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Utilization of rice husk ash in green natural fiber-reinforced cement composites: Mitigating degradation of sisal fiber

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ABSTRACT

This study aims to explore a novel approach to improve the durability of sisal fiber in cement composites by using by-products of biomass power plant: rice husk ash (RHA). The effects of two RHAs on the fiber's degradation were investigated indirectly by testing flexural behavior of sisal fiber-cement composite beams and directly by means of uniaxial tensile properties, thermal decomposition, crystallinity indices and microstructures of embedded fibers, after exploring up to 30 wetting and drying cycles. Allowing the distinction between pozzolanic activities, the efficiency of RHA was compared with two fly ashes and combinations of two clay minerals (metakaolin and nanoclay) with a cement substitution level of 30 wt.%. The durability of composites was improved considerably by incorporating RHA owing to the mitigation of fiber's degradation: the ultimate tensile strength and cellulose fraction of embedded fibers were improved by 384% and 45%, respectively. Fine RHA and the combination of metakaolin and nanoclay yield similar efficiency in mitigating degradation of sisal fiber, and are better than the coarse RHA and fly ashes. The correlations between cement hydration and sisal fiber degradation were analyzed. The results indicate that degree of hydration, calcium hydroxide content and alkalinity of the cement matrix play decisive roles in alkali attacks and mineralization of fiber's cell walls.

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1. Introduction

The increasing environmental concern and awareness of industrial pollution are forcing the construction and manufacturing industries to search for innovative materials that are reliable, sustainable and can replace conventional synthetic fibers as reinforcement of structural materials. Natural fibers, such as sisal, jute, cotton, flax, hemp, and kenaf, have already been considered as potential alternatives to steel fiber, asbestos fibers, glass fiber and polymer fibers, given their good reinforcing effect, environmental friendliness and ready availability in fibrous form and by the fact that they can be extracted from plant leaves at low cost [1]. Natural fiber reinforced composites also offer additional advantages such as reduced dependence on non-renewable energy/material sources, lower pollutant emissions, lower greenhouse gas emissions, enhanced energy recovery, and biodegradability [2]. Therefore, in the last four decades, considerable efforts have 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 to produce cost-effective construction materials that promote sustainable development [3]. Composites with natural fiber reinforcements are currently considered among the most promising structural materials in sustainable engineering technologies [4]. Among various 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, high output, and renewability [5]. With a recorded fracture toughness values 50–60 times that of the matrix material, Coutts [6] proposed that sisal pulp reinforced mortars would be suitable for use in construction, due to their readily availability in large quantities in many countries and they represented a continuous renewable source.

Fig. 1 illustrates the molecular structures of the three main components of natural fibers: cellulose, hemicellulose, and lignin. Cellulose is a linear polymer made of glucose subunits linked by β-1,4 bonds, and the basic repeating unit is cellobiose [7]. The main chain of hemicellulose is characterized by a β-1,4-linked-D-xylopyranosyl, which carries a variable number of neutral or uronic monosaccharide substituents [8]. Lignin biosynthesis is a kind of three-dimensional network heteropolymer, which consists of the β-O-4 ether linkages, followed by other types of ether and C—C linkages such as α-O-4, β-β, β-5, and 5–5 [9–11]. Among the three main natural polymers, hemicellulose and lignin are amorphous, and cellulose, owing to its high tensile strength [7], is the main structural component, which is responsible for the resistance of plants to mechanical stress.

With the increasing attention on utilization of sisal fiber in construction materials, a systematic investigation of engineering properties of sisal fiber-reinforced cement composites (SFRCC), such as tensile

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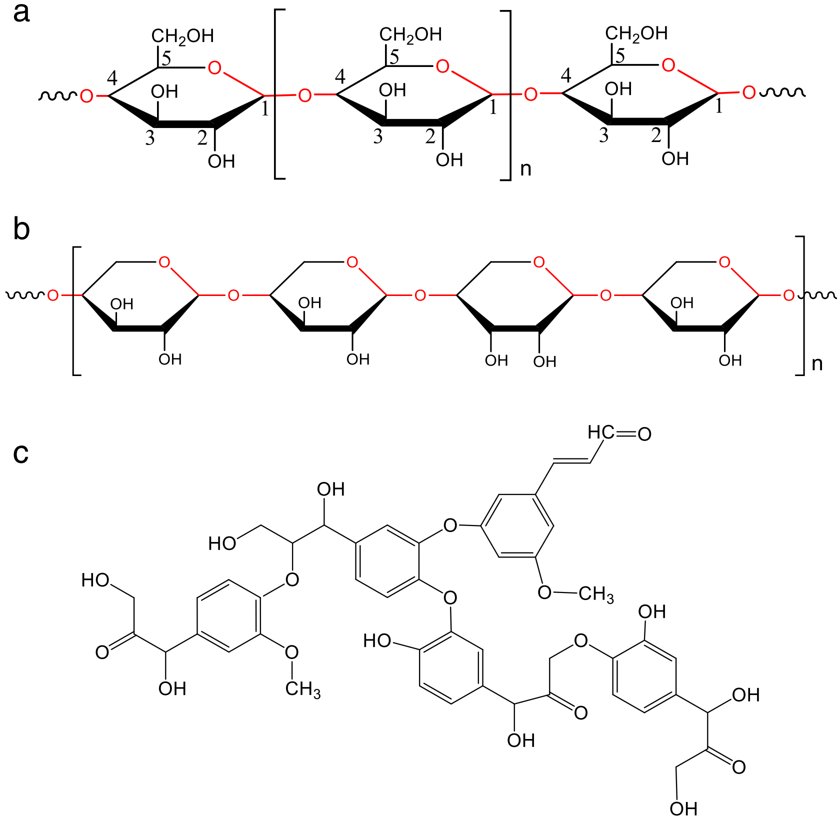

