensile ductility and multiple micro-cracking characteristics. The Design of Experiment (DOE), micromechanical modeling, and material sustainability indices (MSI) are integrated to simultaneously achieve higher strength, ductility, and material greenness. The concept and design process of the integrated design method are first outlined in the following section. Then, analytical and experimental investigations are conducted to demonstrate the applicability and effectiveness of the design method. Consequently, a green and ductile (and, therefore, durable) EGC material is systematically developed.

2. Integrated design method

Fig. 1 illustrates the design scheme of the proposed integrated method. It consists of three design phases: matrix, composite, and environmental designs, each of which utilizes a specific material design technique.

The matrix design phase is aimed at meeting requirements in fundamental engineering properties such as compressive strength. Design variables (types of ingredients, mix proportions, curing regime, etc.) are optimized to achieve required performances, with the aid of a statistics-based design method, called Design of Experiment (DOE). Specifically, the method used in this study was developed by Taguchi [18] and has been applied to numerous science and engineering fields. In this approach, effects of design variables (or “input factors”) on performance (or “output”) are systematically quantified without explicitly testing every combination of input factors. Out of a number of possible combinations of input variables, only a portion of them is selected to test, based on a fractional-factorial design planned by using an orthogonal array (OA). The test results are then investigated based on the Analysis of Variance (ANOVA) method. The detailed theories can be found in literature (e.g. Ref. [19]). With this technique, experimental costs can be substantially reduced, yet robust information about the relationship between design variables and properties of interest is obtained.

Once a desired matrix is developed, fiber and fiber/matrix interface properties are tailored to impart high tensile ductility and multiple-cracking characteristics to the material. The micromechanical modeling is a design technique adopted in the composite design phase [20]. For given matrix and fibers, micromechanical parameters (matrix fracture toughness, bonding properties between fiber and matrix, etc.) that govern the composite tensile properties are measured by experimental techniques. Then, the composite tensile behavior is simulated by using an analytical model based on fracture mechanics, micromechanics and probabilistic models. The simulation result guides modification on micromechanical parameters for achieving desired tensile ductility and tight multiple cracking. With the aid of the micromechanical modeling, rapid development of various types of Engineered Cementitious Composites (ECCs), including lightweight, self-compacting, sprayable, and self-healing ECCs, has been realized.

The last phase is the environmental design that evaluates overall sustainability of the developed composite. In this study, the Material Sustainability Indices (MSI) are employed to measure the embodied energy consumption and carbon footprints associated with the material production [21]. MSI values represent a partial life cycle analysis (LCA) of the material greenness that accounts for raw material acquisition, processing, and manufacturing while the use and disposal phases are omitted. MSI are useful for quantifying the overall environmental performance of materials, regardless of
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