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Flexural performance and toughness of hybrid steel and polypropylene fibre reinforced geopolymer

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HIGHLIGHTS

- For a hybrid system, steel fibres provide positive effects on the properties PFRG.
- Higher first peak load and post peak response were observed in hybrid FRG.
- Both toughness and equivalent flexural strength improve with the percentage of steel fibres.

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ABSTRACT

In this study, the effects of steel and polypropylene fibre hybridization on the flexural performance of fibre-reinforced geopolymer were investigated. Fibre reinforcement has emerged as a way to improve the brittleness of geopolymer. There are currently several types of fibres available on the market. When polypropylene fibre is used, it usually yields a large drop in strength immediately after the first crack, as well as a lower post-peak response, owing to its high flexibility and low stiffness. To resolve these issues, a hybrid system is introduced using fibre with high strength and stiffness such as steel fibre. In the present study, two hybridization systems are investigated: replacement and addition systems. For a replacement system, the polypropylene fibre is replaced gradually with steel fibre at a rate of 0.2% by volume. For an addition system, the steel fibre is added into the mixture at the same rate. The results indicate that the hybridization of steel fibre can improve the flexural response, toughness, and residual strength of polypropylene fibre reinforced geopolymer to different degrees. Both the load dropping and second peak are found to improve almost instantaneously. The toughness and residual strength also increase gradually with an increase in steel fibre content.

1. Introduction

Global warming is a major environmental problem, the main cause of which is the emission of greenhouse gases such as carbon dioxide, hydro fluorocarbons, and methane into the atmosphere. The accumulation of these gases increases the greenhouse effect and causes a rise in the earth's surface temperature, changes to the climate system, and natural disasters of greater severity.

In the construction industry, cement manufacturing alone emits about 13,500 million tons of carbon dioxide per year, which accounts for about 7% of the total carbon dioxide emissions globally [1]. Of all the common ingredients in a concrete mixture, cement results in the highest carbon emissions with an emission factor of about 700–900 kg per ton. In an attempt to reduce the CO_2 emissions of concrete, many studies have targeted lowering the cement content in concrete mixtures by partially or totally replacing the cement with a mineral admixture or industrial by-product such as fly ash, slag, or silica fume.

Geopolymer was first introduced in 1984 [2] as a cementitious material that contains no Portland cement. The CO_2 emissions of geopolymer are far less than those of conventional cement [3,4]. Geopolymer can be manufactured using any raw materials containing silica (SiO_2) and alumina (Al_2O_3) as major compositions reacting with a concentrated alkaline solution, and having thermal energy to accelerate the reactions [5,6], for example, fly ash, blast furnace slag, metakaolin, or rice husk ash. The properties of geopolymer also depend on the curing condition. In general, high-temperature curing is recommended for geopolymer [7]

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because the heat can accelerate the geopolymerization reactions and promote an early gain in strength. Mermerdaş et al. [8] concluded that the curing temperature and duration are both significant factors in the activation of geopolymer. A curing temperature of 60 °C is considered the optimum temperature when applying a curing duration of 19–24 h depending on the type and content of the binder.

The mechanical properties of geopolymer have been found to be quite similar to those of hardened cement in that the material exhibits excellent compressive strength but is poor in tensile strength (brittle). For conventional concrete, to improve the brittleness, small fibres are randomly mixed into the concrete mixture, which is called fibre reinforced concrete (FRC). For plain concrete, once a crack begins under loading, the crack will propagate quickly and cause a rapid loss in load carrying capacity. For FRC, on the other hand, the fibre distributed among the matrix will intercept the crack, causing it to slow down and even come to rest. This effect is the so-called crack bridging effect, which improves the toughness of the concrete and maintains the ability to carry a load after the first crack appears.

In the case of geopolymer, the use of fibre to improve the brittleness is comparatively new compared to conventional concrete. There have been a few studies carried out in the area of fibre reinforced geopolymer (FRG). For example, Genesa et al. [9] studied the basic properties of steel fibre reinforced geopolymer (SFRG) with fibre volume fractions varying from 0.25 to 1.0% and a concrete strength of 40 MPa. They found increases in both compressive and splitting tensile strengths of about 8.51% and 61.63%, respectively, in SFRG with the fibre volume fraction at 1%.

