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Interfacial properties and structural performance of resin-coated natural fibre rebars within cementitious matrices

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ABSTRACT

This paper investigates the interface and behaviour of continuous natural fibre rebar reinforced cementitious composites. Various resins were used to coat sisal fibres which were then used as reinforcement within the composites. Non-destructive tests (SEM, OM, FTIR) were employed to evaluate the interfacial bonding and interaction between the sisal, resin and cementitious matrix. The results showed that the uncoated fibre could not develop a compact interface due to the moisture absorption/desorption of the fibre, which caused low mechanical properties of the composite. The coating was able to improve the strength of the rebars and reduce the OH^- concentration, which improved the interfacial bonding and integrity. The flexural stress-strain relation of the composites exhibited three regions with two clear dips, reflecting the progressive stress transfer and failure of the composite constituents and their interactions. The comparable mechanical properties to those of steel rebar reinforcement demonstrate the potential of the resin-coated sisal fibre rebar for structural applications.

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1. Introduction

Various forms of fibres have been developed to overcome the limitations of concrete as a quasi-brittle material that is weak in tension. Fibres typically act to restrict crack growth within concrete. Natural fibres are traditionally classified into four categories according to their origin: stem/bast, leaf, fruit/surface and wood/cellulose [1]. Leaf fibres provide the fundamental rigidity and strength of leaves and are extracted by means of scraping and drying crushed leaves. In comparison to stem/bast fibres, the leaf fibres are commonly tougher, rougher in texture and stronger on average. For example, the strength and stiffness of sisal fibre range from 550 to 750 MPa and 17–38 GPa compared to those of jute fibre from 300 to 800 MPa and 10–30 GPa respectively [2–8].

Sisal fibres, being the most common type of leaf fibres, are produced from various varieties of the agave plant, which is indigenous to the arid regions of Africa and South America, mainly Brazil – the biggest commercial producer of Agave sisalana amounting to an estimate of 150,000 tonnes [9]. Known to have one of the strongest natural fibres, the agave plant is characterised by its leaves, which grow to a length of over one metre, and yield a long creamy white and very strong fibre. Sisal is a fast-growing plant that remains reproductive for 10–12 years and produces 180 to 240 leaves in a lifetime. In addition, having a total annual production of approximately 300,000 tonnes with a low-cost production, sisal fibre is increasingly being used in the building industry, particularly for plaster reinforcement. As sisal has been used for many years for reinforcing gypsum products, there is an emerging potential for sisal fibres being used to reinforce other composites for low-cost housing applications, namely reinforcing concrete matrices [10–13].

The characteristics and performance of the fibre-reinforced composites depend on the properties of the individual components within the composites including the fibre, the individual matrices and the interfaces between them. One must, therefore, investigate the nature of each of these components to gain a comprehensive understanding of the properties of the final composite. When considering vegetable fibre reinforced composites, the major research challenge has been trying to achieve a strong interface, especially a dense interfacial transition zone, within the composites. However, the surface chemistry of natural fibres and the negative effects of moisture diffusion between the fibre and the inorganic-bonded-matrix (e.g. mortar) on the interfacial bonding complicate this. In realising and optimising the requirements for

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exceptional bonding mechanism, i.e. mechanical, electrostatic, interdiffusion or chemical bonding between the fibre and matrix [14], the fibre and matrix can such reach their individual strength such that the load applied is uniformly distributed within the lattice structure [15]. Moreover, for natural fibre-inorganic composites, there exists an additional major challenge: hydrophilic nature of natural fibre complicating with the essential presence of moisture for the inorganic matrix (requirement for curing). Hence, this paper is to systematically analyse and characterise the interfacial systems of the natural fibre (sisal fibre as an example) – inorganic matrix (cement-based as a candidate) composites (FRC). The findings of this research will result in a better understanding of the interface and interaction of natural fibre with the cementitious constituent, provide fundamental information for further development of the natural fibre inorganic composites, and such facilitate and promote the use of natural fibres as a structural reinforcement for cementitious composites that could be a viable alternative to steel in some applications.

2. Experimental plan

2.1. Raw materials

Natural fibre sisals (*Agave sisalana*) were purchased online in a form of ropes comprised of 3-ply twined yarns to make up 3 mm diameter string of the desired length. It is graded as type-1 sisal, which is the finest known quality. Additionally, four types of resins (slow cure time) were bought from a commercial supplier for coating sisal fibres; epoxy, polyurethane, vinylester and polyester. The properties of the resins can be summarised in Table 1. 3 mm marine grade steel wire rope was used as a comparison. Standard CEM II Portland-limestone (~6–20%) cement (Class 32,5 R), complying with BS EN 197-1 [16] was used for making the matrix along with sharp sand bought from a commercial building material supplier.

