PASMAT 2015
(MATERIALS FOR AFRICAN DEVELOPMENT)

WORKSHOP ON SUSTAINABLE BUILDING MATERIALS

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Knowledge is Freedom

Background

- 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

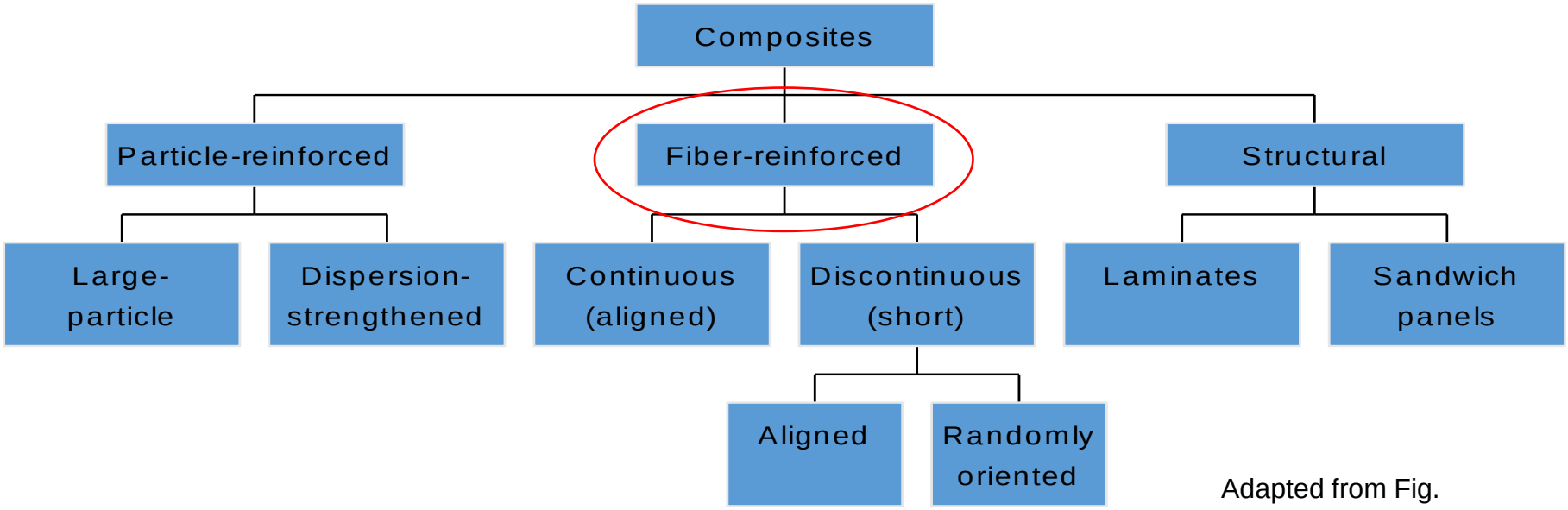
Problem Statement

- 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

Literature Survey

Composite Survey



Adapted from Fig. 16.2, *Callister 7e*.

Literature Survey (cont.)

Composite Survey: Fiber

Particle-reinforced | **Fiber-reinforced** | Structural

- Critical fiber length (l_c) for effective stiffening & strengthening:

fiber strength in tension

fiber diameter

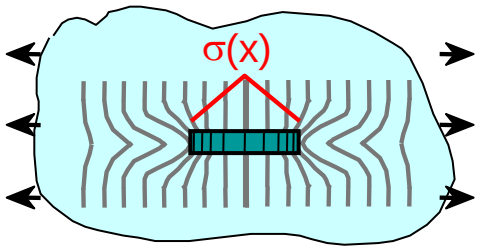
$$\text{fiber length} > 15\,\frac{\sigma_f d}{\tau_c}$$

shear strength of **fiber-matrix** interface

- Why? Longer fibers carry stress more efficiently!

Shorter, thicker fiber:

$$\text{fiber length} < 15\,\frac{\sigma_f d}{\tau_c}$$

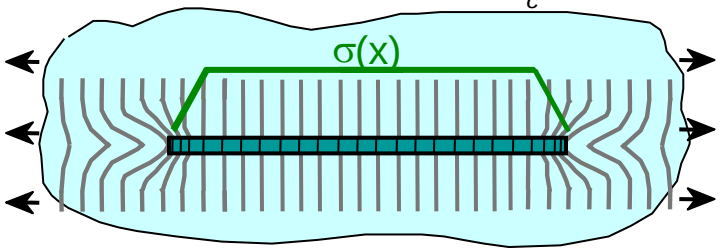


Poorer fiber efficiency

Adapted from Fig. 16.7, *Callister 7e*.

