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Degradation rate of natural fiber in cement composites exposed to various accelerated aging environment conditions

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ABSTRACT

This paper reports the influence of different accelerated aging conditions on degradation of sisal fiber in the matrices of cement composites. Seven aggressive conditions, including dynamic wetting and drying cycling and static environments with various temperature and humidity, were studied. The dynamic wetting and drying cycling presented a superior accelerating effect on both the alkali hydrolysis of fiber's amorphous components and the mineralization of cell wall. The findings indicate that the cyclic changes of humidity at relative high temperature ($\geqslant$70 °C) accelerate the degradation of natural fiber in cement matrix more effectively than the static aggressive conditions.

1. Introduction

In the last two decades, considerable effort has been directed towards the use of various natural fibers, which are available in abundance in tropical and sub-tropical countries, as reinforcement of cement composites for producing cost-effective high-performance construction materials that promote sustainable development [1]. Composites with natural fiber reinforcements are currently considered amongst the most promising structural materials in sustainable engineering technologies [2]. Due to their excellent mechanical properties, natural fiber-reinforced cement composites constitute a new and distinct group of building materials with almost the same performance as that of conventional cement composites reinforced with metallic, organic or synthetic fibers [3]. Among the natural fibers, sisal fiber promises to be a suitable natural reinforcement of cement composites on account of its low cost, low density, high strength and elastic modulus, no health risk, ready availability in many countries, and renewability [4]. The degradation of natural fiber due to the alkaline pore solution in the cement matrix seriously decreases the durability and may cause premature failure of the composite. Therefore, restraining the degradation of natural fibers in a cement matrix has been the central issue that needs to be solved before promoting the widespread application of natural fiber in various composites.

Three basic methods was selected to improve the durability of natural fiber reinforced cement: (i) Modification of cement matrix – using pozzolanic materials as replacement of Portland cement to reduce or clear the calcium hydroxide, which is the primary cause of alkaline environment in cement. Ground granulated blast furnace slag [5,6], silica fume, fly ash, and metakaolin [7–9], "calcined clay" (metakaolin and calcined waste crushed clay brick) [10–12], have been investigated. The results indicate that, owing to their high pozzolanic activity, these amorphous supplementary cementitious materials could effectively consuming the calcium hydroxide in cement matrix and thereby improve the durability of natural fiber-reinforced cement composites. (iii) Special curing treatment for the composites. Lia, Pimentel, and Tonoli et al.'s research shows that polymers [13] and accelerated carbonation (CO_2 saturated environment) [14,15] also contributed to increase durability. (iii) Pretreatment on natural fiber including chemical, physical and physicochemical methods. Silane coating, hornification, autoclave, sodium silicate, potassium silicate [16–19] have been approved can improve the mechanical properties and durability of natural fiber in cement based materials effectively. Compared with method (i), the curing treatment of composites and pretreatment of natural fiber may cause more procedure and high cost, and have to consider the compatibility between modifying agent and cement matrix, as well as its effect on the interfacial properties of fiber–cement. For cement modification, the dosage of the cementitious materials must be determined carefully in order to achieve similar or higher performance compared to the composites prepared only with ordinary Portland cement [17].

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In spite of much research on the mechanical characteristics of sisal fiber as reinforcement of cement based composites, their durability in different aging condition (Table 1), and treatment methods to improve their durability, it is still unknown how various influence factors contribute to the deterioration of sisal fiber and what are the most effective accelerated aging conditions to evaluate their durability in a relatively short period of time. Essentially, to characterize the degradation of sisal fiber in a cement matrix and to determine the most effective accelerated aging condition, four main aspects should be studied and compared: (i) knowledge of the mechanical properties of pure cement paste subjected to accelerated aging conditions (ii) knowledge of the mechanical properties of FRCC subject to accelerated aging conditions, (iii) interfacial behavior between fiber and the cement matrix, (iv) tensile strength loss of strands of sisal fiber in cement subjected to same aggressive methods.

