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A novel pull-out device used to study the influence of pressure during processing of cement-based material reinforced with coir

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HIGHLIGHTS

- The development of an original pull-out test on one coir bundle.
- The highlighting of coir fibre as a good candidate to reinforce low cost concretes or stabilized clays.
- The highlighting of process parameters influence (consolidation load) on the pull-out force of coir fibres.

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ABSTRACT

This paper deals with the use of plant fibres, such as coconut, as reinforcement in cementitious materials; such additions modify the mechanical properties of the composite in its hardened state. This enhancement depends on both the fibre's physical and chemical properties. For reinforcement of the mineral matrix, the interfacial properties are paramount in ensuring fibre effectiveness. Fibre reinforced cementitious material can also be enhanced by processing, such as extrusion, that will improve the interfacial bond through the application of pressure.

An original experimental procedure has been carried out to study the influence of cementitious matrix consolidation pressure on interfacial bond strength; samples with a coir bundle were made to be submitted for pull-out tests from the hardened paste. Results show that the fibre–matrix adhesion can be controlled by matrix consolidation in the fresh state. It suggests that high-pressure processing such as extrusion can improve the mechanical behaviour of the interfacial bond between the coir and cementitious matrix leading to better composites mechanical properties. Therefore, the forming process requires careful analysis in order to optimise the reinforcement ability of the natural fibre.

1. Introduction

Over the last decade, plant fibre reinforced cement-based materials have received increasing attention. Compared with synthetic fibres, plant fibres can provide a significant reduction in processing costs and have many environmental advantages: biodegradability, renewability, and a favourable life cycle assessment (LCA) [1]. Plant fibres are widely available in most developing countries and are often derived from agricultural waste, and therefore could be considered as a potentially useful local material.

Among natural fibres, coir is a low cost fibre [2] extracted from the tissues surrounding the seed of the coconut palm (*Cocos nucifera*). The coir's natural function is to protect the nut from breaking, by absorbing the shock when the coconut falls, and from rotting by reducing water penetration. Coir is also the only natural fibre resistant to salt-water exposure. These properties are achieved by means of the complex multilayer microstructure and biochemical composition of coir. The main producers of coconut palms in the world are India, Sri Lanka, Brazil and Southeast Asia. In 2009, worldwide coir production was in the order of 500,000 tons per year [3].

The biochemical composition of coconut fibre depends on its origin and maturity (brown and green coir). Coir is composed of approximately 45% cellulose, which is half that of other commonly used bast fibres such as flax or hemp. Cellulose microfibrils act as reinforcement within the fibre; therefore, the low quantity of cellulose combined with high microfibrillar angle (around 30–50°) induces low stiffness and tensile strength; however, ductile properties could be reached (higher strain at break) [4,5]. A high amount of lignin, between 20% and 59%, is found in coir; this is

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combined with a moderate quantity of hemicelluloses: 8–28% [6–8].

Cement-based materials are currently reinforced with synthetic fibres (steel, glass and synthetic polymeric fibres) to enhance their mechanical properties, notably their flexural strength and toughness. The principal advantage of synthetic fibres is that they are standardised and chemically inert in a cementitious matrix. To reinforce cement-based materials with plant fibres in place of conventional fibres requires a careful analysis, as vegetal fibres absorb water [9,10] and could release extractive compounds into the fresh mix. These compounds can affect the setting time [11,12], prevent cement hydration [13,14] and therefore modify the interface area between fibre and matrix in the fresh state and during hardening [15]. Problems such as a set-retarding or an even set-inhibiting effect when mixing vegetable particles with mineral binders can create a complex Interfacial Transition Zone (ITZ) between lignocellulosic aggregates or fibres and the binder matrix. This ITZ can alter the efficiency of the reinforcement ability.

Plant fibres are used in ordinary concretes and in soil reinforcement [6,16–27], and also in the production of lightweight cement boards [7]. Careful selection of plant fibres, which takes into account its physico-chemical nature, is highly important and has to follow a biomimetic approach. Coir could therefore be a good candidate to enhance cement toughness, but not suitable for producing high performance structural concrete [28].

As a comparison, the strength of the interfacial bonds in plant fibre reinforced thermoplastic composites depends on many parameters, including the fibre's surface biochemistry, roughness and residual thermal stress due to differential expansion between fibre and matrix [29–31]. In the case of fibre reinforced cementitious composites, Bentur and Mindness [32] noted three ways in which fibres can effectively improve the mechanical performance of a brittle matrix: (1) physical and chemical adhesion; (2) friction; (3) mechanical anchoring due to the fibre surface roughness. In addition, they considered that the mechanical properties of cementitious material are significantly improved in the case of low matrix porosity. Low porosity can result from the processing parameters, such as a low water/cement mass ratio (W/C < 0.3), casting pressure [28] or extrusion [33,34].