2.2. Sample preparation

Dry sisal rope of 600 mm sizes was pre-stressed using a torsion machine of known pressure (20 rotational cycles). Known amounts of resin were thoroughly mixed and sonicated for approx. 10 min to remove most of the bubbles. The clear resin was then brushed uniformly onto the exposed surface of the sisal rope while it was under torsional stress for an application time of approx. 2 min (Fig. 1a). This resin coating keeps the fibres intact as well as keeping the overall rebar rigid and uniform, maintaining reliability. The resin is also used to protect the fibres from chemical attacks, prolonging their durability. Once the resin coating becomes sufficiently hard after about 24 h (at 22 °C and 50% relative humidity), the ropes were cut to lengths of 150 mm in order to fit the prismatic moulds of $40 \times 40 \times 160$ mm^3. Samples were fitted with two tensile rebar reinforcements per mould using mesh spacers and silicone glue, such that a minimum of 5 mm cover is kept at the bottom and outer sides of the reinforcements (Fig. 1b). The sisal fibres were not treated in an effort to improve the interfacial strength between the fibre and resin, the effectiveness of which has been proven by some studies [17–22]. Samples of uncoated steel rebar were fitted in the same way.

The mix proportion used for making the cementitious matrix used was a 1:1.5 ratio of cement to sand with water to cement (w/c) ratio of 0.4. The sand used was oven dried at 100 °C for 24 h and sieved to a particle size distribution of ≤1 mm. The fresh mortar was fabricated using a bench-top mixer before casting into the moulds and compacting for 1 min using a vibrating table, conforming to EN 196-1 [23]. The moulds were then covered with a plastic film and water sprayed on top of the plastic film to protect and control the moisture loss. After 24 h, the cementitious composites were de-moulded and left to cure at room temperature and pressure of 22 ± 1 °C and ~100 kN/m^2 with relative humidity of 50% within a curing chamber till the ages of 7, 14 and 28 days.

To improve the reliability of the investigation, four samples of each type of composite were tested and the mean values were used. Control variables were maintained, such as keeping the proportions of the ingredients the same and applying the same amount of resin used on the rebar (6 g of any resin applied for every 60 cm length of twined sisal rope), such that coated sisal rebars have diameters of 3.5 ± 0.2 mm when measured via a Vernier caliper (~0.3 ± 0.02 vol% of fibre content within mortar samples). The geometry of the rebars within the composites was all kept constant (precise to ±0.5 mm) to ensure that the positions of the rebars were not a contributing cause of variations (Fig. 1).

2.3. Characterisation

A series of tests have been carried out to characterise the developed composites, and a summary of the test methods conducted and their purpose is identified in Table 2.

3. Results and discussions

3.1. Functional groups of sisal and its rebars for interface bonding

Fourier transform infrared spectroscopy (FTIR) was used to determine the functional groups of sisal fibres and their coated counterparts (rebars) (Fig. 2). A large quantity of OH functional groups was found within sisal fibres (Fig. 2a) as the 3290 cm^{-1} peak denotes in Table 3. Sisal is a natural fibre, which is chemically comprised of cellulose, hemicellulose and lignin with impurities including pectin and wax. The presence of cellulose defines the chemical and physical properties of the fibre as it makes up the majority (70%) of the biological structure. Cellulose contains many chemical bonds that vary in type and extent compared to that of the synthetic resins. Hydroxyl is one example of these where its presence is particularly plentiful in sisal as the glucose chains are held together using hydrogen bonds between hydroxyl groups to form microfibrils. These OH bonds may be the primary reason for the strong interface bonding between the fibre and the matrix since strong hydrogen bonds are formed.

Epoxy also has hydroxyl groups within the chemical structure which may also promote hydrogen bonding, however, the

Table 1
Typical properties of the various resins used.

	Resin:hardener by weight	Mix density (gcm^{-3}) @ 25 °C [BS EN ISO 5350-Part B1]	Flexural strength (MPa) [BS EN ISO 178 [32]]
Epoxy (E)	5:1	1.11	81.42
Vinyl-ester (V)	1:0.015	1.32 @20 °C	153
Polyester (P)	1:0.02	1.09	78
Polyurethane (PU)	Part A 1:1.2 Part B	1.03–1.08	–

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