Longer, thinner fiber:

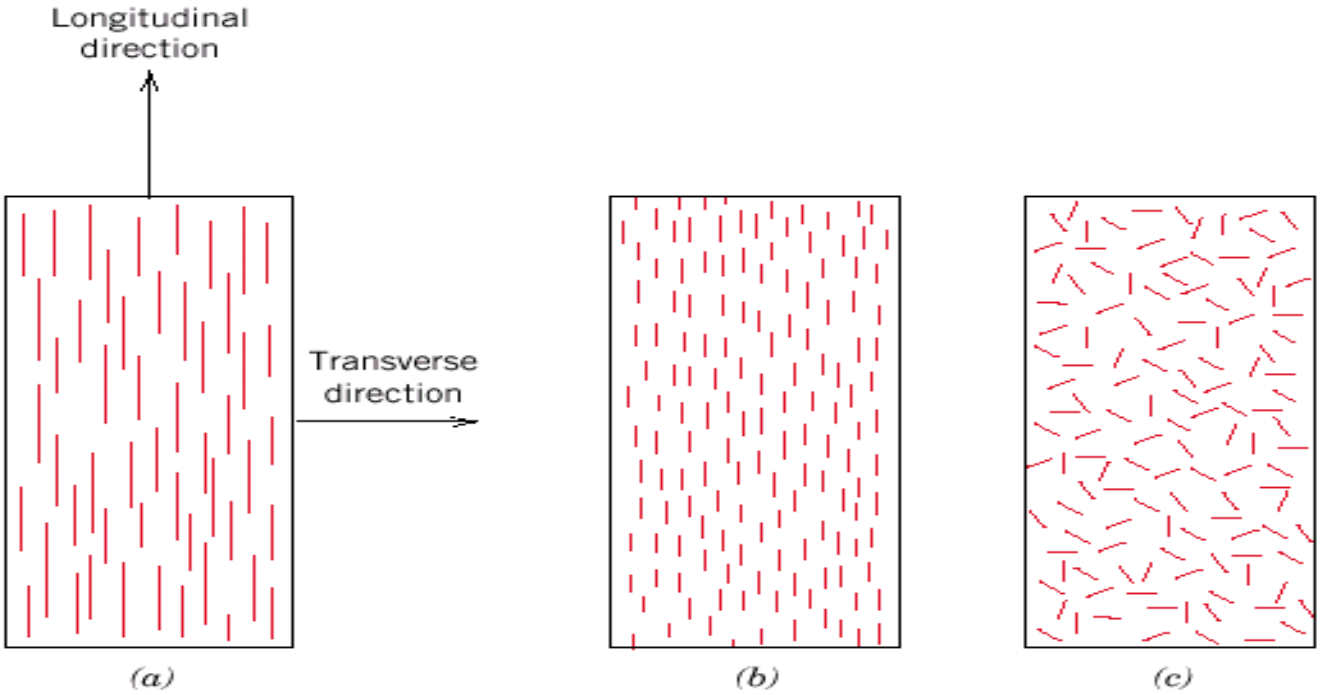
$$\text{fiber length} > 15\,\frac{\sigma_f d}{\tau_c}$$



Better fiber efficiency

Literature Survey (cont.)

Fiber Alignment



Adapted from Fig. 16.8, *Callister 7e*.