Direct characterisation of reinforcement/concrete interface bond strength is tedious work and requires specific devices such as pull-out tests [35,36] and a wide range of samples especially when dealing with natural fibres such as cellulose fibres [37], coconut fibres [28] and coconut rope-concrete [3]. Concerning pull-out experiments on fibre-reinforcements, the samples consisted of beams and the fibre's direction was not controlled in the mineral matrix. This makes the data very difficult to interpret. On the other hand, for rope-concrete and steel bar reinforcement, the experimental size is at least one scale higher than for fibre reinforcement. Nozahic and Amziane have developed an interfacial shear strength measurement device on a single sunflower particle during the structural build-up and hardening of a pozzolanic matrix [15]. The device measures the shear strength mobilisation at the particle interface during the hardening of the matrix, as carried out in Amziane et al. [38] with a plate. Using this method, they compared the shear strength mobilisation of treated and untreated sunflowers. In the present study, the fibres will not be chemically treated, and will be dried after washing. The first purpose of the present paper is to directly characterise the coir fibre/cement matrix adhesion and further understand the interfacial phenomena during hardening and at the hardened state of the matrix. The second purpose is to evaluate the optimised processing conditions i.e. consolidation pressure during casting or extrusion on the interfacial properties of the coir fibres/cementitious matrix.

An original pull-out device has been developed with samples whose consolidation pressure has been controlled.

2. Materials and methods

2.1. Materials

2.1.1. Cementitious matrix

The matrix has been chosen to produce an extrudable paste in its fresh state. The paste consisted of a mix of cement and kaolin, with a cement/kaolin ratio of 1:1 by weight, and a water/cement ratio of 0.4. This mixture filled the narrow cavities in the purpose made moulding device [39]. This type of mixture was chosen here for two main reasons: First, kaolin is usually added to cement pastes or mortar for extrusion processes as it provides cohesion in the fresh mix and decreases internal and wall friction inside the extruder. The second reason is to explore the development of cement or lime stabilized clay blocks as low-cost and low-environmental-impact building materials.

The kaolin used was a Powdered Polwhite BB from Imerys® (Kaolins de Bretagne, Ploemeur, France). The specific gravity of the clay was 2.65, the largest clay grain size approximately 40 µm and mean grain size of the order of 9 µm. The specific area of the kaolin powder was 105 cm^2/g. A Portland cement CEM I 52,5N CE CP2 with a specific gravity of 3150 kg/m^3 was used. The specific surface of this cement, measured using a Blaine apparatus, was 3390 cm^2/g. The mean standard compressive strengths (of a standard mortar) of this cement were high: 28 MPa after 2 days and 63 MPa after 28 days of cure.

Compressive and flexural strengths (at 28 days) of the matrix were measured on $40 \times 40 \times 160\ \text{mm}^3$ samples. The mean flexural strength and compressive strength were 5.9 MPa and 18.8 MPa respectively. So the direct tensile strength can be estimated around 3.8 MPa by using Eurocode 2 formula [40]:

$$\sigma_t = \sigma_{bt}/(1.6 - d/1000) \tag{1}$$

With σ_t the direct tensile strength, σ_{bt} the bending strength and d the thickness and its shear strength can be estimated to be around 7.5 MPa by using the Boulekbache et al. empirical formula [41]:

$$\tau = 0.72\sigma_c^{0.8} \tag{2}$$

where σ_c is the compressive strength of the concrete.

2.1.2. Coir fibres

The coir fibres used here came from Indonesia. Two types of fibres were studied: raw fibres from the island of Sumatra and manufactured fibres from the island of Western Java provided by a car-seat padding manufacturer. The two types of fibre were treated in different ways. The treatment of raw fibres was as follows: the coir bales were soaked in water for three days to release compounds and then hackled to extract some of the dust and pith. Manufactured fibres have undergone the same treatment as raw fibres but with a supplementary water cleaning process. Some of the manufactured fibres were also manually rewashed in the laboratory to remove almost all other particles. This latter treatment consisted of immersing the fibres in tap water for 24 h and hand washing to remove any residual chemical compounds.

Regardless of their origin and treatment, the fibres are organised in bundles of single fibres of sufficient length for tensile characterisation and pull-out testing. In addition, bundles of individual fibres require only a few manufacturing operations

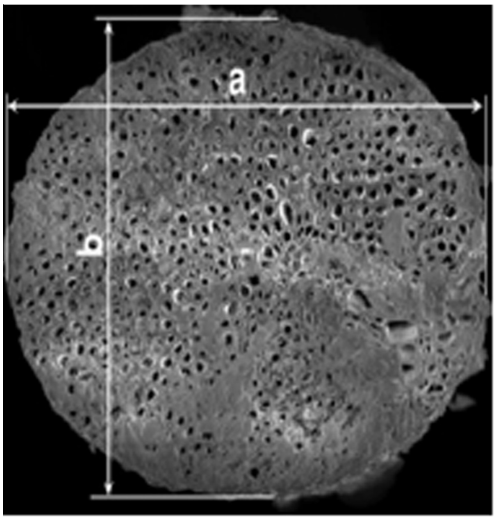

Fig. 1. Typical transversal section of coir bundles (length *a* = 200 µm; *b* = 190 µm).