Cement & Concrete Composites 31 (2009) 721–730

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Cracking mechanisms in durable sisal fiber reinforced cement composites

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ARTICLE INFO

Article history:
Received 21 February 2008
Received in revised form 13 March 2009
Accepted 24 July 2009
Available online 30 July 2009

Keywords:
Natural fiber
Cement composites
Crack formation
Image analysis

ABSTRACT

Fiber reinforced cement composite laminates with long sisal fibers were manufactured using a cast hand lay up technique. A matrix with partial cement replacement by metakaolin and calcined waste crushed clay brick was used in order to improve the durability aspects. Mechanical response was measured under tension and bending tests while crack formation was investigated using a high resolution image capturing procedure. Crack spacing was measured using image analysis and correlated with the applied strain under both the tensile and bending response. Various stages of loading corresponding to initiation, propagation, distribution, opening, and localization of a crack system in the specimen are discussed. The effect of flexural cracking on the location of neutral axis during the bending tests was measured using strain-gages.

1. Introduction

The need for economical, sustainable, safe, and secure shelter is an inherent global problem and numerous challenges remain in order to produce environmentally friendly construction products which are structurally safe and durable. This paper addresses the development of strain hardening cement composites using sisal, a natural fiber with an average tensile strength of 400 MPa and strain at failure of 3% as reinforcement in concrete. These composites provide an exciting opportunity to the housing construction industry and may generate economic incentives particularly in developing countries since the availability and production of composite reinforcement requires a low degree of industrialization. Furthermore, in comparison to the most common synthetic reinforcing fibers, natural fibers require less energy to produce and are the ultimate green products.

Natural fibers have been traditionally used as a substitute of asbestos in the form of chopped, short, and/or in a pulp form for the production of thin elements for roofing and cladding. An increased use of these materials for applications such as cladding, internal, and external partitioning walls is possible and may lead towards the development of low cost-sustainable materials [1–8]. Natural fiber cement composites have been mainly reinforced by short or pulp cellulose fibers. Nevertheless, their application in the construction industry is still quite limited due to the lack of understanding in how to improve the durability while making ductile materials.

Continuous fiber reinforced cement based composites are a new class of sustainable construction materials with superior tensile strength and ductility [9,10]. The enhanced strength and ductility is primarily governed by the composite action that exists such that the fibers bridge the matrix cracks and transfer the loads, allowing a distributed microcrack system to develop. These materials are strong enough to be used as load bearing structural members, in applications such as structural panels, impact and blast resistance, repair and retrofit, earthquake remediation, strengthening of unreinforced masonry walls, and beam-column connections [11].

Vegetable fiber cement composites produced with ordinary Portland cement matrices undergo an aging process in humid environments during which they may suffer a reduction in post-cracking strength and toughness. The aging process is due to fiber mineralization and results in reducing the tensile strength of fibers and decreasing the fiber pullout ligament after fracture. This mineralization process is a result of migration of hydration products (mainly $Ca(OH)_2$) to the fiber structure. Efforts to develop durable and structural cement composite laminates reinforced with long sisal fibers has shown much promise recently [12,13]. A recently developed matrix that lowers Calcium Hydroxide production (only 50% Portland cement as compared to conventional systems) increases the long term durability of natural fiber, reduces CO_2 emissions, and presents an economical and sustainable approach. The modified matrix has shown no strength and toughness reduction in accelerated aging tests [13]. The present study is focused on the implementation of this matrix in lieu of a Portland cement matrix which invariably results in a low durability performance record [13].

A fundamental understanding in toughening mechanisms and how cracks form and propagate in the brittle matrix composites

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doi:10.1016/j.cemconcomp.2009.07.004

is important for optimization, analysis, and design. The cracking mechanism in a multilayer sisal fiber reinforced composite is addressed in this paper. An experimental procedure was used to monitor and analyze the distributed cracking formation, the stiffness degradation, and the crack spacing distribution functions during flexural bending and tensile tests. Photographs of the crack formation at periodic strain levels were processed by image-analysis techniques and correlated with the applied stress levels. The differences between the flexural results and tensile results were studied by comparing the strain distribution profiles in the loading configuration. In the tension test, the strain distribution was verified by the uniform nature of cracking across the specimen, whereas in the flexural test, the movement of the neutral axis was experimentally determined by strain-gages attached to compression and tensile composite surfaces. Analysis of the flexural strains allows a direct comparison between material properties obtained from tensile and flexural data.

