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Mechanical behaviours of green hybrid fibre-reinforced cementitious composites

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HIGHLIGHTS

- Development of cementitious composites reinforced with bagasse fibre and steel fibre.
- Calibration of the mechanical properties of the bagasse fibres.
- Calibration of the mechanical properties of the new green composites.
- Evaluation on the influence of the content of bagasse fibres and fly ash.

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ABSTRACT

New green cementitious composites reinforced with bagasse fibre and steel fibre with ultra-high volume of fly ash are developed in this paper. The mechanical properties of bagasse fibre such as the tensile strength, Young's modulus and stress–strain relationship are determined via conducting single fibre tensile test. Mechanical behaviours of the new composites, including compressive strength, Young's modulus, bending behaviour and uniaxial tensile behaviour, are investigated experimentally. The influence of the content of bagasse fibres and fly ash on the mechanical behaviour of the composites is also evaluated. The obtained results show that the compressive strength, Young's modulus, modulus of rupture and tensile strength of the composites decrease with the deduction of the content of the fly ash and bagasse fibre, but the bending toughness and tensile ductility of the material increase with fly ash content and peak as fly ash to cement ratio achieves 2.0. It is found that the mechanical properties of the composites are comparable to those of conventional concrete and are very promising green and sustainable construction and building materials and have strong potential to be used in engineering practice.

1. Introduction

Research and development of eco-friendly, green and sustainable construction and building materials using recycled or industrial by-products/wastes have been attracting increasing research interest in recent years. Fibre-reinforced concrete (FRC), by adding discrete short fibres randomly in cementitious composites exhibits substantially improved engineering properties in tensile strength, flexural strength, fracture toughness, and resistance to fatigue and impact [1–4]. In some cases, in order to create excellent mechanical characteristics such as multiple-cracking behaviour and outstanding strain capacity, some specific methods were used to deal with the fibre, and usually the proportion of cement utilised for this kind of material is extremely high [5–7]. Unfortunately, although the increasing usage of cement increases the mechanical behaviour of the composites, the large amount of CO_2 emission released during the manufacture of the cement has caused severe and adverse environment impacts [8–10]. Therefore it will be desirable that some industrial wastes can be used to partially replace the cement.

Fly ash, a by-product of fire power station, was reported to be effective in improving both the short- and long-term mechanical properties of cementitious composites in many aspects, especially the outstanding ductility of the composites when applied in high volume [11,12]. Additionally, the application of fly ash poses positive advances in protecting sustainable environment. The utilisation of fly ash can transfer the existing waste into useful material with potential benefits. Due to the use of cement partially replaced by using the fly ash, the CO_2 emission arising from the

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manufacturing of the cement can also be significantly reduced, which is absolutely beneficial to the environment.

Steel fibres and synthetic reinforcing fibres [2] have been commonly used as reinforcing fibres in FRCs. Natural fibres such as banana fibre, bagasse fibre, coir fibre, jute fibre, sisal fibre have also been used to reinforce concrete [13,14]. Application of natural fibres rather than the synthetic fibres, which are the by-products of the agriculture and are ecofriendly and cheap poses another promising way in improving the sustainability of the fibre reinforced composites. The early studies on natural fibre reinforced cementitious composites were not paid much attention as natural fibres were fragile and easy to get degraded especially in alkali media [15,16]. However, through specific modification, natural fibres have been proven to be capable of improving the mechanical behaviour of the composites even after long-term weathering conditions [17–23].

Bagasse fibre, which is the by-product of the cane sugar industry, has been used to reinforce cementitious composites, and it was found that bagasse fibre was able to change the setting behaviour and improve the basic mechanical properties of the composites [24,25]. Compared to other natural fibres, bagasse fibre could better improve the long-term durability of fibre-reinforced cementitious composites when the composite specimens were cured through long-term curing conditions like weather curing, wetting and drying cycles or water immersion [17].

In previous studies, fly ash and natural fibres were used in cementitious composites separately, and the effects of combined application of these two on the mechanical behaviour of the composites have not been studied. With the use of high volume fraction of fly ash, the matrix got a lower alkali degree, which could reduce the corresponding degradation of the natural fibres [26]. Therefore, the composites with both fly ash and natural fibres may exhibit improved mechanical properties, especially after long-term curing. Although the synergic effect of different fibres [2,27,28] or the coupled effect of natural fibre and recycled material such as granulated blast furnace slag [29] on the mechanical behaviour of the composites has been investigated, the combined influence of high volume of fly ash and natural fibres on the mechanical behaviour of cementitious composites has not been studied systematically yet and this need to be further investigated.