To study the effects of the exposure conditions on sisal fiber direct comparison of neat PC with sisal fiber–cement composites, or direct comparison of raw sisal fiber with alkaline solution treated fiber can be misleading, since cement matrix has three different effects at the same time: (i) the alkaline pore water produced by PC hydration, dissolves the lignin and hemicellulose of fiber, which are sensitive to $Ca(OH)_2$ and high alkalinity [20,25], (ii) alkaline hydrolysis of cellulose molecules, which leads to degradation of molecular chains and then a reduction in degree of polymerization and lower tensile strength [20,25], (iii) the crystallization of lime in the lumen of the fibers and middle lamellae leading to a decrease in the technical fiber flexibility and strength [20,27].

Here we report on the durability of sisal fiber-reinforced cement composites subjected to seven exposure conditions by testing the reduction of flexural properties, which were reasonably well understood and predictable. However, strength of the composites is influenced by a number of factors, including the strength of the matrix, and the matrix/fiber interfacial bond, in addition to the fiber strength [28]. In contrast to the mechanical properties of fiber–cement composites, the strength of the embedded fibers is a direct way to investigate their deterioration. It is logical here to study the tensile properties of sisal fiber immersed in cement matrices as an essential approach to evaluate its degradation rate exposed to the aggressive environments. The two-parameter Weibull distribution model was applied to deal with the variation in tensile properties of the sisal fibers. In addition, the degradation of sisal fiber was also determined by testing composition change, crystallinity indices, and microstructures after accelerated aging treatment, characterized by means of thermal gravimetric analysis (TGA), X-ray diffraction (XRD), and scanning electron microscopy (SEM), respectively.

2. Experimental program

2.1. Characterization of the raw materials

The sisal fibers used in this investigation were extracted from the sisal plant in Madagascar, without knots or other impurities, provided by Bast Fibers LLC of Creskill, NJ, USA. Official methods proposed by the Association of Official Analytical Chemists (AOAC) [29] were followed to determine the moisture content of sisal fiber in quintuplicate: 20 g fiber were oven dried to constant weight in a circulating air environment at 110 °C. Then the fibers were removed from each ceramic crucible and cooled in a glass desiccator. The moisture content was determined by the average of weight loss ratios calculated as follows:

$$\omega = 100\% \times \frac{W_i - W_d}{W_i} \quad (1)$$

where ω is the moisture content in percent, W_i is the initial weight of sisal fiber, and W_d is the residual weight of sample after drying and cooling.

The raw sisal fiber with a beige color features a moisture content of 10.4 ± 3%, with an average diameter of 202.5 μm, which was determined by scanning electron microscope. Among the three main organic components, hemicellulose [30] and lignin [31] are amorphous with relative low polymerization degree, so they have a higher hydrolysis rate and solubility in alkaline medium than cellulose, which is the main reason for the degradation and relative low durability of sisal fiber in cement matrix. The content of these three compositions determines the mechanical properties and stiffness of fiber and its degradation rate. The procedure used to determine the content of cellulose, hemicellulose and lignin according to the methods proposed by Xu et al. [32] and Viera et al. [33] was followed. The lignin content was determined using the Klason method [34]. The physical characteristics and chemical analysis on clean and dry sisal fibers are summarized in Table 2.

The microstructure of the sisal fiber was performed on a Hitachi 4700 scanning electron microscope (SEM) under an accelerating voltage ranging of 5.0 kV. Fig. 1a and b shows the microstructures of surface and cross section of a sisal fiber, respectively. The fiber's rough surface assures a desirable bond strength between fiber and

Table 1
Overview of durability of sisal fiber and sisal fiber–cement composites investigated.

Study object	Composite	Treatment medium[a]					Aging conditions[b]	Reference
		1	2	3	4	5		
Sisal fiber	–	●	●	●	●		RT	[20,1]
		●	●	●			W&D	[1]
Sisal–cement composites	CH free	●					W&D	[10]
		●					HT	[15]
		●					W&D	[15]
		●					F&T	[15]
		●					WDC	[15]
	Mortar	●		●			RT	[20–22]
		●					W&D	[10,20,23,24]
						●	OD	[20,21]
	Concrete	●					RT	[25]
		●					HT	[26]
		●					W&D	[25,26]
						●	OD	[25]

[a] 1 – Tap water; 2 – Solution of calcium hydroxide; 3 – solution of sodium hydroxide; 4 – Cement saturated water; 5 – Opening air.
[b] RT – Room Temperature; HT – High Temperature; W&D – wetting and drying cycle; F&T – freezing–thawing cycles; WDC – Repeated wetting–drying-carbonation, OD – Outdoor weathering.