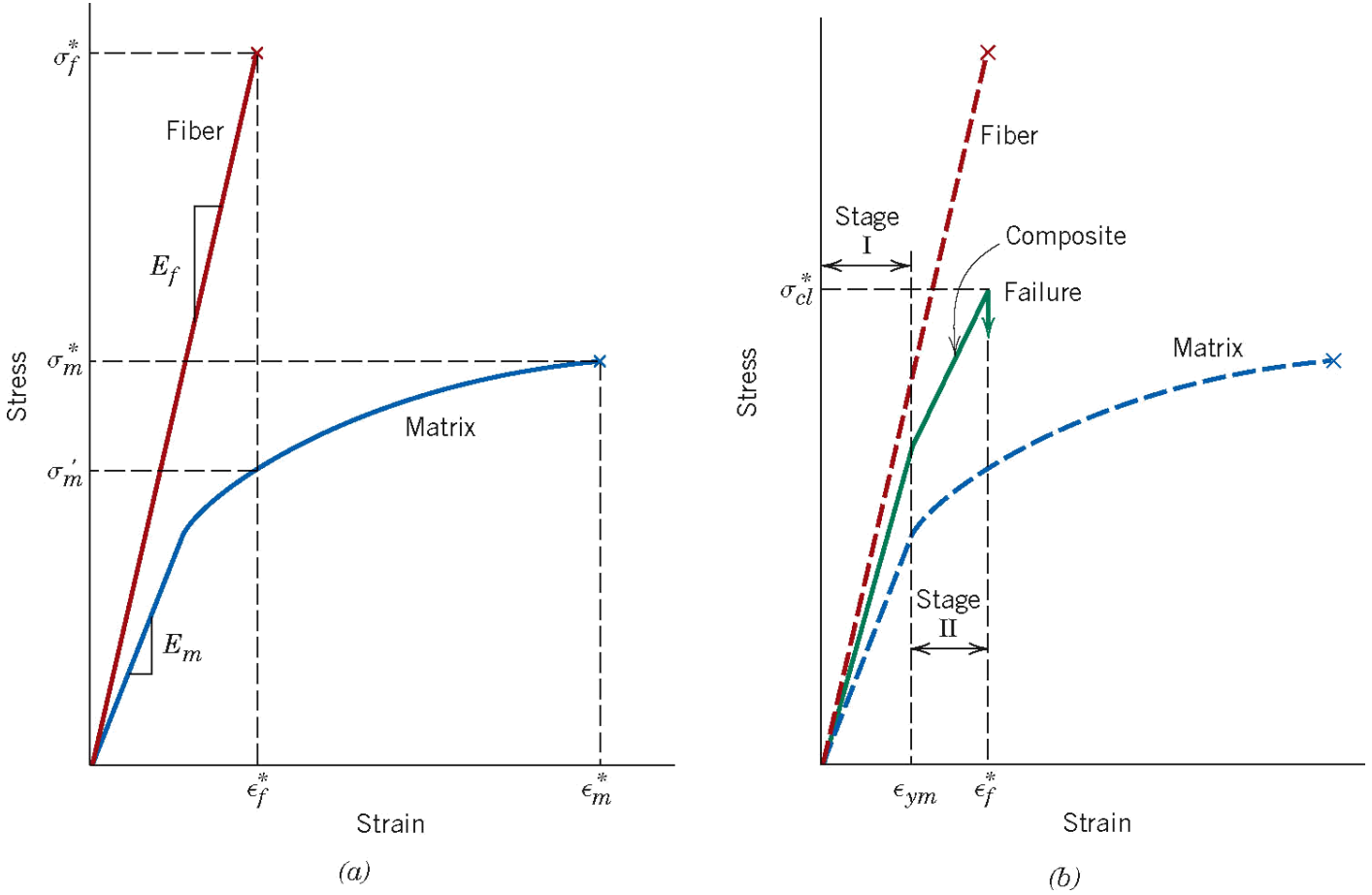
aligned continuous

aligned discontinuous

random discontinuous

Literature Survey (cont.)

Behavior under load for Fibers & Matrix



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 $\varepsilon_c = \varepsilon_m = \varepsilon_f$

isostrain

$\therefore$ $\boxed{E_c = E_m V_m + E_f V_f}$

longitudinal (extensional) modulus

f = fiber
m = matrix

Literature Survey (cont.)

Composite Strength: Transverse Loading

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

$$\sigma_c = \sigma_m = \sigma_f = \sigma \qquad \varepsilon_c = \varepsilon_m V_m + \varepsilon_f V_f$$

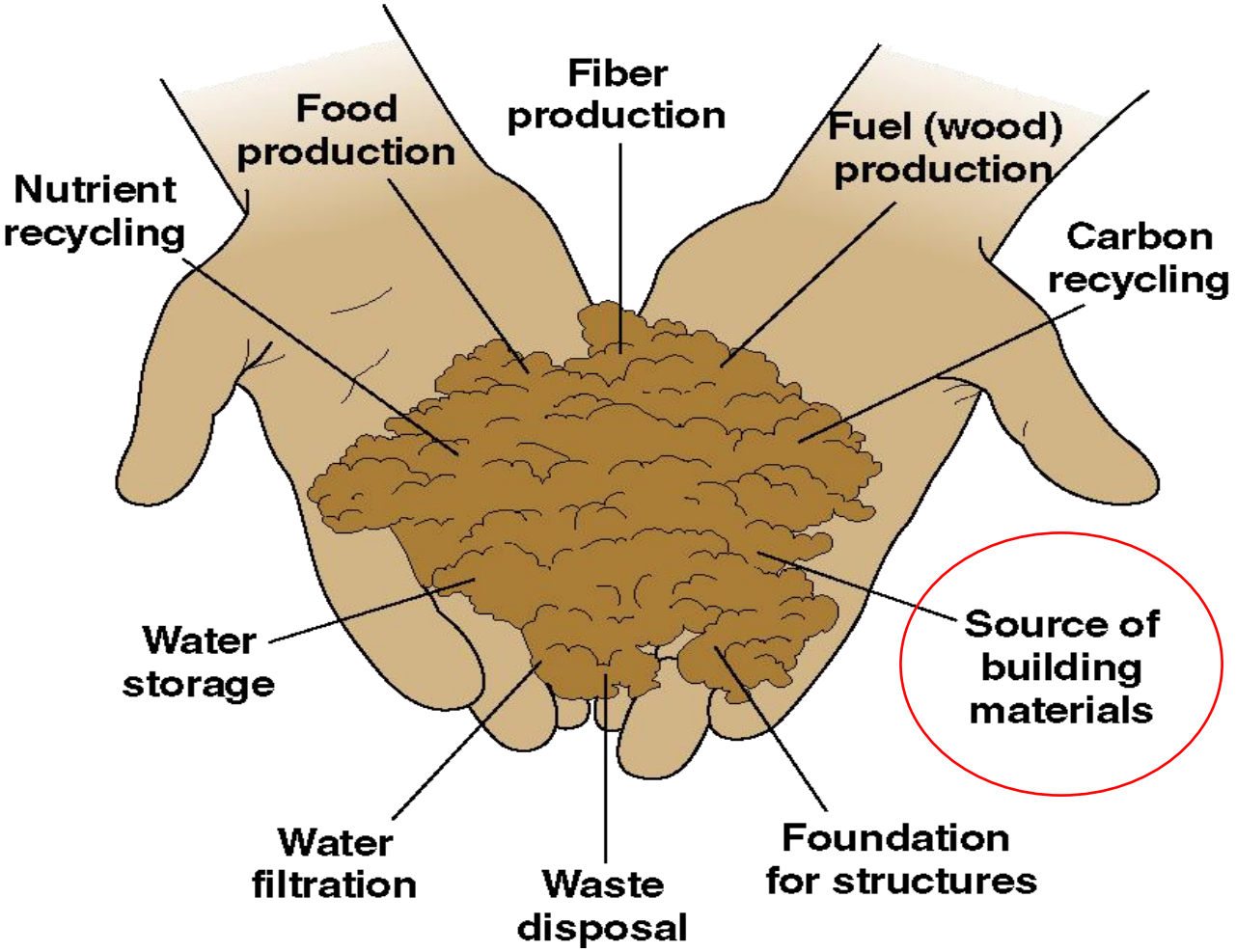
$$\therefore \quad \frac{1}{E_{ct}} = \frac{V_m}{E_m} + \frac{V_f}{E_f}$$

transverse modulus

Literature Survey (cont.)

