

EFFECT OF PULLOUT ON MECHANICAL BEHAVIOR OF NATURAL FIBER-REINFORCED EARTH-BASED COMPOSITES

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Abstract

This study presents an experimental investigation on pullout tests of natural fiber (straw) from earth-based matrices. A specially designed single fiber pullout apparatus was used to provide a quantitative determination of interfacial properties that are relevant to toughening brittle materials through fiber reinforcement. The parameters investigated included a specially designed high strength earth-based matrix comprising of 60% laterite, 20% clay and 20% cement. The mediums from which the fiber was pulled included a control mortar mix without fibers and a mortar mix with 5, 10 and 20 percent fibers by volume. The results indicate that increasing the fiber embedment length and the fiber volume fraction in the cement matrix increase the peak pullout load and the pullout work. The implications of the results are then discussed for potential applications in the design of robust earth-based building materials for sustainable eco-friendly homes.

Keywords: Pullout; Interfacial properties; Toughening

1.0 Introduction

The toughening provided by fibers in fiber-reinforced composites via crack bridging depends significantly on the mechanical properties of the matrix, the fibers, and the fiber-matrix interface [1]. The interfacial strength between the matrix and the fibers is often the key to composite toughening and fracture properties [2]. Prior work has also shown that the best overall toughening of ceramic matrix composite may require debonding and frictional sliding to occur at the interfaces between the fibers and matrix [1].

The mechanics of interfacial de-bonding have been studied by number of authors [3-5]. These studies have shown that the initial elastic deformation is truncated by load drops, corresponding to the onset of interfacial debonding. This is followed by fiber pull-out, during which frictional stresses and residual clamping stresses resist the pull-out of the fibers from the matrix materials [6]. In brittle-matrix composites, the interfacial strengths are often characterized by the debond stress or the frictional pull-out stress [7]. The interfacial strengths also have a strong influence on composite strength and composite fracture toughness

[8]. This has motivated several researchers to study the fiber/matrix interface properties in such composites. An investigation by Marshall et al. and other authors was focused at determination of the force required to slip a fiber through a matrix [9, 10]. Other efforts centered on measuring interfacial strength via fiber pull-out tests [11, 12]. For cement matrix composites, there have also been considerations of load-deflection behavior in fiber pull-out process [13-15].

During the fiber pull-out process, Kelly and Tyson [2] showed that the force required to pull out a stiff fiber from a softer metal matrix is a linear function of the embedded length of the fiber in the matrix. In a related study, Greszczuk [16] developed a relationship between interface strength as a function of the embedded length of the fiber.

In modeling fiber pullout, characterization of fractional stress of fiber embedded in a matrix has been an open issue for a long time [17]. Most studies focus directly on measuring frictional stresses using theoretical models that are guided by experimental observations and measurement. Hence, depending on

experimental results, most authors assume either a constant friction stress or coulomb friction [18]. A review of prior work on the modeling of fiber pull-out behavior, can be found in Ref. [19].

However, there have been no prior studies of the interfacial strengths of earth-based natural fiber composites that are being developed for structural applications in affordable housing. This will be explored in this study, using a combination of experiments and analytic models. These will be used to study the fiber pull out behavior of earth-based composites. The toughening due to fiber pull-out will also be modeled using crack-tip shielding concepts. The implications of the models will then be discussed for the design of robust/sustainable housing.

2.0 Materials Used

Natural fiber-reinforced earth-based composites were produced from locally sourced materials obtained directly from their deposition sites in Abeokuta, Ogun State, South-West Nigeria. These included: laterite (lateritis)[20], clay (which was used as a stabilizer) and straw fibers (*Andropogon virginicus*) [21]. The clay was obtained from Abeokuta, Ogun State, Nigeria. The fine-grained, clay (consisting primarily of hydrated silicates of aluminum with traces of iron oxide) also serves as a binder in the predominantly lateritic matrix[22]. Type I Ordinary Portland cement (composed of calcium silicate) was procured from Lafarge cement factory, Ewekoro, Ogun State, Nigeria. The cement was also used as a binder.

