# Analysis of Hemp Reinforced Composites

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## Abstract

Industrial, infrastructural, and biodegradable structural applications using hemp fibers are of interest to enhancing environmental sustainability. The purpose of this research is to develop innovative techniques and combinations of constituents to use composites in agricultural, infrastructural and other relevant industries. The products including graphite or hemp reinforced polymers with different volume fractions and orientations are considered. While a large number of products could be used in the commercial production, we explore only two laminates in this investigation. Broad aspects of mechanical response for composites and their products are provided in the user manual of a software package developed at AdTech Systems Research in collaboration with Air Force Research Laboratory. After identifying important constituents for composites and desirable applications, an attempt was made to investigate a set of sample cases by running ASCA Code for 2 representative composite laminates. Using analytical techniques, effective response characteristics of representative composites are predicted and given in this paper. Based upon this research a set of influencing factors will be identified, specific number of composite laminates will be chosen, manufactured, analyzed and tested for their performance characteristics. Further research is in progress for comparative studies between predicted and experimental values.

## Keywords

Hemp, composites, micromechanics, micromechanics, response characteristics.

## 1. Introduction

Composites have several advantages over conventional infrastructure and aircraft production materials, including reduced weight, reduced number of fasteners, corrosion resistance, and an extended product life. In addition, composites can be designed specifically for certain industrial applications to achieve desired stiffness and strength characteristics. Composites are used on virtually all Department of Defense (DoD) weapon systems, civil engineering and medical applications. Composite structures are proven to reduce weight, fatigue, and corrosion damage, resulting in improved range, payload capability, speed/maneuverability, and stealth. The ability to custom design structural sections, key in the context of this research, reduces touch labor hours related to component production and development. The main disadvantage and largest criticism of using composite materials is the raw materials cost. The current life cycle cost models not taking into account various aspects of estimated cost-ratios is one of the most important challenges decision makers face in determining whether to continue or start production of a new structural system.

Composite manufacturing techniques and lack of consideration has placed composite materials at a disadvantage compared to metallic materials. Current models treat an increase in raw materials costs as an increase in total life cycle cost. These models do not take into consideration the potential cost savings based on reduced part count and touch labor hours in aircraft production through the use of composites. This lack of consideration leads to an inflated estimated life cycle cost when composites are incorporated into aircraft structures.

This understanding will be utilized in inventing innovative techniques and combinations of constituents; using composites containing agricultural products – namely hemp, *Cannabis sativa* containing <0.3% Δ9-tetrahydrocannabinol which produces strong bast fibers. Hemp fibers have been used for over 10,000 years in textiles and ropes. From the mid-15th to early 19th centuries, hemp was an essential commodity for producing canvas and ropes for military and trading ships. Modern industrial applications for hemp fiber include hempcrete insulations and composites. This work evaluates hemp as a method for reinforcing laminates for DoD, industrial, and agricultural applications.

### 1.1 Objectives

To develop micro and macro level analysis method for investigating response characteristics of hemp reinforced composite laminates. The properties available in literature (Bhoopati et al. 2019) are used in an Automated System for Composite Analysis (ASCA) to analyze hemp reinforced composites. In order to show the significance of interlaminar stresses in free edge regions leading to delamination, a relevant graphite reinforced laminates are considered and analyzed. This work provides a foundation for experimental work to develop appropriate micro/macro model input parameters and comparisons for composite response characteristics.

## 2. Literature Review

ASCA (Soni, 1994) provides analysis techniques for micro and macro mechanical response of composites widely used in aircraft, spacecraft, and auto industry. Extensive work (Bhoopati et al. 2019, Sullinsa 2016, Ivens et al. 1997, Schwarzova et al. 2017, Sharzad 2011, Sharzad 2013) on hemp fiber reinforced composite is steering the research towards the use of environmentally friendly applications. There is not much mechanics related work done in hemp reinforced composites. As an example, we have selected two cases of hemp fiber reinforced EPON 828 matrix laminates using fiber constituent properties from reference (Sullinsa 2016). For hemp fiber the Young's modulus is 2.9 msi (second case 5,8 msi) and Poisson ratio is 0.15. The matrix material properties of EPON 828 with Young's modulus 0.42 msi and Poisson ratio 0.35 are used from reference (Soni, 1994). For graphite AS4 fiber and matrix H3501-6 are used from reference (Soni, 1994). For fiber AS4 the Young's modulus is 34.1 msi and Poisson ratio is 0.22 and for matrix H3501-6 the Young's modulus is 0.62 msi and Poisson ratio is 0.34.