In this paper, new green cementitious composites reinforced with bagasse fibre and steel fibre with ultra-high volume of fly ash are developed. Mechanical behaviour of the new composites, including compressive strength, Young's modulus, bending behaviour and uniaxial tensile behaviour, is investigated experimentally. The influence of fly ash content on the mechanical properties of the composites is studied by varying the fly ash to cement ratio from 1.2 to 1.6 and 2.0 with the bagasse fibre content fixed at 3% by volume. The influence of bagasse fibre content on the mechanical behaviour of the composite is evaluated by varying the fibre content from 3% to 8% and 12% of volume fraction with fly ash to cement ratio fixed at 1.6. The mechanical properties of the refined bagasse fibres including the Young's modules, tensile strength and stress–strain relationship are also studied and presented in this paper. Finally research findings are concluded.

2. Green hybrid fibre-reinforced cementitious composites

New green cementitious composite reinforced with bagasse fibre and steel fibre with ultra-high volume of fly ash are developed in this research aiming for an eco-friendly and sustainable construction and building material by using the industrial wastes. The new green composites are a special type of FRCs, which are comprised of cement, sand, water, fly ash, water reduce agent reinforced with bagasse fibres and steel fibres. The steel fibres are used to achieve strength for the composites, and the fibres utilised are coppered micro steel fibres WSF0213 provided by Ganzhou Daye Metallic Fibres Co., Ltd. The geometry and material property parameters of the steel fibre obtained from the provider are presented in Table 1. The volume fraction of steel fibre is fixed at 0.7%, as the cementitious composites containing steel fibre content between 0.5% and 1% showed better tensile strength and ductility [28].

Bagasse fibres are used in the composite to obtain good ductility. The original bagasse fibres used were provided by Australian Prime Fibre Company, and they were refined in the vertical crushing machine by SOILCRETE AUSTRALIA Company. The crushed bagasse fibres were then sieved using a 2.36 mm screen to remove the coarse parts. The bagasse fibre has irregular cross section with a shape close to a circle as shown in Fig. 1 examined by optical microscope. The composition of the raw sugar cane bagasse fibre [30] from elemental analysis and botanical analysis are given below:

- From elemental analysis (wt.%): Carbon:45.5; Hygrogen:5.6; Oxygen:45.2; and Nitrogen:0.3, and
- From botanical analysis (wt.%): cellulose: 41.8; hemicellulose: 28.0 and lignin: 21.8%.

Cellulose, hemicellulose and lignin are the most important botanical components for natural fibres. Among these chemical compounds, cellulose is the main structural component for the natural fibres, which provides strength and stability to the whole fibre. Therefore, the natural fibres with high cellulose content, such as sisal fibre and banana fibre (with cellulose 65% and 64% by weight) usually dramatically improve the mechanical properties such as flexural strength and flexural toughness of the cementitious composites [13,19,20]. However, the components like hemicellulose and lignin are more easily hydrolysed in alkali environment [22]. Hence, surface modification is necessary to remove hemicellulose and lignin firstly in order to improve their long-term durability [23].

To reduce the bagasse fibre degradation by the chemical attack from the highly alkaline cementitious matrix, the fibres were boiled in a 3% NaOH solution with fibre concentration of 6.4 g/L at a temperature of 100° for 2 h so as to remove the non-cellulose part of the bagasse fibres [25]. After this, the bagasse fibres were dried in an oven, and then soaked in 6% silane solution for 2 h aiming to coat the bagasse fibres with specific material which could improve the bonding behaviour between bagasse fibres and the cementitious matrix [25]. Finally, the bagasse fibres were dried in the oven again for 2 h. Fig. 2 shows the surface morphology of the modified bagasse fibres, and the interface between the bagasse fibre and cementitious matrix could be observed in Fig. 3. It can be observed that the modified bagasse fibre is covered with a layer of silane, which could effectively increase the bonding behaviour between bagasse fibre and the surrounding cementitious media as shown in Fig. 3.

Mechanical properties of the bagasse fibres including tensile strength and Young's modulus are tested in this research. Due to the large scattering of the fibre geometric specifications, a large number of fibres need to be tested to get an average value of the

Table 1
Specifications of the steel fibre.

Fibre	Tensile strength (MPa)	Young's modulus (GPa)	Specific gravity	Diameter (μm)	Length (mm)	Aspect ratio
Steel 65	fibre	2600	200	7.8	200	13