PASMAT 2015
(MATERIALS FOR AFRICAN DEVELOPMENT)

WORKSHOP ON SUSTAINABLE BUILDING MATERIALS

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The choice of materials for building is greatly influenced by the cost and availability.

Industrialized societies have developed various composite materials which are applied in all works of construction (including buildings).

Unfortunately, developing countries where alternative materials exist have failed to explore such opportunities.

There is therefore, the need to explore new ways of producing robust building materials from locally available materials.
Problem Statement

- There has been great progress in both the production and application of reinforced materials (except little for earth-based materials)
- Need for sustainable and affordable housing
- Problem of cement and conventional building materials

- Potential for making affordable and attractive homes from earth (laterite) and local building materials
- The scientific and engineering bases for the application of natural fibers for reinforcement are very limited
Composite Survey

Adapted from Fig. 16.2, *Callister 7e*. 
Composite Survey: Fiber

Particle-reinforced | Fiber-reinforced | Structural

- **Critical** fiber length \( (l_C) \) for effective stiffening & strengthening:

  \[
  \sigma_f \frac{d}{\tau_c} > 15 \text{ length fiber}
  \]

  - fiber strength in tension
  - fiber diameter
  - shear strength of fiber-matrix interface

- Why? Longer fibers carry stress more efficiently!

  **Shorter, thicker fiber:**
  \[
  \sigma_f \frac{d}{\tau_c} < 15 \text{ length fiber}
  \]
  Poorer fiber efficiency

  Adapted from Fig. 16.7, Callister 7e.

  **Longer, thinner fiber:**
  \[
  \sigma_f \frac{d}{\tau_c} > 15 \text{ length fiber}
  \]
  Better fiber efficiency
Fiber Alignment

aligned continuous

aligned discontinuous

random

Adapted from Fig. 16.8, Callister 7e.
Behavior under load for Fibers & Matrix

(a) Fiber

(b) Composite

Stage I

Stage II

Failure

Matrix

Stress

Strain

\( \sigma_f^* \)

\( E_f \)

\( \sigma_m^* \)

\( E_m \)

\( \epsilon_f^* \)

\( \epsilon_m^* \)

\( \sigma_{cl}^* \)

\( \epsilon_{ym} \)

\( \epsilon_f^* \)
Literature Survey (cont.)

Composite Strength: Longitudinal Loading

**Continuous fibers** - Estimate fiber-reinforced composite strength for long continuous fibers in a matrix

- Longitudinal deformation

\[ \sigma_c = \sigma_m V_m + \sigma_f V_f \]

but \[ \varepsilon_c = \varepsilon_m = \varepsilon_f \]

\[ \therefore E_c = E_m V_m + E_f V_f \]

longitudinal (extensional) modulus

\[ f = \text{fiber} \]
\[ m = \text{matrix} \]
Composite Strength: Transverse Loading

- In transverse loading the fibers carry less of the load and are in a state of ‘isostress’

\[
\sigma_c = \sigma_m = \sigma_f = \sigma = \varepsilon_c = \varepsilon_m V_m + \varepsilon_f V_f
\]

\[\frac{1}{E_{ct}} = \frac{V_m}{E_m} + \frac{V_f}{E_f}\]

\[\text{transverse modulus}\]
Soil’s main important uses for humanity are summarized here:
Laterite and Clay

A soil type rich in iron and aluminum. When moist, laterites can be easily cut into regular-sized blocks and hardens as the moisture between the particles evaporates.

Laterite (lateritis)

A fine-grained, firm earthy material that is plastic when wet and hardens when heated. Consisting primarily of hydrated silicates of aluminum with traces of iron oxide.

Clay

Adapted from “Teaching Clay Mineralogy”. A compilation by David Mogk, Dept. of Earth Sciences, Montana State University.
Straw is the dry stalks of cereal plants. It is an agricultural by-product obtained after the grain and chaff have been removed.
Ordinary Portland Cement

Definition: “Cement is a crystalline compound of calcium silicates and other calcium compounds having hydraulic properties” (Macfadyen, 2006).
Overview of Prior work (1)

- The mechanical properties of fiber-reinforced composites have also been studied by several authors (Balaguru and Shah, 1992; Shah et al., 1993; Savastano et al., 2005, ...). They have focused on the effects of reinforcement on mechanical properties of the composites.

- Savastano et al. studied Brazilian waste fibers (Banana beaten kraft, By-product sisal kraft, Waste E. grandis kraft, e.t.c) as reinforcement for cement-based composites and Potential of alternative fiber cements as building materials for developing areas (2000)

- Agopyan et al. evaluated the durability of vegetable fiber reinforced materials (1992)
Overview of Prior work (2)

- Coutts RSP also studied Wood fiber-reinforced cement composites (2005)
- P.F. Becher studies the microstructural design of toughened ceramics using crack bridging model (1991)
- Eissa and Batson have used resistance curve behavior experiments to study the fracture toughness of steel fiber-reinforced concrete. They showed that fiber-reinforcements result in increased toughness (1996)
- For cement matrix composites, there have been considerations of load-deflection behavior in fiber pull-out process
Overview of Prior work (3)

• In brittle-matrix composites, Hsueh C. H. (1990) showed that interfacial strengths are characterized by the debond stress or the frictional pull-out stress.