3.0 Sample Preparation

The fiber pull-out specimens had a prismatic shape of 25 mm x 25 mm x 100 mm. Matrix materials were dry mixed manually with the aid of a hand trowel. This was done for about 2 minutes (for homogenization), followed by the addition of water at water-cement ratio of 0.5. The mixtures were then molded to the stipulated shapes. The surfaces of the fibers were cleaned and embedded at the center of the specimen. The natural fibers were then aligned with a fixture, without any significant pre-tension, prior to molding. The samples were then prepared in a mold using a hydraulic press at a pressure of 2 MPa for 5 minutes. This pressure was chosen after optimization. The samples were cured for 28 days in air at average temperature of 23°C and an average relative humidity of 80%.

4.0 Experimental Procedures

The stages of the experiments are presented schematically in Figure 5.1. This shows a schematic diagram required for the study of the interfacial strengths of natural fiber-reinforced earth-based composites. The effects of fiber embedment length and fiber volume fraction (on the fiber pull-out characteristics) were considered. Three different fiber embedment lengths: 15 mm, 20 mm and 25 mm were tested. Three different fiber volume fractions (5%, 10% and 20%) were used within the matrix.

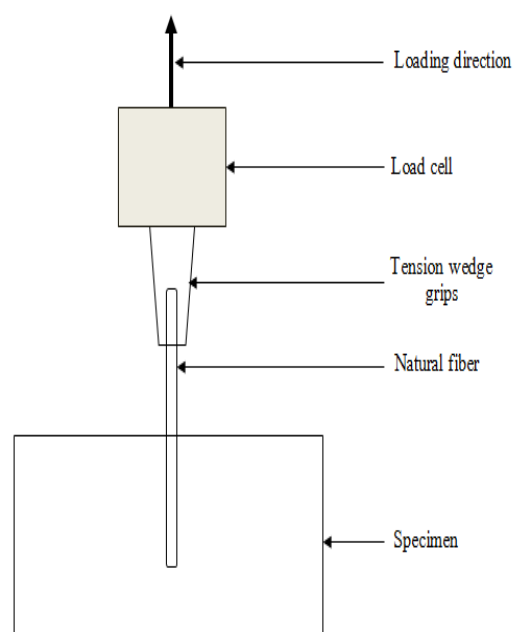


Figure 1: Schematic diagram of the pullout specimen

An Instron 3360 series (Norwood, MA, USA) electro-mechanical testing machine was used to obtain plots of load versus displacement of the embedded fiber. This was done at a loading rate of 3.3 N/s. The samples were tested at room temperature with average relative humidity of 65%. The other ends of the embedded fibers were held firmly by tension wedge grips attached to a 2 kN load cell, while the specimen was fixed securely to the Instron with the aid of G-clamps, as shown in Figure 5.2. The fiber displacement was monitored using an in-situ optical microscope.

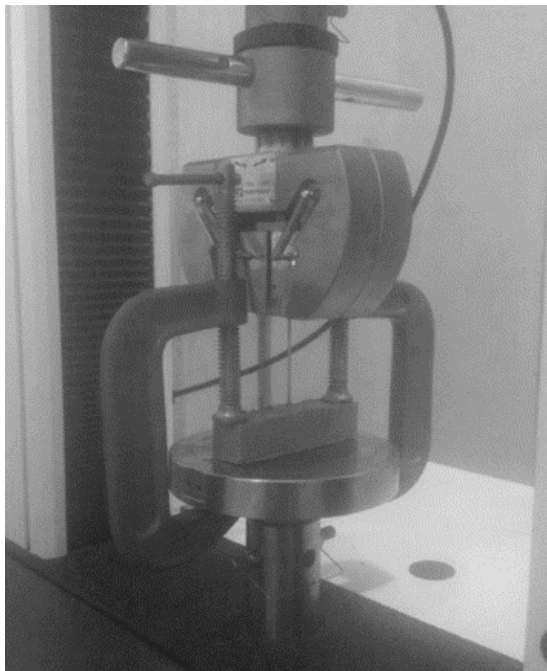


Figure 2: Experimental setup for pullout of natural fiber from earth-based cementitious matrix

5.0 Results and Discussion

The results of the singlefiber pull-out tests are presented in Figures 5.6, 5.7 and 5.8. The pullout curves obtained in this study can be divided into three stages, as obtained in prior work on other ceramic matrix composites in the literature. These include: (i) a linear elastic deformation stage; (ii) a partial fiber debonding stage, and (iii) a frictional pull-out stage. This is shown schematically presented in Figure 5.5. Frictional bond strength values were also calculated by dividing the maximum pullout load by embedded fiber surface area.