Fig. 1. Structure of cellulose (a), hemicellulose (b), and lignin (c).

properties [12,13], impact strength [14,15], drying shrinkage [12], and interfacial bond between fiber and cement matrix [16], was performed. However, in spite of sisal fiber's advantages, its efficiency in cement based materials is limited by its relatively low durability in alkaline environments, which means it loses strength when used as reinforcement of a cement matrix exposed to service environments [17]. When exposed to the alkaline matrix of Portland cement (PC), their mechanical properties can deteriorate due to alkaline hydrolysis, thereby compromising the durability of natural fiber-reinforced cement composites [18]. 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.

The replacements of PC by calcined clay (metakaolin and calcined waste crushed clay brick) [19–21] and 50 wt.% metakaolin [22] have recently been verified to improve the durability of SFRCC significantly. By producing a matrix totally free of calcium hydroxide (CH), no cement hydration products were observed to migrate to the fiber lumen, middle lamella and cell walls to cause embrittlement. Silica fume [7,23], fly ash [24], ground granulated blast furnace slag [25–27] and metakaolin [24, 28] show similar effects on improving the durability of natural fiber-reinforced cement composites by reducing the alkalinity of cement matrix. Recent investigations show that sealing the matrix pores by small beads of wax or zinc stearate powder [23] and acrylic polymer [29], and accelerated carbonation of the matrix (CO_2 saturated environment) [30–32] also contribute to an increase of durability. In addition, hornification [33] and slurry pretreatment of the fiber [32] were also proven to be effective ways to restrict the degradation of natural fibers. Compared with cement matrix modification, pretreatment of natural fiber requires more effort and higher cost, and needs to consider the compatibility between modifying agents and the cement matrix, as well as its effect on the interfacial properties of fiber-cement. Therefore, it is more logical to arrest the degradation of sisal fiber and to improve the durability of SFRCC through modifying the hydration of cement by reducing the content of $Ca(OH)_2$ and the alkalinity of matrix.

Rice husk ash (RHA) is a by-product of the burning of rice husk. More than 100 million tons of rice husks is produced each year as a waste material in agricultural processes. In order to rationally dispose this renewable biomass, power plants fueled by rice husk have experienced an unprecedented development in several countries, such as Thailand, China, Philippines, India, Surinam, Malaysia, and the United States. Rice husk can convert about 20% of its weight to RHA after incineration [34]. Therefore the disposal of rice husk ash has become an important issue. Given the high amorphous silica content and high specific surface area, in recent years there has been increased interest in the use of RHA as a partial cement replacement material to supply high pozzolanic reactivity (Fig. 2). As a kind of renewable supplementary cementitious materials (SCM), RHA has been elucidated to show desirable modifying effects on properties of cement composites, such as higher compressive and flexural strengths [35,36], enhanced workability [37], declined bulk density [38,39], improved durability [40,41], increased degree of cement hydration at later age [42], and reduced amount of calcium hydroxide (CH) [43]. However, the effect of RHA on degradation of natural fiber in the matrix of cement composites still lacks in-depth and systematic investigation.

Ziraba et al. [44] reported that that a 45% replacement of PC by RHA can minimized the deterioration of sisal fiber-mortar composites subjected to wetting and drying cycles by altering pore solution compositions. The incorporation of RHA generates benefits related to the reduction in clinker consumption and the decrease of matrix alkalinity, and consequently reducing natural fibers' degradation [45]. In addition, the partial substitution of RHA for cement also contributes to a protection of the link between individual fiber cells and to slow down the embrittlement process of natural fiber composite [46]. The positive effects of RHA on improving durability of natural fiber-reinforced

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