ScienceDirect

Journal of the Mechanical Behavior of Biomedical Materials

Volume 142, June 2023, 105831

Self-organized mycelium biocomposites: Effects of geometry and laterite composition on compressive behavior

Precious O. Etinosa [a], Ali A. Salifu [b], Salifu T. Azeko [c], John D. Obayemi [a], Emmanuel O. Onche [d e], Toyin Aina [a d], Winston O. Soboyejo [a d]

Show more

Share Cite

https://doi.org/10.1016/j.jmbbm.2023.105831

Get rights and content

Abstract

This study investigates the compressive deformation and the effect of structural architecture on the compressive strength of bioprocessed mycelium biocomposites reinforced with laterite particles. In the mycelium blocks, lignocellulosic hemp hurds function as reinforcing and nutritional substrates. The mycelium acts as a supportive matrix, binding the hemp hurds and the laterite particles which are integrated for further reinforcement to improve the compressive strength of the composite. The compressive behavior of the composites is elucidated using a combined approach of experimental and theoretical studies. The deformation mechanisms are investigated via in-situ observations of the specimens under uniaxial compressive loading. The experiments show that the compressive deformation results in progressive micro-buckling in slender specimens, whereas thicker samples exhibit a soft elastic response at small strain levels followed by continuous stiffening at larger strains. Based on the experimental observations and the morphological characterization, a column buckling analysis was developed for the mycelium-hemp composites to further explain the observed deformation phenomena.

Introduction

In recent years, material engineering and design concepts have tried to incorporate sustainability within the motif of biodegradation. Several studies have focused on engineering renewable materials from a variety of naturally available resources such as bamboo (Sun et al., 2022), (Onche et al., 2021), eggshell membrane (Baláž, 2014), cotton plant biomass (Holt et al., 2012), and silk protein (Vepari and Kaplan, 2007). Many natural materials also provide a unique advantage due to the combination of interesting properties that often result from their filamentous and hierarchical architectures (Islam et al., 2018; Meyers et al., 2008; Wegst et al., 2014). Some of these unique properties have been used in bioinspired and sustainable engineering designs. However, although the chemical compositions of the materials and structures in these designs are well established, there is still only a limited understanding of the structure-property relationships and the interplay and mechanistic intricacies required for robust material design and process optimization (Islam et al., 2018).

The natural ability of saprophytic fungi to digest and bind lignocellulosic material is explored to develop natural bio-composite materials for potential applications in design, buildings, and architecture. Within this context, mycelium-based composites are interesting materials because of their sustainability. Mycelium is the root structure of fungi. It consists of hyphae, which are microscopic tubular filaments of varying geometries depending on the strain. The diameter of a typical hypha is in the range of 1–30 μm (Islam et al., 2018), (Geitmann and Emons, 2000) (Fig. 1d and e). The fungus starts as a spore and develops into a hypha that grows out through apical tip elongation (Islam et al., 2018). Each biologically active hypha fuses with other hyphae through anastomosis (Fig. 1e). This rapidly creates a large fractal network structure that colonizes an organic substrate through hydrolytic enzymatic secretions (Howard et al., 1991). Consequently, a self-organized composite material forms in which the mycelium simultaneously functions as a supporting matrix and a natural binder, embedding biodegradable substrates which act as reinforcements and nutritional particles (Appels et al., 2019a). The growth rate, density of colonies, and topological distribution of filaments within the network, are a function of the fungal species, choice of substrate, and environmental culturing conditions (Appels et al., 2019b; Haneef et al., 2017; Ziegler et al., 2016). A typical component of the hypha cellular wall is chitin nanofibril, which offers strength and mechanical rigidity to the structure (Michalenko et al., 1976; Zhao et al., 2005; Etinosa and Soboyejo, 2022; Stocks and Thomas, 2001).