• Evans et al (1986) showed that fiber bridging requires at least modest interfacial strength to transfer load to the fiber and high fiber tensile strength to sustain the applied stress within the wake of the crack tip.
Bricks of different material compositions (matrices and reinforcements) were produced from the materials acquired.

The cementitious materials were dry mixed manually with the aid of a hand trowel for about 2 minutes for homogenization.

The matrices were prepared by direct mixing of dry constituent material(s) followed by addition of water at approximate water-cement ratio.

Samples were prepared in varying dimensions in a mold using a hydraulic press at optimized pressure for 5 minutes. This pressure was chosen after optimization.
The samples were cured for 28 days in air at average temperature of 23°C with average relative humidity of 80%.

Fired clay (control samples) was also obtained by firing of molded clay at ~800°C for 6 hours in a kiln.

Samples of dimensions 25×12.5×100 mm³ were used for compressive strength, flexural strength and Pull-out test while 12.5×25×100 mm³ specimens were for Single-edged notched bending (SENB) to study their fracture toughness and resistance curve behavior.
Composite Processing (3)

Percentage composition by volume of matrix and fiber in the composite samples.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Volume of matrix (%)</th>
<th>Volume of fiber (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>95</td>
<td>5</td>
</tr>
<tr>
<td>II</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>III</td>
<td>80</td>
<td>20</td>
</tr>
</tbody>
</table>
Materials Characterization
Materials Characterization

SEM micrograph of Composite Sample
Materials Characterization

Optical microscopy images showing crack bridging by fibers
SEM images of fracture surfaces showing evidence of debonding and fiber pullout.
Compressive strength is given by: \( \sigma = \frac{F_A}{A_o} \)

Flexural strength is given by: \( \sigma_f = \frac{3F_AL}{2BH^2} \)

Where:
- \( F_A \) is the peak load at the onset of fracture and \( A_o \) is the initial cross-sectional area.
- \( L \) is the loading span;
- \( B \) and \( H \) are the specimen breadth and height, respectively.
Composite Mechanistic Model (1)

Rule-of-Mixtures

The constant strain rule of mixture assumes that the applied load is parallel to the fiber direction.

For a two phase whisker/fiber-reinforced composite, the strength may be estimated from rule of mixture:

\[ \sigma_c = V_m \sigma_m + V_f \sigma_f \]

\( V_m \) and \( V_f \) are volume fractions of the matrix and fiber, respectively. \( \sigma_m \) and \( \sigma_f \) are matrix and fiber strengths, respectively.
Composite Mechanistic Model (2)

Short Fiber Theory

For short and randomly oriented whisker/fiber-reinforced composite, the average fiber strength is given by:

\[ \bar{\sigma}_f = \eta_o \eta_f \sigma_f \]

\( \eta_o \) (orientation efficiency factor) accounts for the decrease the composite strength due to random orientations of the fibers.

It has values of 0.375 and 0.2 for random two-dimensional and three-dimensional orientation respectively

\[ \eta_f = \frac{l}{2l_c} \]

is known as the fiber efficiency factor for short fibers

Hence, the composite strength may be estimated from rule of mixture

\[ \sigma_c = V_m \sigma_m + V_f \sigma_f \eta_f \eta_o \]
Fracture Toughness

Fracture toughness is given by:

\[ K_c = Y \sigma_c \sqrt{\pi a_o} \]

where:
\( Y = F(a/w) \) is a compliance function,
\( \sigma_f \) = flexural stress at the peak load
\( a_o \) is the initial crack length.

The compliance function for the single edge notched bend (SENB) specimen can be obtained in the ASTM E399-90

\[
Y = f \left( \frac{a}{w} \right) = \frac{3(a/w)^{1/2}}{2(1 + 2(a/w)(1 - a/w)^{1/2})} \times \left[ 1.99 - (a/w)(1 - a/w)(2.15 - 3.93 \frac{a}{w} + 2.7 \frac{a^2}{w^2}) \right]
\]
Schematic representation of the model used to determine the shielding contribution provided by bridging ligaments in the wake of a crack

*Budiansky et al.*

\[
K_c = K_m + \Delta K_b
\]

- \(K_c\) is the fracture toughness of the composite,
- \(K_m\) is the matrix fracture toughness,
- \(\Delta K_b\) is the toughening due to bridging.
For small scale bridging, in which the size of the bridging zone is much smaller than crack length. The toughening is given by:

\[
\Delta K_b = \Delta K_{SSB} = \alpha V_f \sqrt{\frac{2}{\pi}} \int_{0}^{L} \frac{\sigma_y}{\sqrt{x}} \, dx
\]

Where \( V_f \) is the volume fraction of bridge zone, \( L \) is the length of bridging, \( \sigma_y \) is the uniaxial yield stress, and \( x \) is the distance from the crack-tip.