Laterite and Clay

Soil's main important uses for humanity are summarized here:



Literature Survey (cont.)

Laterite and Clay

Laterite (lateritis)

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

Clay

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

Adapted from “Teaching Clay Mineralogy”. A compilation by David Mogk, Dept. of Earth Sciences, Montana State University

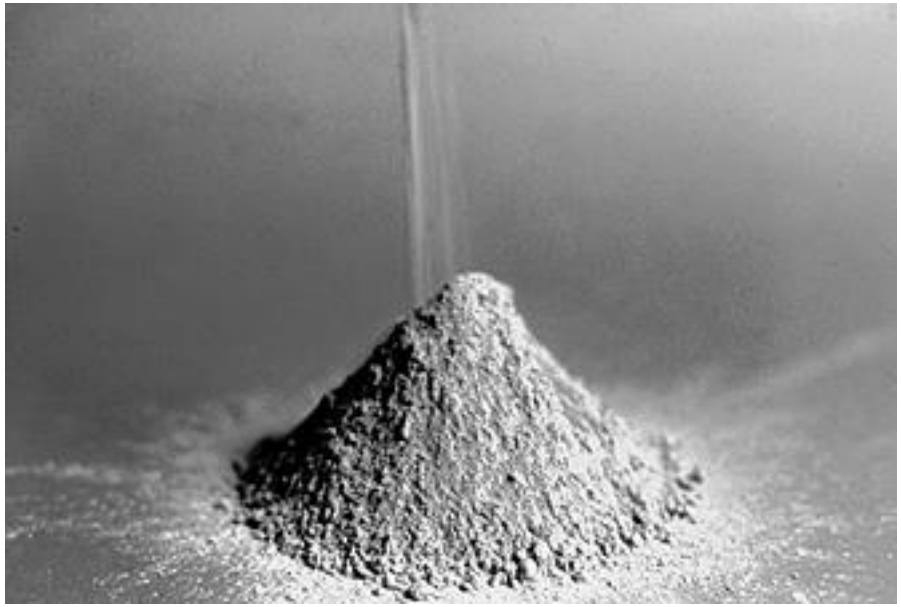
Literature Survey (cont.)

Straw (Andropogon spp.)

Straw is the dry stalks of cereal plants. It is an agricultural by-product obtained after the grain and chaff have been removed

Literature Survey (cont.)

Ordinary Portland Cement



Definition: "Cement is a crystalline compound of calcium silicates and other calcium compounds having hydraulic properties" (Macfadyen, 2006).

Literature Survey (cont.)

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)

Literature Survey (cont.)

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

Literature Survey (cont.)

Overview of Prior work (3)

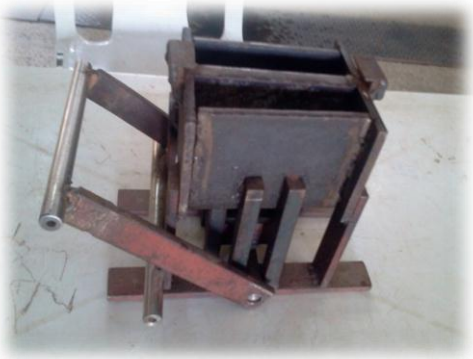
- In brittle-matrix composites, Hsueh C. H. (1990) showed that interfacial strengths are characterized by the debond stress or the frictional pull-out stress
- Evans et al (1986) showed that fiber bridging requires at least modest interfacial strength to transfer load to the fiber and high fiber tensile strength to sustain the applied stress within the wake of the crack tip

Composite Processing (1)

- 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.

Composite Processing (2)

- The samples were cured for 28 days in air at average temperature of 23^{O}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 mm^3 were used for compressive strength, flexural strength and Pull-out test while 12.5×25×100 mm^3 specimens were for Single-edged notched bending (SENB) to study their fracture toughness and resistance curve behavior.



Composite Processing (3)