2. Experimental program

2.1. The sisal fiber

The sisal fibers used in this investigation were extracted from the sisal plant in a farm located in the city of Valente, state of Bahia – Brazil. The sisal plant leaf is a functionally graded composite structure which is reinforced by three types of fibers: structural, arch, and xylem fibers. The first occurs in the periphery of the leaf providing resistance to tensile loads (see Fig. 1). The others present secondary reinforcement, occurring in the middle of the leaf, as well as, a path for nutrients. The fibers were characterized earlier to have an irregular cross-section with mean area ranging from 0.04 to 0.05 mm^2 and a mean density, elastic modulus, and tensile strength of 0.9 g/cm^3, 19 GPa and 400 MPa, respectively [14].

Sisal fibers contain numerous elongated fiber-cells which are about 6 to 30 μm in diameter [15]. The microstructure of the

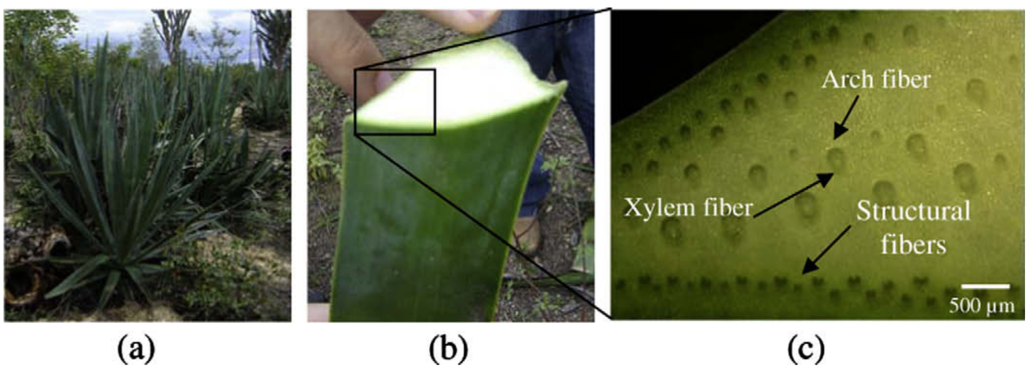

Fig. 1. The sisal plant (a), leaf (b) and leaf cross-section showing different fiber types (c) [14].

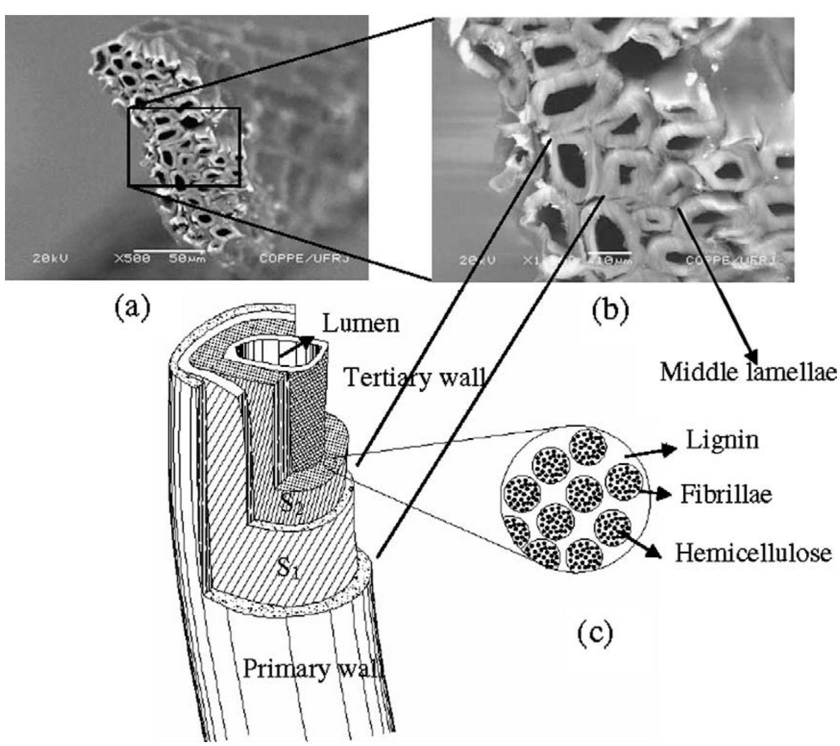

Fig. 2. Fiber-cell microstructure: (a) cross-section view showing the fiber-cells, lumens and middle lamellae, (b) magnification of the cross-section and (c) schematic drawing showing the different layers of an individual fiber-cell [13].