## 3. Methods

Broad aspects of mechanical response of composites and their products are given in reference (Soni, 1994). We started with a micromechanics model using 3-dimensional model called NDSANDS (N-Directional Stiffness AND Strength). Figure 1 shows the flow of sequence of calculations. Using constituent properties of fiber and matrix with volume fraction of the constituents, we calculate the ply stiffness properties. Further, using the ply properties, ply orientations, and thickness, we calculated the effective laminate properties based upon a composite Laminate Analysis (CLAP) module of ASCA. In addition, we computed interlaminar stresses for AS4/H3501-6 laminate. This shows the important aspect of interlaminar stress variability causing free edge effect.

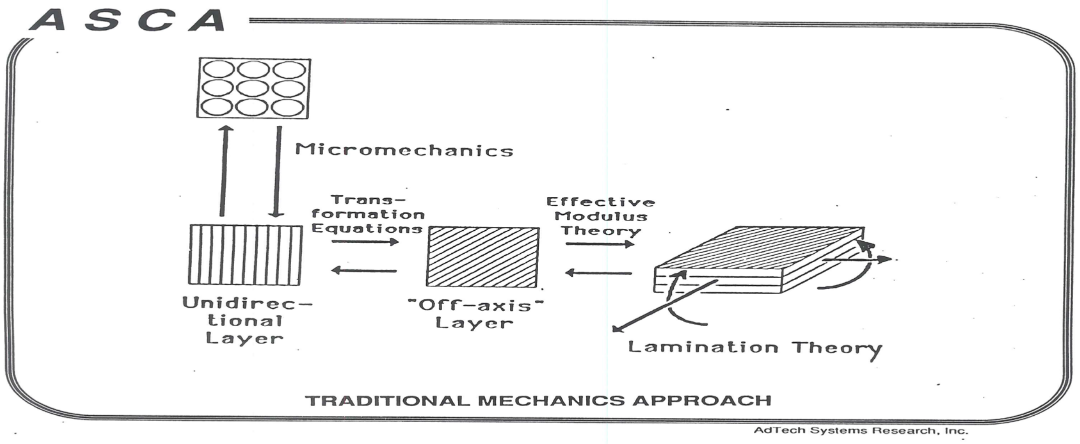


Figure 1. Micro and macro modeling for composites.

## 4. Data Collection

We have used hemp fiber properties from reference. For hemp fiber the Young's modulus varies from 2.9 msi to 5.8 msi and Poisson ratio is 0.15. The matrix material properties of EPON 828 with Young's modulus 0.42 msi and Poisson ratio 0.35 are used from reference (Soni, 1994). For computation of effective properties, we have used Young's modulus values 2.9 msi and 5.8 msi separately. For graphite AS4 fiber and matrix H3501-6 are used from reference (Soni, 1994). For fiber AS4 the Young's modulus is 34.1 msi and Poisson ratio is 0.22 and for matrix H3501-6 the Young's modulus is 0.62 msi and Poisson ratio is 0.34.

## 5. Results and Discussion

This research evaluates hemp reinforced composite laminates using different ratios of fibers and matrix. There are a number of parameters considered for product development, such as, natural fibers, matrix batch quantities and relevant processing parameters. After making the laminates stress and strength characteristics will be measured, calculated, and compared. Part one of this research is to determine how changing constituent parameters affect laminate material properties. As shown in section 4, micromechanics model (Soni, 1994), provides lamina properties from fiber and matrix constituents' properties. Micromechanics model (Soni, 1994), CLAP module provides the effective laminate properties. The material properties that are estimated are Young's modulus, Poisson's ratio and Shear modulus. Variation of material density along thickness will also be of interest.

### 5.1 Results for Hemp fiber and EPON 828 matrix laminates

Using the abovementioned input properties for both Hemp/EPON 828 laminates, with $E_A$=2.9 msi and $E_A$=5.8 msi, we calculated ply properties using NDSANDS. Using ply properties in CLAP module, effective laminate properties for a fiber volume fraction of 0.55, were computed for $(0/90)_s$ laminate (Figure 2) and provided in Tables 1 and 2.