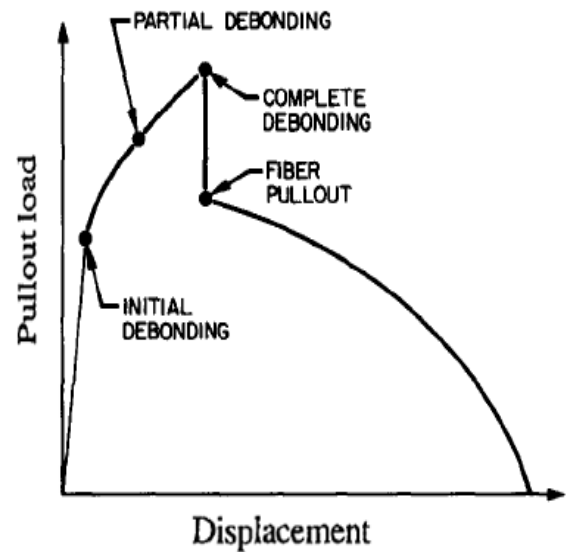
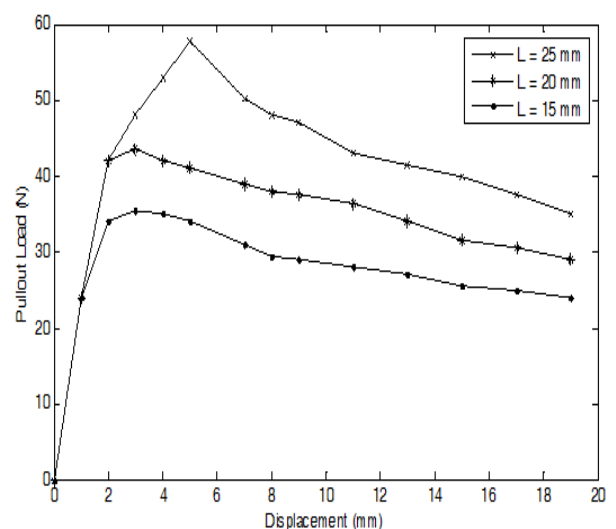
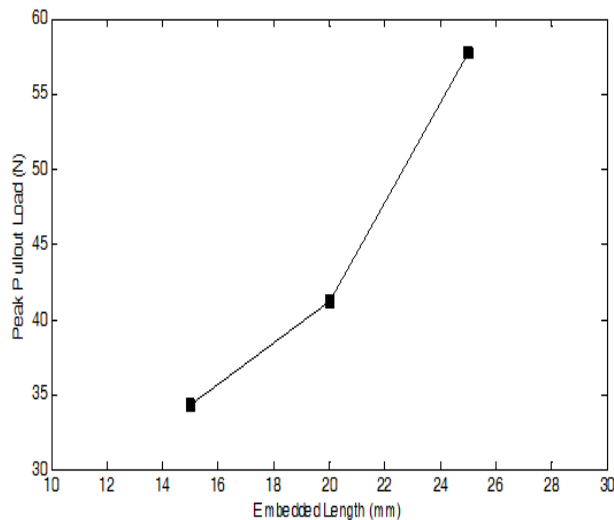


Figure 3: Schematic diagram showing load-displacement relationship for embedded fiber during fiber pullout test

All specimens tested failed by fiber debonding and pullout. Figure 4 shows the effect of embedment length on peak pullout load. A significant increase was observed in the peak fiber pull-out load (while keeping other parameters constant) with increasing fiber embedment length (from 15 mm to 25 mm). This is attributed to the increase in the fiber/matrix contact area that occurs with increasing fiber embedment length.



