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Development of durable cementitious composites using sisal and flax fabrics for reinforcement of masonry structures

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ABSTRACT

Natural fibres are one of the most studied materials. However, the use of these fibres as reinforcements in composite materials for structural applications, especially for existing or historical masonry structures, remains a challenge. In this study, efforts were made to develop sustainable composites using cementitious matrices reinforced with untreated bi-directional fabrics of natural fibres, namely, flax and sisal fibres. The fibres were mechanically characterised by tensile tests performed on both single yarns and fabric strips. Ageing effects due to fibre mineralisation in alkaline cement paste environments may cause a reduction in the tensile strength of natural fibres. The matrices used to study fibre durability were a natural hydraulic lime-based mortar (NLM) mix with a low content of water-soluble salts and a lime-based grouting (NLG) mix containing natural pozzolans and carbonated filler. Tensile tests on impregnated single yarns subjected to wetting and drying cycles by exposure to external weathering were conducted at different ages to quantify these problems. Composite specimens were manufactured by the hand lay-up moulding technique using untreated fibre strips and an NLG matrix. The mechanical response of natural fibre reinforced cementitious (NFRC) composites was measured under tension, and the effect of the matrix thickness was also addressed. Both sisal and flax fibres showed good adhesion with the NLG matrix, making them capable of producing composites with ductile behaviour and suitable mechanical performance for strengthening applications in masonry structures.

1. Introduction

Natural fibres are one of the most studied materials, and because fibres such as sisal, henequen, coconut (coir), flax, bamboo, hemp, jute, wood and palm are strong, lightweight, cheap and non-polluting, they have become attractive alternatives to conventional fibres, e.g., glass, aramid and carbon fibres, as reinforcements in composite materials [1,2]. Furthermore, unlike brittle or mineral fibres, natural fibres exhibit a high degree of flexibility that enables them to bend rather than fracture when processed or being intensively mixed with a matrix. This study focussed on sisal and flax fibres. These fibres, due to their good mechanical properties, may have important implications for many different applications [3–5].

It is well known that cement is the most important building material and is mainly used as a binder in concrete production, but due to its brittleness, low tensile strength and poor resistance to crack opening and propagation, bars or fibres are used for reinforcement. In recent years, scientific interest has been directed toward natural fibre reinforced cementitious (NFRC) composites, and scientists have studied their performance in construction applications. In particular, short fibres, long fibres and textile laminates of cellulosic fibres have been investigated using inorganic matrices [6–8].

Despite encouraging results, some deficiencies in the durability of NFRC composites have been observed. It was observed that composites produced with an OPC (ordinary Portland cement) matrix undergo an accelerated ageing process due to fibre mineralisation and alkali attack related to variations in humidity and are subject to a reduction in post-cracking strength and toughness [9,10]. Furthermore, fibre degradation leads to an increase in fibre fracture and a decrease in fibre pull-out. Several methods have been developed to improve the durability of natural fibres reinforcing cement matrices without yielding satisfactory results. Pre-treating fibres with sodium silicate, sodium sulphite, magnesium sulphate, barium, iron or copper compounds and sulphite salts have not prevented fibre degradation [11]. Impregnating fibres with water-repellent agents and incorporating fly-ash in cement matrices has been observed to reduce fibre mineralisation in "Agave Lechuguilla" and "Hemp" fibres [12,13]; however, studies conducted by Gram using polyvinyl acetate, amide wax, silicone oil, tar, rubber

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latex, asphalt and stearic acid have shown that various methods of fibre impregnation are ineffective for improving durability. [11]. Impregnating fibres with organic compounds has been shown to slightly reduce the brittleness of aged fibres [10]. The best results have been achieved by matrix modification. Both sealing the pores of a matrix by adding small amounts of zinc stearate powder or wax in fresh cement paste and impregnating the hardened matrix with sulphur have been shown to preserve the long-term properties of natural fibres [11]. Similarly, reducing matrix alkalinity by adding silica fume, slag, natural pozzolans or using both high-alumina cement and magnesium phosphate cement does not affect the toughness of composites or the bond between matrices and fibres [11,14,15].

To produce an NFRC composite with improved durability, this study focussed on the use of hydraulic lime-based matrices instead of a Portland cement matrix. The matrices were a natural hydraulic lime-based mortar (NLM) mix with a low content of water-soluble salts specially created for strengthening masonry structures and a lime-based grouting (NLG) mix containing carbonate filler and pure pozzolan with a high content of reactive silica (fly-ash family). These matrices meet the requirements BS EN 998/2 [16] for M15 mortars used in masonry structures.

Using natural hydraulic lime (NHL) mortars guarantees the absence of any OPC binder and therefore the absence of harmful amounts of water-soluble salts, such as calcium sulphates, that are inevitably found in any OPC binder. From a mechanical point of view, the low modulus of elasticity that such binding materials have favours a natural compatibility with existing masonry structures and to an even greater extent with historical buildings and monuments. Moreover, unlike OPC binders, lime-based mortars develop their final mechanical properties after more than 28 days, allowing them to better adapt to masonry structure deformations during the hardening phase.