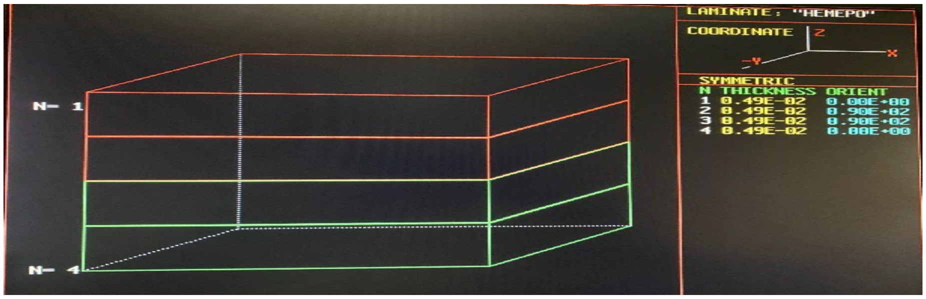
Table 1. Properties of a ply and of the $(0/90)_s$ laminate.

| | Hemp ($E_A$ =2.9 msi) /EPON 828, $V_f$=0.55 | $(0/90)_s$ |
|---|---|---|
| | $E_{11}$=1.78 msi | $E_x$=1.05 msi |
| | $E_{22}$=$E_{33}$=0.3 msi | $E_y$=1.05 msi |
| | $\nu_{12}$=$\nu_{13}$=0.26 | $\nu_{xy}$=0.075 |
| | $\nu_{23}$=0.3 | $G_{xy}$=0.366 msi |
| | $G_{12}$=$G_{13}$=0.366 msi, G23=0.114 ms | |
| | | |

Table 2. Properties of a ply and of the $(0/90)_s$ laminate

| | Hemp-1 ($E_A$ =5.8 msi) /EPON 828,$V_f$=0.55 | $(0/90)_s$ |
|---|---|---|
| | $E_{11}$=3.38 msi | $E_x$=1.92 msi |
| | $E_{22}$=$E_{33}$=0.434 msi | $E_y$=1.92 msi |
| | $\nu_{12}$=$\nu_{13}$=0.25 | $\nu_{xy}$=0.06 |
| | $\nu_{23}$=0.31 | $G_{xy}$=0.433 msi |
| | $G_{12}$=$G_{13}$=0.433 msi | |
| | $G_{23}$=0.166 msi | |

The notations used in tables 1 and 2 are conventional material properties, E, ν and G representing Young's modulus, Poisson Ratio and Shear modulus with subscripts representing the corresponding direction. Laminate properties were calculated by using ASCA's Composite Laminate Analysis Program (CLAP) module.



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LAMINATE: "HEMEPO"
SYMMETRIC
N THICKNESS ORIENT
1 0.49E-02  0.00E+00
2 0.49E-02  0.90E+02
3 0.49E-02  0.90E+02
4 0.49E-02  0.00E+00
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Figure 2. (0/90)$_s$ Laminate Orientation and Stacking Sequence

### 5.2 Results for AS4 fiber and H3501-6 matrix laminate

A Representative Volume Element with fiber and matrix was considered. Using a sample composite material consisting of AS4 fiber and H3501-6 matrix, effective ply properties of AS4/3501-6 composite were calculated. The model called, "Automated System of Composite Analysis", has been used to analyze aircraft grade composite laminates for the DoD. Four cases of different Volume Fraction ($V_f$) of fiber were considered for predicting the ply properties using the Representative Volume Element model. These values of $V_f$ are 0.55, 0.33, 0.22, 0.16. For fiber material AS4 the Young's modulus is 34.1 msi, Poisson ratio is 0.22 and for matrix material H3501 the Young's modulus is 0.62 msi, Poisson ratio is 0.34. Figure 1 shows the sequence of composite laminate layup. We started with the selection of fiber and matrix materials. Fibers were embedded in matrix as shown at the top element of Figure 1. Circles represent the tows of the fibers surrounded by matrix. Based upon the properties of fiber and matrix materials, effective ply properties were computed. For the case of $V_f$=0.55, computed ply properties are given in Table 3.

Table 3. Properties of a ply and of the quasi-isotropic laminate

| | | |
|---|---|---|
| | AS4/3501, $V_f$=0.55 | $(0/45/90/-45)_s$ |
| | $E_{11}$=19.0 msi | $E_x$=7.29 msi |
| | $E_{22}$=$E_{33}$=1.23 msi | $E_y$=7.29 msi |
| | $\nu_{12}$=$\nu_{13}$=0.26 | $\nu_{xy}$=0.3 |
| | $\nu_{23}$=0.38 | $G_{xy}$=2.79 msi |
| | $G_{12}$=$G_{13}$=0.67 msi | |
| | $G_{23}$=0.44 msi | |

The notations used in table 3 are conventional material properties, E, ν and G representing Young's modulus, Poisson Ratio and Shear modulus with subscripts representing the corresponding direction. Laminate properties are calculated by using ASCA's Composite Laminate Analysis Program (CLAP) module.