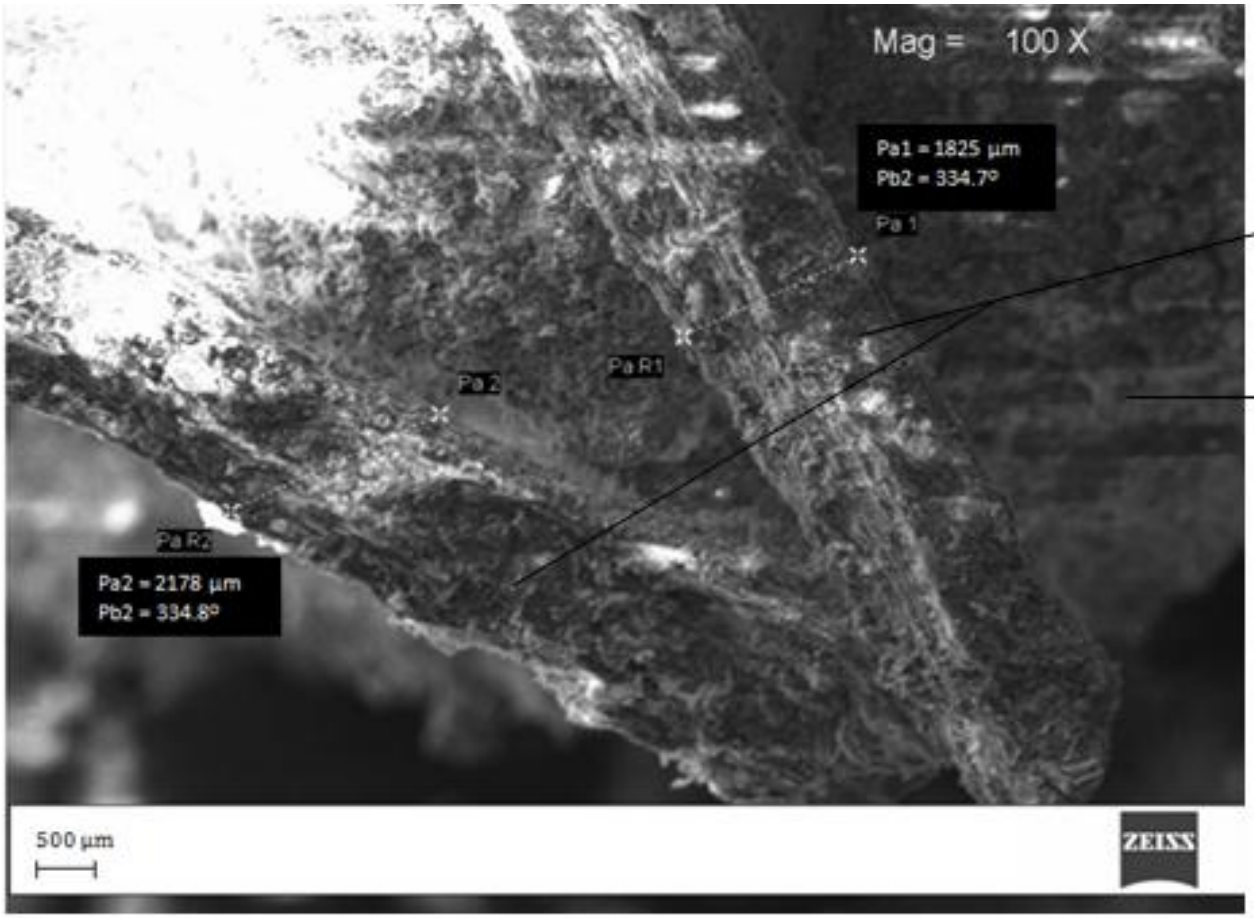
Percentage composition by volume of matrix and fiber in the composite samples.