The use of NFRC composites in civil infrastructure systems is currently rather limited; however, potentially relevant applications such as repair and retrofit structures, strengthening of unreinforced masonry (URM) walls and beam-column connections are currently being developed [6,17–19]. Consequently, a deeper understanding of fundamental mechanisms that govern the mechanics of NFRC composites is important for analysis, modelling and design.

The uniaxial tensile behaviour of natural fibre reinforced cementitious (NFRC) composites was studied. The composites were prepared with untreated bi-directional sisal and flax fabric strips and an NLG matrix; their tensile strength and the effect of matrix thickness were also investigated. A significance level of 5% (95% confidence interval) was considered to indicate statistical significance.

2. Experimental method

The experimental program was as follows:

a) Study of the physical and mechanical properties of flax and sisal fibres.
b) Determination of the mechanical behaviour of mortars.
c) Assessment of fibre durability.
d) Composite sample preparation and study of tensile behaviour.

All results were validated by statistical analysis focussing on the variability of the measured values.

2.1. Materials

Flax, also known as linen (Linaceae family), is an erect annual plant that grows 0.5–1.25 m tall with a stem diameter of 16–3.2 mm. Bast fibres are separated from inner bark by retting, and the ultimate fibre length is between 9 and 70 mm. The use of flax for linen cloth production dates back at least to ancient Egyptian times. Flax grows in moderate climates, and currently, the main flax-producing countries are China, France and Belarus [20]. There are two types of flax: fibre flax and seed flax, which produce thin strong fibres and coarser fibres, respectively [5]. The fibres studied were produced in Italy and supplied as rolls of bi-directional fabric, as shown in Fig. 1a and c.

Like banana, agave and pineapple fibres, sisal fibres are obtained from the leaves of monocotyledonous plants. Sisal plant, or Agave sisalana, grows sword-shaped leaves measuring 1.5–2 m tall. The name of the plant is derived from the Yucatan port of Sisal, from which the plant was exported to the world. Each leaf is approximately 1–2 m long, 10–15 cm wide and 6 mm thick, and an average of 1000 fibres can be obtained from a single leaf. Sisal leaf fibres are bundles that measure 1–2 m long, and the ultimate sisal fibre length is 1–8 mm [20]. Sisal fibres are traditionally used in making twine, rope and woven fabrics for manufacturing bags to transport agricultural products. The sisal fibres studied were extracted from sisal plants cultivated in Colombia. Samples were obtained from transporting bags, and the fabric type and geometry are shown in Fig. 1d and f. A random sampling of fabrics from three different producers was performed, and experimental errors caused by varying the plant source and the fibre morphology were considered.

The matrices used were premixed NHL-based mortars that are CE-marked and comply with the European standard BS EN 459 [21]. The matrices can be classified as masonry mortars type M15 according to BS EN 998/2 [16] and were supplied by specialists in producing and trading materials for building recovery and restoration in Italy. The NLM matrix is a mortar mix with a low water-soluble salt content; there is no presence of chromium VI, and the mortar must be mixed with approximately 22% water according to the product data sheet. Due to its mechanical strength, the NLM matrix can be used for the consolidation of masonry structures and for fibre reinforced cementitious mortar (FRCM) applications. The NLG matrix is a grouting mix with added natural pozzolan and carbonate filler; the matrix must be mixed with approximately 30% water according to the product data sheet and can be used for the recovery and pre-consolidation of ancient brick or stone walls.

The main properties of the matrices provided by the supplier and determined by flexural and compression tests, are presented in Table 1.

2.2. Fibre characterisation

Physical properties such as fibre *diameter*, yarn *density* and *linear density*, yarn *area* and fabric *mass per unit area* were studied. By SEM analysis (see Fig. 2a and b), it was possible to quantify the diameter of single-fibre samples. The testing procedures specified in ASTM: D 792–08 were used to determine the yarn density (ρ) of specimens weighing 1 to 5 g immersed in distilled water. The yarn linear density (T_X) was measured in accordance with EN ISO 1889:2009 [22] and using samples measuring 1 m in length. To determine the yarn area (A_y), the fabric area (A_f) was calculated by Eq. (1) [23] and divided by the number of yarns ($A_y = Af/N_{yarns}$):

$$A_f = b_f \cdot T_X \cdot N_f / (10^4 \cdot \rho) \quad (1)$$

where b_f is the width of the fabric in centimetres and N_f is the number of threads observed in one centimetre of fabric.

According to ISO 3374:2000 (E) [24], the fabric mass per unit area ρ_A was determined using specimens measuring 50 mm × 50 mm, using different weft yarns.