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Geopolymer concrete-filled pultruded composite beams – *Concrete mix design and application*

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ABSTRACT

The limited research on the geopolymer concrete mix design for targeting a specific strength is identified an obstacle for their effective design and wide use. In this paper, a mix design procedure has been proposed for fly-ash based geopolymer concrete and its use as infill hybrid composite beam is investigated. Then, the structural performance of geopolymer concrete filled hybrid composite beam is investigated to determine their possible application in civil infrastructure. Firstly, a detailed procedure of mix design for fly-ash based geopolymer concrete is presented. Secondly, three hybrid beams filled with geopolymer concrete were prepared and tested in a four-point bending setup to evaluate their flexural modulus and modulus of rupture. Numerical and analytical evaluation of the behaviour of hybrid beam were performed and results showed a good agreement with the experimental investigation. Thirdly, the suitability of the beam for a composite railway sleeper is evaluated and compared with existing timber and composite sleepers. Finally, the beams' performance in a ballast railway track is analysed using Strand7 finite element simulation software and the results showed that the new concept of using geopolymer concrete as infill to pultruded composite section satisfied the stiffness and strength requirements for a railway sleeper.

1. Introduction

In the last decades, extensive research has been undertaken by academics and engineers alike to develop energy efficient and sustainable materials. The principle of sustainable construction stands on a basis of material together with structural design optimisation, which results in lower life-cycle costs. Geopolymer concrete (GPC) and fibre reinforced polymer (FRP) are two engineering materials which gained wide attention from researchers and engineers because of their many advantages. Fig. 1 shows some of the immediate and long-term benefits that fibre reinforced plastics [1–3] and geopolymer concrete [4–8] technologies are able to provide.

Ordinary Portland Cement (OPC) production causes between 0.8 and 1 tons of carbon dioxide (CO_2) emission for every ton of cement produced [9,10] which corresponds to 5–10% global CO_2 emissions. Geopolymer cement, contrary to OPC, does not depend on calcining calcium carbonate, which is the major source of CO_2 emission in the production of OPC concrete [11,12], and can reduce emissions by up to 90% for each cubic metre of OPC concrete replaced. In addition GPC offers other advantages such as improved fire resistance (up to 1000 °C), high level of resistance to a range of different acids and salt solutions, immunity to deleterious alkali–aggregate reactions, low shrinkage and low thermal conductivity, and an inherent protection of steel reinforcing due to high residual pH and low chloride diffusion rates [13–17]. Moreover, the incorporation of fibre reinforcement can improve the performance of geopolymer concrete under impact loads [18]. Researchers are now investigating the performance of geopolymer concrete for manufacturing railway sleepers where the sleepers are subjected to millions of cyclic loads [19]. The railway sleeper should be electric nonconductive and the geopolymer concrete showed superior electrical resistance [20].

Before the widespread application of geopolymer concrete in civil infrastructure, a detail guideline is required for selecting the suitable concrete ingredients and determining their relative quantities with the object of producing as economically as possible a concrete of certain minimum properties. Previously, some studies

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have been conducted for this purposes [11] but still it is insufficient as it does not fulfil some basic design criteria which is comprehensively discussed in the next section. Therefore, it is the demand for geopolymer concrete researchers, engineers and end-users that a suitable design guideline be established to achieve the specified minimum properties but still maintaining its economical use.

As for FRP, a recent study by Daniel [21] comparing the energy consumption of various materials such as steel, aluminium, composites and reinforced concrete for construction from the stages of extraction of raw materials, production and fabrication of the material, delivery of the material to the construction site and maintenance throughout the design life of the structure, found out that composites consume approximately half the total amount of energy as any other construction material considered. In addition, FRP's have many other advantages such as low weight, corrosion immunity, high fatigue strength, high damping and electromagnetic neutrality [3]. In this manner, GPC and FRP materials promise to be a greener construction option than any other materials.

The aforementioned information motivates the authors to combine these materials in the development of a hybrid beam to effectively utilise the good characteristic properties of each material. The hybrid beam is developed by filling a pultruded composite section with geopolymer concrete. The behaviour of a similar structure using ordinary cement concrete has been investigated by a number of researchers and their results showed that by combining these two materials will lead to a more efficient infrastructure. The flexural performance of traditional concrete-filled FRP tubes have been studied by Fam et al. [22] and their study concluded that concrete filling can provide internal support which prevents local buckling as well as increase flexural strength and stiffness of the beam. On the other hand, confinement of concrete using FRP tubes can provide a potential enhancement in the ductility and strength performances as focused by Mohamed et al. [23]. Their experimental investigations on concrete-filled FRP beams showed lower deflection, higher cracking load level, higher ductility, higher stiffness and superior strength than the beam reinforced with spiral steel. Dagher et al. [24] investigated the similar structure as an arch member and they observed an insignificant strength reduction after 2 million cycles of fatigue loading.