Samples	Volume of matrix (%)	Volume of fiber (%)
I	95	5
II	90	10
III	80	20

Materials Characterization

Materials Characterization

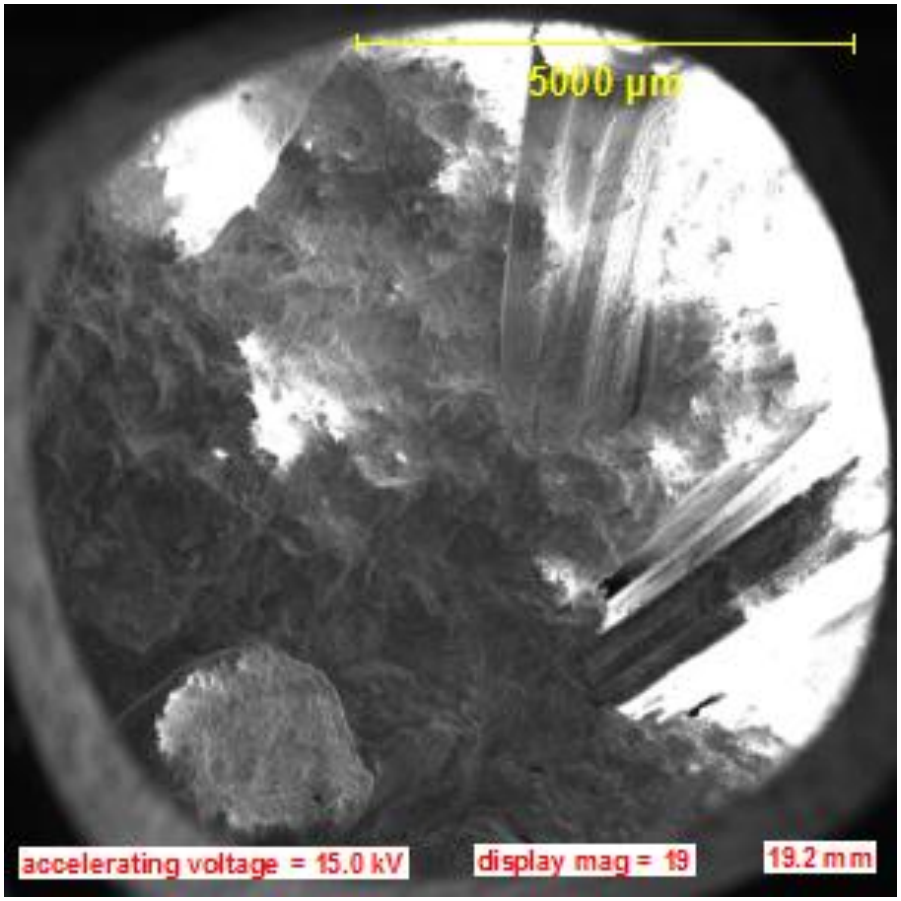
SEM micrograph of Composite Sample

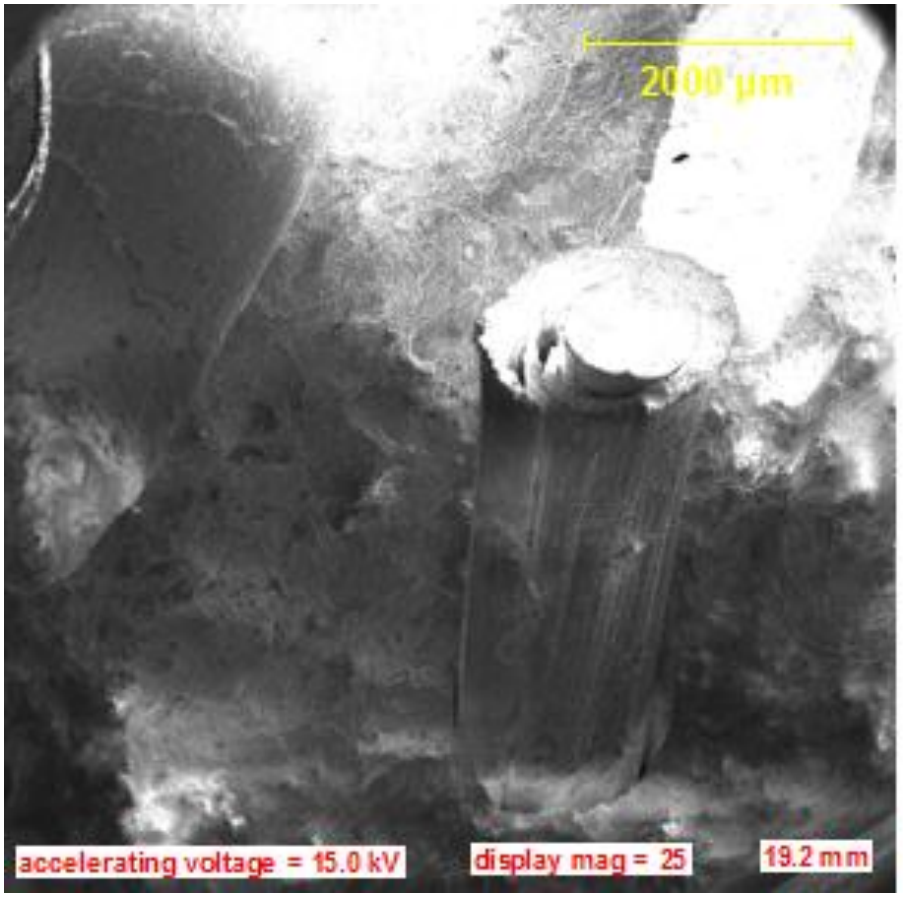


Materials Characterization

Optical microscopy images showing crack bridging by fibers

Materials Characterization



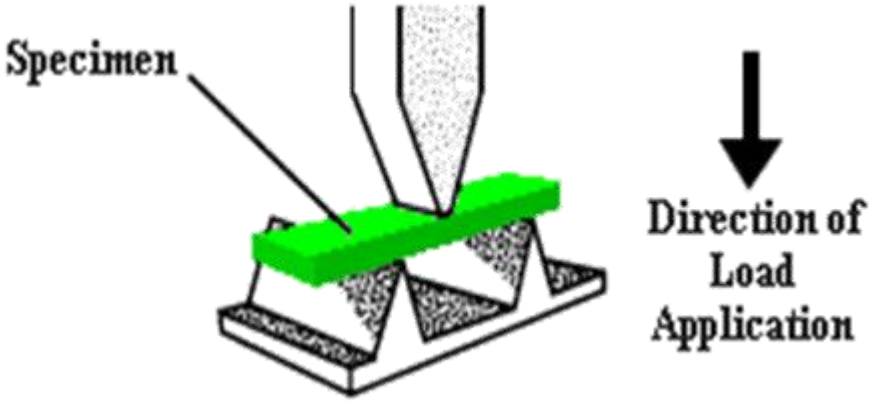


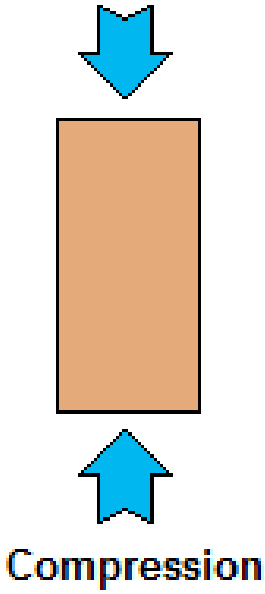
SEM images of fracture surfaces showing evidence of debonding and fiber pullout.