Reed et al. [10] carried out tests on polypropylene FRG at three different proportions of 0%, 0.05%, and 0.15% by weight and under two types of curing (ambient and oven). Their results showed an increased compressive strength at a 0.05% weight fraction ratio but a decrease at 0.15%. Shaikh [11] compared the flexural behaviours of steel fibre reinforced concrete (SFRC) and SFRG, and concluded that both SFRC and SFRG exhibit similar deflection hardening behaviours, although SFRG was shown to behave in a more ductile manner with larger deflections at peak load.

In terms of fracture properties, Alomayri et al. [12] investigated the mechanical and fracture properties of geopolymer mixed with cotton fibre at 0.3–1.0% by weight. They found the optimum cotton fibre content is around 0.5% by weight, which provides the highest flexural strength and fracture toughness of about 11.7 MPa and 1.12 MPa. $\sqrt{m}$, respectively.

Deepa Raj et al. [13] also studied the fracture properties of steel FRG using a three-point bending test on notched beams. The notched beams had a b/W ratio of 0.40 and fibre volume fractions of 0.25%, 0.50%, and 0.75%. The effect of the fibres was found to enhance the fracture properties of geopolymer such as the fracture energy and fracture toughness by 10–40% as compared to plain geopolymer.

Karmar and Kumar [14] investigated the effects of a hybrid fibre between steel and micro polypropylene fibre on properties including the compressive, flexural, and splitting tensile strengths. The fibre combination used was steel fibre at 0.5% by volume with the addition of micro polypropylene fibre at 10–50% of the steel fibre volume. Their results showed that the optimum volume fractions of micro PP fibre was 20% for compressive strength and 30% for flexural strength.

In theory, a hybrid system is a combination of two or more types of fibre in an FRC mixture with an objective of using the strength of one type of fibre to supplement the weaknesses of the other [15]. There are two basic systems in hybrid FRC, replacement and addition. A replacement system is when one type of fibre is replaced with another type of fibre; in this case, the fibre volume fraction will remain constant. An addition system is when a supplement fibre is added to the base fibre; in this case, the fibre volume fraction will increase with the additional volume.

Briefly, polypropylene (PP) fibre was first invented to provide resistance to non-loading cracks in concrete. However, with advanced technologies in material science, a number of synthetic fibre types available on the market are capable of enhancing the toughness and maintaining the residual load carrying capacity (after cracking) in concrete. However, polypropylene fibre does have certain drawbacks owing to its low stiffness and flexibility. When subjecting to loading, and immediately after the first cracking, the load carrying capacity of PP-FRC tends to drop sharply until the individual fibres are stretched to a certain point, at which the load then increases again [15,16]. These are two of the weaknesses of PP fibre that require improvement, and a hybrid system might provide a solution.

This study therefore aims to investigate the flexural performance of hybrid fibre reinforced geopolymer (HyFRG) applying steel and polypropylene fibre. Both are macro-type fibre designed specifically to enhance the mechanical strength and toughness of concrete. Polypropylene fibre is used as the base, while steel fibre is used as a supplement. Steel fibre is used to replace or add to the polypropylene base FRC at an incremental rate of 0.2% of volume fraction. The flexural performance is achieved in accordance with ASTM 1609. The results in terms of failure mode, toughness, and equivalent flexural strength are calculated and discussed.

2. Experimental procedure

2.1. Materials

The materials used as a binder phase consist of fly ash and silica fume. The fly ash is obtained from an electricity power plant in Lampang province, Thailand, and has a particle size of about 1–100 μm (Table 1) and the silica fume is a by-product from the industrial production of silicon and ferro-silicon alloy, and has a particle size of about 0.03–0.3 μm (Table 1). The chemical solutions consist of a sodium hydroxide solution (NaOH) prepared using hydroxide pellets mixed with water at a constant concentration of 14 M and a sodium silicate solution (Na_2OSiO_3) with specific gravity of 1.60 at 20 °C. Two types of macro fibre were used: steel and polypropylene, the properties and shapes of which are as shown in Table 2. A chemical admixture, superplasticizer type F (ASTM C494-81), was also used in the mix to ease the mixing procedure.

2.2. Mix proportions

Prior to determining the mixture proportion, a pre-test was carried out to determine the optimum sodium hydroxide solution concentration that provides the greatest compressive strength of the geopolymer mortar, the results of which are shown in Fig. 1.

Table 1
Chemical composition of fly ash and silica fume.

	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	LOI
Fly Ash	36.02	20.58	15.91	18.75	2.24	0.07
Silica Fume	88.30	1.17	4.76	0.48	1.05	–