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Improving degradation resistance of sisal fiber in concrete through fiber surface treatment

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ABSTRACT

As part of an ongoing effort to improve the sustainability of reinforced concrete, recycled concrete aggregate is being considered together with natural fibers such as sisal fiber as replacement of synthetic reinforcement. Since natural fibers are known to undergo potential deterioration in the alkaline cement matrix especially in outdoor erosive environment, they need to be treated to improve their durability. This paper describes two such methods (thermal and Na_2CO_3 treatment) and evaluates their effects on the degradation resistance of sisal fiber and durability of sisal fiber-reinforced concrete with recycled concrete aggregate. Concrete specimens were subjected to cycles of wetting and drying to accelerate aging. The microstructure, tensile strength and Young's modulus of sisal fiber as well as the weight loss of the composite were evaluated. Of primary interest were the effects on compressive and splitting tensile strength of sisal fiber-reinforced concrete. Thermal treatment and Na_2CO_3 surface treatment were shown to improve the durability of the composite as measured by splitting tensile strength by 36.5% and 46.2% and the compressive strength by 31.1% and 45.4%, respectively. The mechanisms of these two treatment methods were also analyzed. The thermal treatment achieved improvement of cellulose's crystallization, which ensured the initial strength and improved durability of sisal fiber. A layer consisting of calcium carbonate sediments, which protects the internals of a fiber from the strong alkali solution formed in the cement hydration process, was formed and filled in pits and cavities on the Na_2CO_3 treated sisal fiber's surface to improve their corrosion resistance and durability and reduced the detrimental effects of Na^+ ions on concrete.

1. Introduction

Concrete is the most widely used construction material worldwide. Because of its adaptability and low cost it lends itself to a wide range of applications, from buildings to bridges and other infrastructure facilities. Its main disadvantage is its low tensile strength and fracture toughness. In order to compensate for the low tensile strength, it has been traditionally reinforced primarily with steel reinforcing bars. Its toughness is effectively improved with the use of uniformly distributed and randomly oriented short fibers to control the initiation and growth of microcracks [1]. Fibers made of a variety of materials, such as steel, glass, polypropylene, and other polymeric materials are known to lead to substantial improvements in fracture toughness. Most of these fibers have some disadvantages, though. For example, steel and carbon fibers are relatively expensive, asbestos fibers are known to cause serious health problems, and the environmental footprint of many synthetic fibers can be substantial. Natural fibers, on the other hand, can improve the sustainability of cement composites by being renewable and are considerably less costly. Composites with natural fiber reinforcements are currently considered amongst the most promising structural materials in sustainable engineering technologies [2]. There has been a growing interest in recent years in utilizing natural fibers in low-cost construction. They have served for useful purposes for a long time, but their application as concrete reinforcement is of more recent origin. In countries where natural fibers of varying types are abundantly available, it makes economical sense to search for appropriate technologies to utilize such fibers as reinforcement of cement composites for housing and other construction. Natural fiber-reinforced concrete (NFRC) constitutes a new and distinct group of building materials which exhibit almost the same performance as that of conventional concrete composites reinforced with metallic, organic or synthetic fibers [3]. In most cases the fibers serve primarily as crack arresters that slow the growth of flaws in the concrete matrix under stress and delay ultimate failure. Whereas the tensile and compressive strengths of such cement composites are barely affected, the increase in fracture toughness can be substantial, with the result of greatly improved behavior under cyclic loads.

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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].

A sisal plant produces between 200 and 250 leaves before flowering [5], each of which contains approximately 700–1400 fiber bundles with a length of about 0.5–1.0 m [6]. The sisal leaf consists of a sandwich structure composed of approximately 4% fiber, 1% cuticle, 8% dry matter, and 87% water [7]. Nearly 4.5 million tonnes of sisal fiber are produced every year throughout the world. Tanzania and Brazil are the two main producing countries [8]. The important properties of sisal fibers reported in the literature are summarized in Table 1.

In spite of sisal fiber's advantages, its usefulness in concrete is limited by the relatively low durability in Portland cement concrete, which means it loses strength when used as reinforcement in a cement matrix exposed to weathering [3,9]. When exposed to the alkaline pore solution of Portland cement concrete their mechanical properties can deteriorate due to the alkaline hydrolysis, thereby compromising the durability of natural fiber-reinforced cement composites [10]. According to the TGA analysis, the constituents of sisal fiber are mainly cellulose, lignin and hemicellulose [11]. Because the low corrosion resistance of lignin and hemicelluloses that exist in the middle lamellae of the fibers and cellulose molecules in high alkali environment [12,13], sisal fiber gradually degrade and lose its reinforcing capacity in cement matrix in later stage of service life.