Strengths Measurement

Compressive strength is given by: $\sigma = \frac{F_A}{A_o}$

Flexural strength is given by: $\sigma_f = \frac{3F_A L}{2BH^2}$





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.
σ_m and σ_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:

$$\bar{\sigma}_f = \eta_o \eta_f \sigma_f$$

η_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:

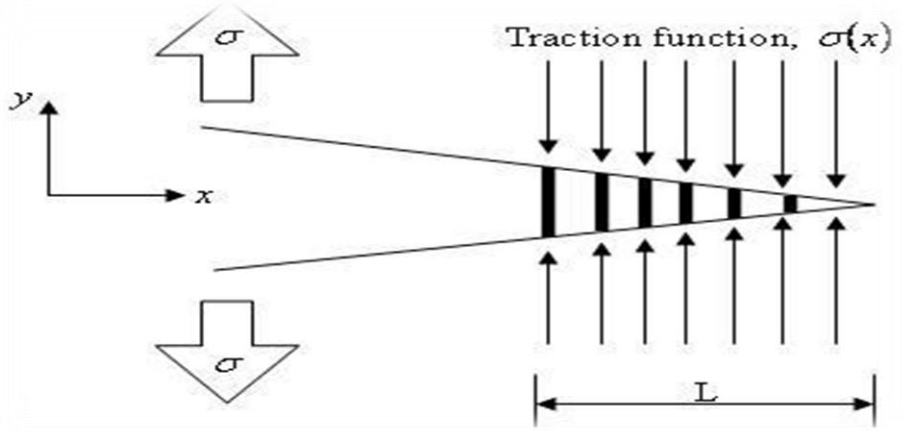
$$K_c = Y\sigma_c\sqrt{\pi a_o}$$

where :
Y = $F(a/w)$ is a compliance function,
σ_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

$$Y = f\left(\frac{a}{w}\right) = \frac{3\left(a/w\right)^{1/2}}{2\left(1+2\,a/w\right)\left(1-a/w\right)^{3/2}} \times \left[1.99 - \left(a/w\right)\left(1-a/w\right)\left(2.15 - 3.93\,a/w + 2.7\,a^2/w^2\right)\right]$$

Toughening Mechanism (Crack Bridging)



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,
ΔK_b is the toughening due to bridging.

Toughening Due to Small Scale Bridging (SSB Model)

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, σ_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.

Toughening Due to Large Scale Bridging (LSB Model)

For large scale bridging, the toughening due to crack bridging is given by:

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

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

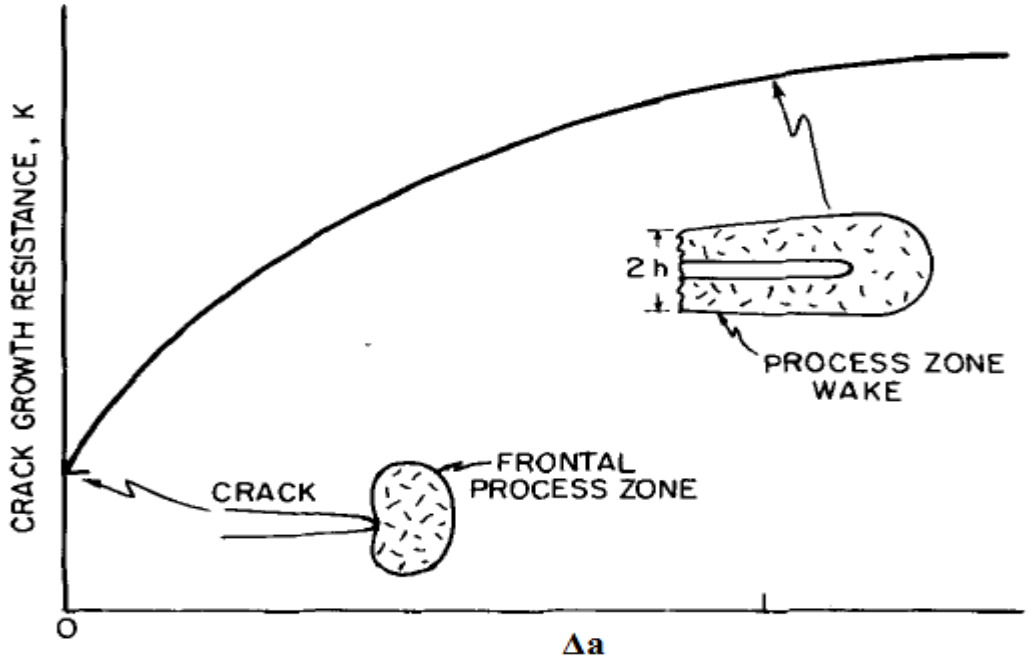
$$h(a,x) = \sqrt{\frac{2}{\pi a}} \frac{1}{\sqrt{1-\frac{x}{a}}} \left(1 + \sum_{(\nu,\mu)} \frac{A_{\nu,\mu}\left(\frac{a}{w}\right)}{1-\frac{a}{w}} \left(1-\frac{x}{a}\right)^{\nu+1} \right)$$

Fett and Munz parameters for SENB specimen subjected to weighted crack-bridging fractions

	μ				
ν	0	1	2	3	4
0	0.4980	2.4463	0.0700	1.3187	-3.067
1	0.5416	-5.0806	24.3447	-32.7208	18.1214
2	-0.19277	2.55863	-12.6415	19.7630	-10.986