Mycelium biocomposites have found useful applications in diverse fields such as: biodegradable packaging (Holt et al., 2012), laminate flooring (Jones et al., 2020a), acoustic foams (Pelletier et al., 2013), (Jones et al., 2020b), flexible and thermal insulations (JoeyYang et al., 2017). However, their structural applications have been limited due to their poor mechanical properties (Jones et al., 2020c). Thus, some recent research efforts have focused on the development of novel methods for the improvement of the strengths of mycelium composites. Appels et al. (2019b) have used a post-processing approach (heat pressing method) to improve the composite strengths of mycelium composites derived from *Pleurotus ostreatus*. They observed a significant improvement in tensile/flexural composite strengths, with tensile strengths increasing by a factor of 3 (0.24 MPa), and flexural strengths increasing by a factor of 2 (0.87 MPa). Jiang et al. (Jiang et al., 2017) (Jiang et al., 2019), fabricated a structural sandwich panel using mycelium composites. They also reported a significant improvement in their flexural strengths.

However, although the above methods have been effective in improving the composite mechanical properties, they are process-intensive and cost-inefficient to implement. This has motivated recent efforts to use reinforcing substrates to improve the mechanical strength of mycelium composites. Ghazvinian et al. (Ghazvinian and Gürsoy, 2022) developed mycelium composites consisting of wheat straw and white oak substrates. They evaluated the mechanical properties and observed that the compression strengths of the composites cultured with white oak sawdust were about 7 times greater than those of mycelium.

Guo et al. (Gou et al., 2021) investigated mycelium composites inoculated with three fungal strains and natural biomass, added as reinforcing particles. Their results revealed that 37.5 wt% of the natural reinforcing particles improved the unconfined compressive strength and the elastic modulus. Similarly, Yang et al. (JoeyYang et al., 2017) also showed that the compressive strengths and elastic modulus of mycelium composites are improved by the inclusion of natural fiber particles. These findings indicate that improvement in the mechanical strength of as-grown composites correlates with the stiffness of the reinforcing substrates. Aligned with this motivation, we investigated a unique bioprocessed mycelium biocomposite developed from *Pleurotus Ostreatus* and hemp hurds, and laterite particles were added for additional reinforcements.

In this study, we explore the compressive deformation behavior of bioprocessed mycelium composites reinforced with self-organized cellulosic fibers, as shown in Fig. 1. The bioprocessed mycelium blocks, comprising cellulosic hemp hurds as reinforcing and nutritional substrates, are intertwined with laterite particles. The laterite functions as a stronger reinforcement that improves the compressive strengths of the composite (Pai et al., 2016), (Nkwaju et al., 2019). The effects of the clay particle weight percentage are elucidated, along with the effects of the hemp hurds, which are known to be highly compatible with fungi (Faruk et al., 2012), (Li and Pickering, 2009) Compressive deformation is studied in square prisms with aspect ratios of 2:1 and 4:1. A combination of *in-situ* optical microscopy and strain mapping is used to study the underlying deformation mechanisms that are associated with compressive deformation. Buckling models are also used to explain the observed deformation phenomena before discussing the implications of the current work for the development of robust mycelium-biocomposites for applications in sustainable housing buildings.

Section snippets

Materials

The fungal inoculum of the selected specie (*P. Ostreatus – a white rot fungi)* (Shakir et al., 2020) and hemp hurds were obtained from Ecovative Design, LLC, Green Island, NY, USA. Hemp was selected as the substrate fiber due to its compatibility with the fungus strain. Red laterite particles were obtained from Tamale Technical University in Ghana. The particles were air-dried and sieved through an ASTM 60 screen to achieve an average particle size of about 250μm (Pai et al., 2016), (Nkwaju et…

Modeling

The critical conditions associated with the global deformation of the slender samples were consistently observed to culminate in buckling phenomena.…

Macrostructure

Photographs, isometric views, and scanning electron microscopy images of the as-grown composite are presented in Fig. 1. These show the structure of the mycelia, and the variations in mycelium density across the cross sections of the composite structure. Visual inspection of the composite structure reveals a density gradient across the sample depth (5cm). Higher concentrations of mycelia networks are also observed at the interfaces, with the highest density of mycelia at the top surface and…