This paper studied a new method of geopolymer concrete mix design procedure and its application as an infill for structural hybrid composite beams. An evaluation of the suitability of this hybrid beam concept for a railway sleeper has also been conducted and presented in this paper.

2. Mix design procedure for alkali-activated fly ash concrete

There has been very limited research on mix design for geopolymer concrete, let alone directives for a practical and systematic procedure that takes into consideration the strength and durability of the final product. In 2008, Lloyd and Rangan [11,25,26] proposed a mix design method for fly ash-based geopolymer concrete but did not discuss how to deal with the effects of the ingredients' specific gravities or air content volume. They assumed a constant concrete density of 2400 kg/m^3 which was not realistic because the density of concrete varies from one mix to another depending on the amounts of each ingredient in it. Sometimes, extra water or a super-plasticiser is needed to improve the workability of fresh geopolymer concrete which has an effect on the total volume of the concrete. Their method did not explore the design for workability which in geopolymer concrete seems to assume a yet more important effect than other types of concrete. As it is necessary to develop a rigorous, but still easy method for a geopolymer concrete mix design, a general procedure illustrated in the flowchart shown in Fig. 2 is proposed.

Like water-to-cement ratio in the Ordinary Portland Cement (OPC) concrete, the strength of geopolymer concrete depends on water-to-geopolymer solids (W/GS) ratio. The alkaline liquid and fly ash are the two sources of geopolymer solid in the mix. The term W/GS ratio is defined as the total mass of water in the concrete mix that is reactive in geopolymeric reaction to the sum of the mass of fly ash, alkaline hydroxide solids and alkaline silicates solids. On the other hand, the sum of sodium hydroxide and sodium silicate solutions are referred as alkaline liquids and the ratio of the mass of alkaline liquid to fly ash is called alkaline liquid-to-fly ash ratio [27]. The particle size distribution of fly ash is provided in Fig. 3 [28]. From the experience of Hardjito and Rangan [29], the amount of fly ash content was chosen as 400 kg per cubic metre of concrete for preparing the design graph. The W/GS ratio linearly increases with the increase in the alkaline liquid-to-fly ash ratio if the molarity of the sodium hydroxide (NaOH) solution and ratio of the sodium silicate-to-sodium hydroxide solutions remain the same in all mixes. The variation

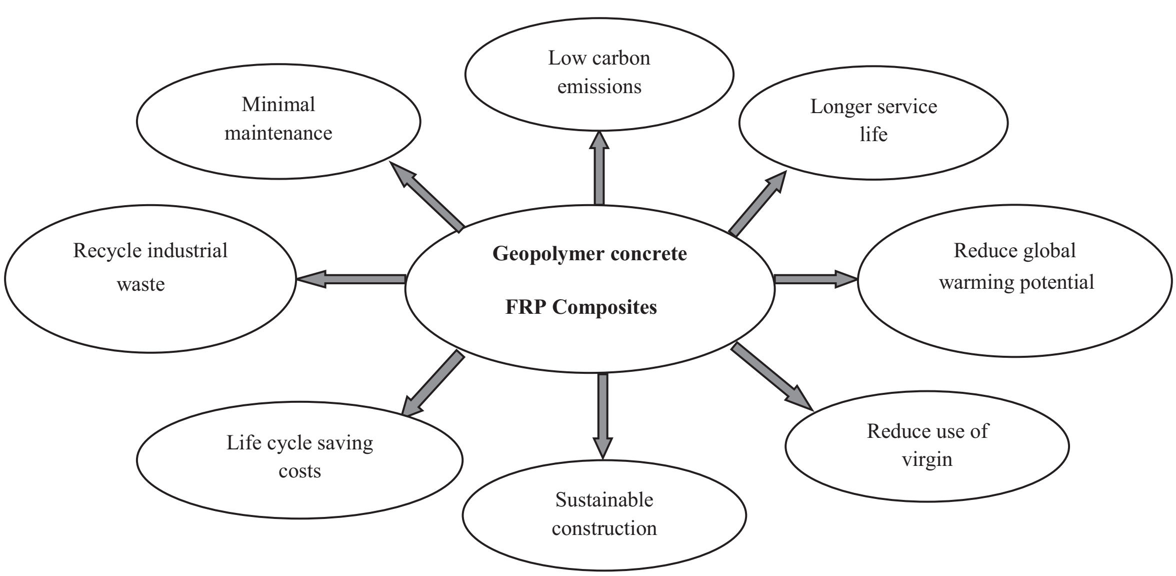

Fig. 1. Immediate of short and long term benefits of FRP's and GPC.