In the case the fracture toughness is taken to correspond to point of instability on the resistance-curve, which is approximated by the peak loads in the fracture toughness experiments.
For large scale bridging, the toughening due to crack bridging is given by:

\[
\Delta K_b = \Delta K_{LSB} = V_f \int_0^L \alpha \sigma_y h(\alpha, x) dx
\]

Where \( h(\alpha, x) \) is the weighting function for traction given by Fett and Munz as:

\[
h(\alpha, x) = \sqrt{\frac{2}{\pi \alpha}} \frac{1}{\sqrt{1 - \frac{x}{a}}} \left( 1 + \sum_{(\nu, \mu)} A_{\nu, \mu} \left( \frac{\alpha}{w} \right) (1 - \frac{x}{a})^{\nu+1} \right)
\]

<table>
<thead>
<tr>
<th>( \nu )</th>
<th>( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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</tr>
<tr>
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<tr>
<td>1</td>
<td>0.5416</td>
</tr>
<tr>
<td>2</td>
<td>-0.19277</td>
</tr>
</tbody>
</table>
Resistance-curve Behavior

- Fracture resistance is a non-unique process which depends on the crack-growth history.
- The history dependence of the fracture resistance can be characterized by a Resistance curve.
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.

The interfacial strength between the matrix and the fibers is often the key to composite toughening and fracture properties.

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.
Fiber Pull-out (2)

- 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
- The specimen was fixed securely to the Instron with the aid of G-clamps
- The fiber displacement was monitored using an in-situ optical microscope
Experimental set-up
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 [32-34]. These include:

(i) a linear elastic deformation stage;
(ii) a partial fiber debonding stage, and
(iii) a frictional pull-out stage
Composite Toughening due to debonding and pull-out (1)

- The choice of the model for this study is motivated by the experimental observation of the frictional bond stress obtained relative to fiber embedment lengths.
- The results show a constant friction stress, $\tau$, between the fiber and the matrix. A model proposed originally by Hutchinson and Jensen (1990) was used.
- This model assumes a constant friction stress between fiber and matrix.
Composite Toughening due to debonding and pull-out (2)

- The fiber-matrix system was modeled by a cylindrical composite comprising a fiber (radius $r_f$) surrounded by matrix with a circular cylindrical outer boundary of radius $r$.

- The area fraction of the fiber is taken as $\rho = (r_f/r)^2$

- A positive mode II fracture is assume to exists along the matrix fiber interface.

- This implies that debonding, sliding and pull-out contributes to toughness

- When the fiber and matrix surfaces are loaded by a constant frictional stress $\tau$ and the fiber slides but does not lose contact with the matrix, the variation of $K_2$ is approximated by [Hutchinson and Jensen (1990) ]:

\[
K_2/(\tau r_f^{1/2}) = (1 - \rho)^{-1/2}(l/r_f)
\]
The expression for the estimation of the composite fracture toughness based on the toughening mechanisms observed in the failure of natural fiber-reinforced earth-based composite is given by [Savastano et al, 1999 & 2000]:

\[ K_R = K_i + \Delta K \]

For toughening by crack bridging and fiber pullout with constant fractional stress, the overall toughening is given by [Shum et al, 1989]:

\[ \Delta K = \lambda \Delta K_B + (1 - \lambda)\Delta K_F \]

where \(\Delta K\) is the total toughening, \(\lambda\) is the toughening ratio due to crack bridging, \(\Delta K_B\) and \(\Delta K_F\) are the shielding due to crack bridging and fiber pullout respectively.
Implications of Current work

- The implications of the current research are very significant for the design of composite materials for sustainable and affordable housing.
- This work has shown an improvement in the mechanical properties of earth-based matrices when they are reinforced with straw.
- Toughening of the composites was enhanced via crack bridging and fiber pull-out precipitated by fiber (straw) reinforcement.
- The results from the test procedures in this study can serve as a basis in micro-mechanical characterization, performance evaluation and quality assurance for sustainable and affordable construction (building) products.
- Hence, sustainable and low cost housing can be achieved using locally sourced materials expounded in this work.
Summary and Concluding remarks (1)

- Composites consisting of earth-based materials reinforced with natural fiber (straw), and plain matrices were prepared. The mechanical properties of the various compositions (in both matrices and composites) were determined. The results were compared to measure the effects of reinforcement.

- Microscopy studies reveal that cracks in whisker-reinforced ceramics can propagate in the matrix and leave intact whiskers which bridge the crack immediately behind the crack tip.

- Whisker bridging occurs as the whisker-matrix interface and debonds when the crack tip approaches the interface.

- Further behind the crack tip, the whiskers are pulled out of the matrix as the crack-opening displacement increases.
Future work

- This study presents motivation for further studies of mechanical properties of earth-based composites.

- Further research is needed to test the durability of earth-based composites under a range of weathering conditions.

- There is also need to explore actual performance of earth-based composites in sustainable building.
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Thank You