(a)



(b)
Figure 4: (a) Effect of embedment length on the pullout behavior of natural fiber from earth-based cementitious matrices and (b) Effect of fiber embedment length on peak pullout load.

Meanwhile, Figure 4b shows that the peak fiber pull-out load does not appear to be directly proportional to the fiber embedment length. This is because the onset of fiber debonding corresponds to the condition at which the interfacial crack driving force is equal to the interfacial fracture toughness at the local mode mixity. Since this will depend non-linearly on the internal crack lengths and elastic properties of the materials, the fiber pull-out loads are unlikely to exhibit a linear dependence of the fiber embedment length.

The results (Figure 5) obtained show that fiber pull-out occurred with a constant frictional bond stress at the interface between the fiber and earth-based cementitious matrices. An average frictional bond strength of about 0.34 ± 0.02 MPa was obtained for earth-based cementitious matrix. Other results obtained for composites (with vary fiber fractions) will be used in the next section to predict the toughening due to debonding and fiber pull-out.

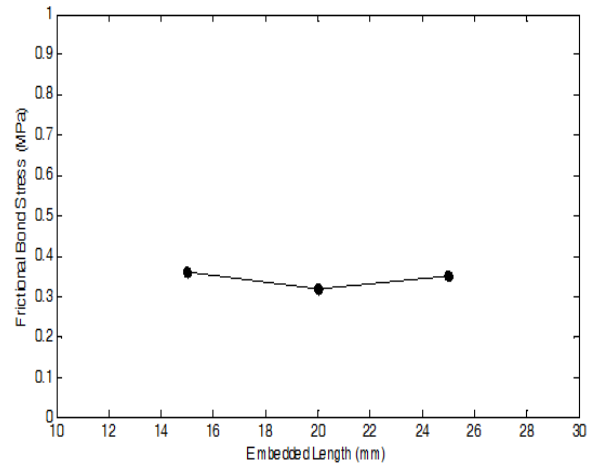


Figure 5: Effect of fiber embedment length on frictional bond strength for earth-based cementitious matrices.

Figure 6 shows the fiber pull-out strengths obtained for fiber volume fractions between 0 to 20 %. While keeping other parameters constant, the result shows that increasing the fiber volume fraction resulted in increasing peak pullout load. This increase in the pull-out load can be attributed to the increase in fiber bundle/composite ligament strength that occurs with increasing fiber volume fraction. Hence, the increase in the volume fraction of fibers provides increased shielding due to crack bridging and fiber pull-out.

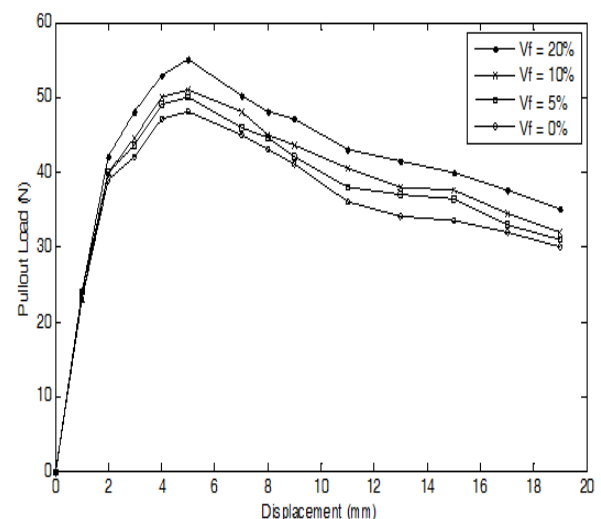


Figure 6: Effect of fiber volume fraction on the pullout of natural fiber from earth-based cementitious matrices

6.0 Summary and Concluding Remarks

Based on experimental results obtained as well as the adopted model, the following conclusions can be made from the current study:

- I. Increasing fiber embedment length resulted in a significant increase in peak pullout load.
- II. Increasing fiber volume fraction within the pullout medium resulted in a significant increase in the peak pullout load.
- III. Debonding with constant frictional stress was obtained for single fiber pullout tests.
- IV. Applying the condition of constant friction stress at fiber-matrix interface indicate that fiber pullout is also a major mechanism of energy absorption during composite failure.

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