Conclusions

1. This study investigates the structural composition and the compressive deformation of bioprocessed mycelium composites reinforced with self-organized cellulosic fibers. The bioprocessed mycelium blocks, comprising cellulose hemp-ducts as reinforcing and nutritional substrates, are intertwined with laterite particles for further reinforcement to improve the compressive strength of the composite. The composite constitutes a multiscale heterogeneous architecture of a random network of the mycelium …

…

Disclosure and declaration

The authors do solemnly declare that there are no conflicts of interest in this work.…

CRediT authorship contribution statement

Precious O. Etinosa: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Ali A. Salifu:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Salifu T. Azeko:** Methodology, Investigation, Formal analysis, Conceptualization. **John D. Obayemi:** Validation, Investigation, Formal analysis. **Emmanuel O. Onche:** Writing – review & editing, Validation, Formal analysis. **Toyin Aina:**…

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

Acknowledgments

The authors are grateful for the financial support from World Bank African Centers of Excellence (ACE) program (Grant No. PAMI P126974) and the Worcester Polytechnic Institute, Worcester, USA.…

Reference (42)

F.V.W. Appels
Fabrication factors influencing mechanical, moisture- and water-related properties of mycelium-based composites
Mater. Des. (2019)

F.V.W. Appels
Fabrication factors influencing mechanical, moisture- and water-related properties of mycelium-based composites
Mater. Des. (2019)

M. Baláž
Eggshell membrane biomaterial as a platform for applications in materials science
Acta Biomater. (2014)

B. Budiansky *et al.*
Compressive failure of fibre composites
J. Mech. Phys. Solid. (1993)

L. Gou *et al.*
Morphological and physico-mechanical properties of mycelium biocomposites with natural reinforcement particles
Construct. Build. Mater. (2021)

L. Jiang *et al.*
Bioresin infused then cured mycelium-based sandwich-structure biocomposites: resin transfer molding (RTM) process, flexural properties, and simulation
J. Clean. Prod. (2019)

L. Jiang *et al.*
Manufacturing of biocomposite sandwich structures using mycelium-bound cores and preforms
J. Manuf. Process. (2017)

M. Jones *et al.*
Engineered mycelium composite construction materials from fungal biorefineries: a critical review
Mater. Des. (2020)

M. Jones *et al.*
Engineered mycelium composite construction materials from fungal biorefineries: a critical review
Mater. Des. (2020)

M. Jones *et al.*
Engineered mycelium composite construction materials from fungal biorefineries: a critical review
Mater. Des. (2020)

View more references

Cited by (0)

Recommended articles (6)

Research article

Retention force, translucency, and microstructural properties of translucent temporary luting cements: An in vitro study

Journal of the Mechanical Behavior of Biomedical Materials, Volume 142, 2023, Article 105781

Show abstract

Research article

Bond strength of various post-core restorations with different lengths and diameters following cycle loading

Journal of the Mechanical Behavior of Biomedical Materials, Volume 142, 2023, Article 105804

Show abstract

Research article

Micro-hydroxyapatite reinforced Ti-based composite with tailored characteristics to minimize stress-shielding impact in bio-implant applications

Journal of the Mechanical Behavior of Biomedical Materials, Volume 142, 2023, Article 105852

Show abstract

Research article

Infiltration OF 5Y-PSZ with thermally compatible glass: Strength, microstructure and failure mode analyses

Journal of the Mechanical Behavior of Biomedical Materials, Volume 142, 2023, Article 105812

Show abstract

Research article

High-versus low-viscosity resin cements: Its effect on the load-bearing capacity under fatigue of a translucent zirconia

Journal of the Mechanical Behavior of Biomedical Materials, Volume 142, 2023, Article 105829

Show abstract

Research article

Influence of height discrepancy between pulp chamber floor and crestal bone in the mechanical fatigue performance of endodontically-treated teeth restored with resin composite endocrowns

Journal of the Mechanical Behavior of Biomedical Materials, Volume 142, 2023, Article 105854

Show abstract

View full text