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



Schematic diagram of a crack growth resistance curve

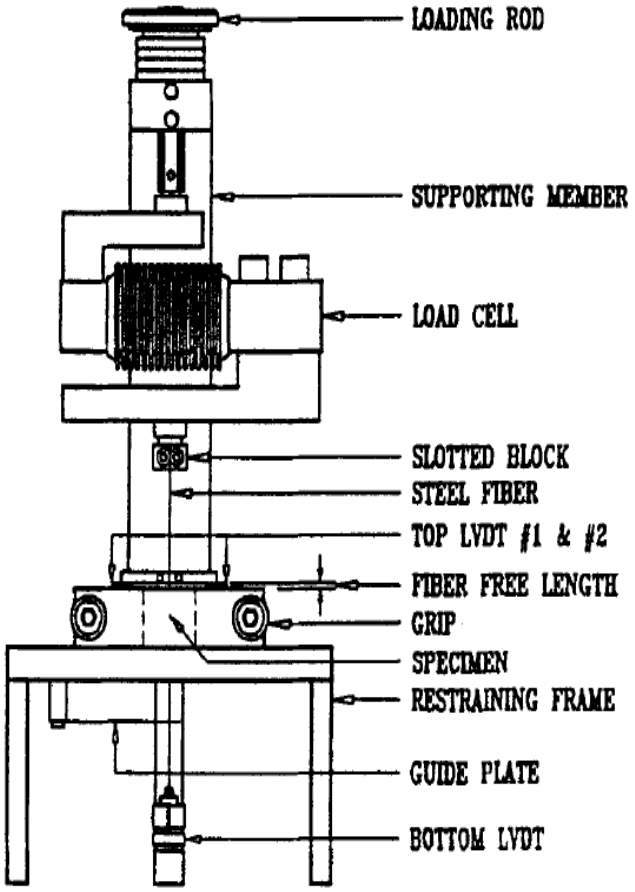
Fiber Pull-out (1)

- 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



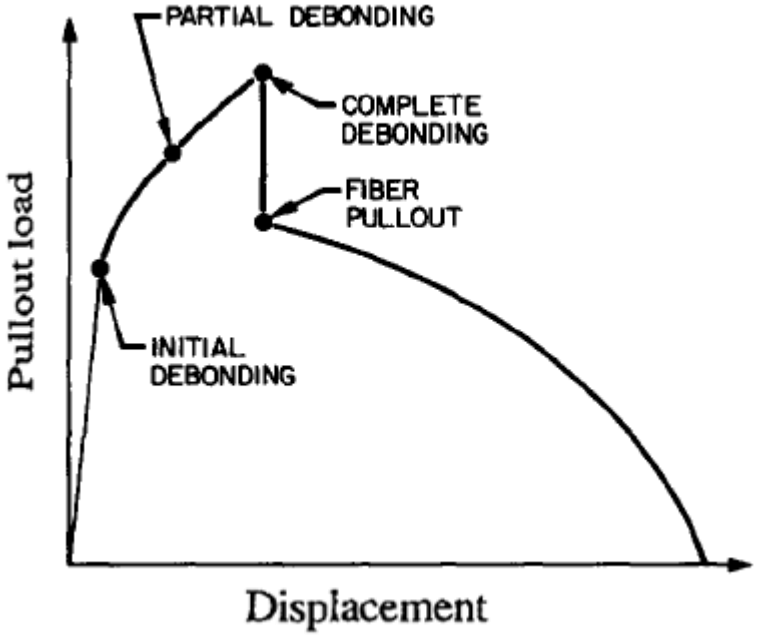
Fiber Pull-out (3)

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;

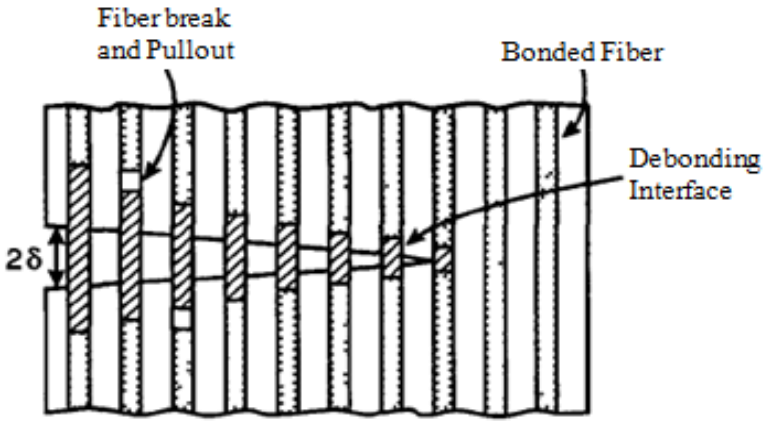
(ii) a partial fiber debonding stage, and

(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 shows a constant friction stress, τ, 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 $\rho = \left(r_f/r\right)^2$
- 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 τ and the fiber slides but does not lose contact with the matrix, the variation of K_2 is approximated by [Hutchinson and Jensen (1990)]:

$$K_2/\left(\tau {r_f}^{1/2}\right) = (1-\rho)^{-1/2}\left(l/r_f\right)$$

Overall Composite Toughening

- 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]:

$$\mathrm{K_R} = \mathrm{K_i} + \Delta\mathrm{K}$$

- 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 ΔK is the total toughening, λ is the toughening ratio due to crack bridging, ΔK_B and ΔK_F are the shielding due to crack bridging and fiber pull-out 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

Acknowledgements

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Thank You