These deterioration mechanisms have attracted the interest of researchers, and substantial efforts have been undertaken in recent years to improve the degradation resistance of sisal fiber in alkaline environment. Fibers were treated with alkali solutions to partially remove the lignin, hemicelluloses and other residues from the fiber surface [14–16]. Barreto et al. [17] treated sisal fibers with NaOH solutions (5% and 10%) at temperatures from 60 to 70 °C for 6 h. Such treatment appears to cause a defibrillation and consequently surface cavities. The results obtained by Yang et al. [14] showed that H_2SO_4 treatment, conjoint H_2SO_4 and alkali treatment both reduce the ultimate strength and Young's modulus of sisal fiber, with little change of elongation at failure, whereas benzol/alcohol dewax treatment can improve the ultimate strength and elongation. Rong et al. [18] studied acetylated and organosilane coupling agent treatment, which can improve flexural strength of unidirectional sisal-reinforced epoxy composites. They showed that thermal treatment improves the crystallinity of cellulose, the tensile strength, Young's modulus, and the elongation at failure by 5.4%, 36.8%, 3.3% and 40.0%, respectively. Claramunt et al. [19] studied the effects of previous hornification of vegetable fibers. In the research work reported by Kuruvilla et al. [20], dicumyl peroxide was used as a kind of modification of sisal fiber in low density polyethylene (LDPE). The unidirectional tensile strength, Young's modulus and elongation at failure of fiber-reinforced LDPE were improved by 34.3%, 34.7%, and 300%, respectively. Also isocyanate treatment, benzoyl peroxide and permanganate treatment, as well as mixed treatments, were studied. Almost all of these treatments referred to above have been studied specifically to improve the properties of sisal fiber embedded in polymer matrices, not in concrete.

Except the durability, the interfacial bond between fiber and concrete matrix was also considered as an additional factor, which affect the mechanical properties of composite. It's well known that natural fiber reinforced cement composites fail by a combination of fiber fracture and pull-out [21,22], however, fiber pull-out is the principal mechanism of failure [23]. Awwad, E. [24] presented that the use of fibers in concrete without prior treatment is not possible because the bond is weakened and the tensile properties are not enhanced in the presence of fibers. The interfacial bond in

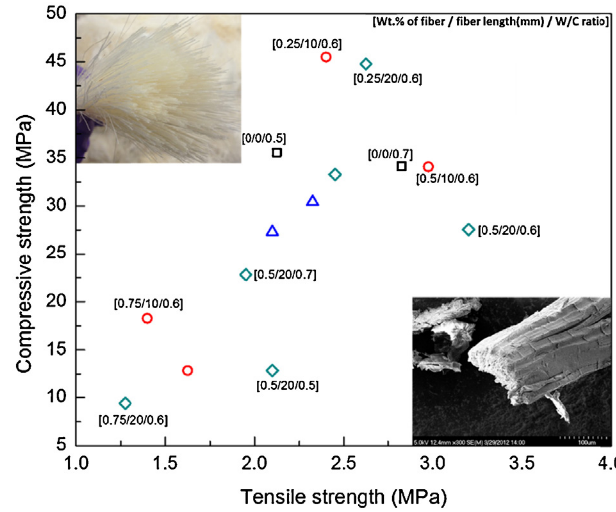

Fig. 1. Effects of fiber content, fiber length and water/cement ratio on the mechanical properties of concrete.

cement-based fiber composites can be affected by several variables such as the water/cement ratio [25], porosity, fiber shape and morphology [26], and compaction [27], and various approaches to promote the bonding strength have been investigated. R. Coutts [28] modified the interfacial bond between wood fiber and cement matrix using coupling agents, and the results indicated that the flexural strength and fracture energy of the composites were significantly improved. According to Paul R Blankenhorn [29], both the acrylic emulsion and alkylalkoxysilane surface treatments of natural fiber provided improvements in the bending strength of fiber–cement composites. Air curing was proposed by R. Coutts [30] and the results showed that this physical method effectively improve natural fiber-cement matrix interface properties by interlocking fibers with the growing cement hydrate needle products. As has been detailed above, several methods for improving natural fiber-cement interfacial property have been developed, however, these methods introduce a step into the mechanical property improvement process, and they are unable to restrain the deterioration of natural fiber in the alkaline environment of concrete. In this sense, it is of interest to enhance both interface and durability of natural fiber in concrete by one surface treatment method.

It was the purpose of the work presented here to identify treatment methods that improve the corrosion resistance of sisal fiber in the alkali environment of concrete and the durability of natural fiber reinforced-concrete in aggressive environment. This work was part of a larger ongoing project at Columbia University to develop an ultra-low cost housing system that utilizes concrete composed of ingredients that are not only of low cost but also environmentally friendly and sustainable. This is the reason why recycled concrete was used exclusively as aggregate, thereby improving the sustainability of the composite and lowering the cost at the same time.

2. Materials and production method

2.1. Materials

2.1.1. Sisal fiber

In this project, a dry and subtly combed sisal fiber from Madagascar, without knots or other impurities, provided by Bast Fibers LLC of Creskill, New Jersey, was used. The moisture content of these fibers was 10.4 ± 3%. From the previous experiment results, shown as Fig. 1 which give the effects of sisal fiber's content, fiber length, and water/cement ratio on compressive strength of concrete, as