### 5.3 Interlaminar Stress Calculations

Using the properties given in table 3, inter-laminar stress components for applied stress in the laminate axis direction of 1 ksi were computed using ASCA. Results for 0 and 45-degree ply interface are given in figure 3. Inter-laminar stress components for the other 3 interfaces (45/90, 90/-45 and mid surface) are shown in figures 4, 5 and 6, respectively. These results provide an indication as to the variation in the stress components at different locations of the laminate. Using these stress components, appropriate criteria can be applied to predict the failure.

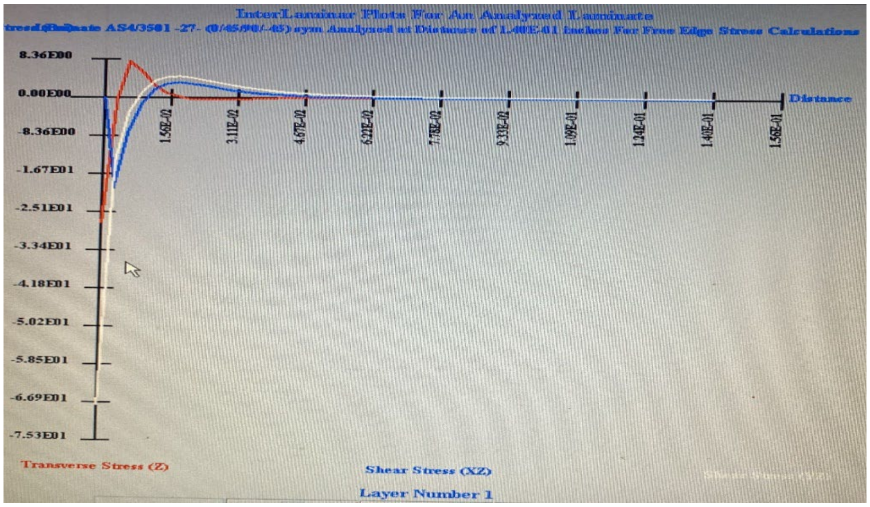

Figure 3. Interlaminar stress components at 0/45 interface of $(0/45/90/-45)_s$ laminate.

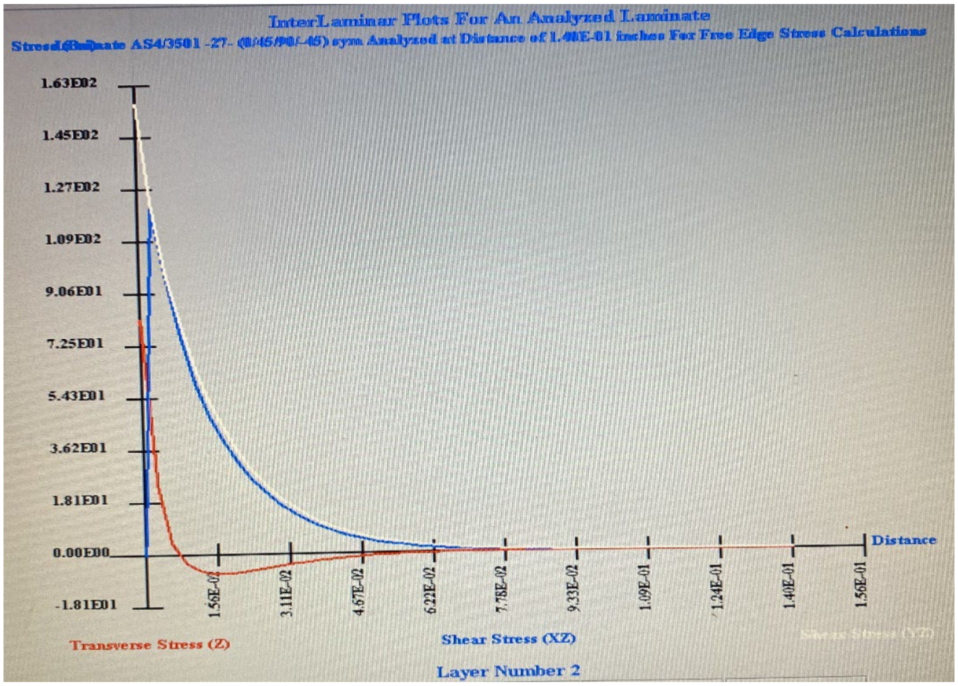

Figure 4. Interlaminar stress components at 45/90 interface of $(0/45/90/-45)_s$ laminate.

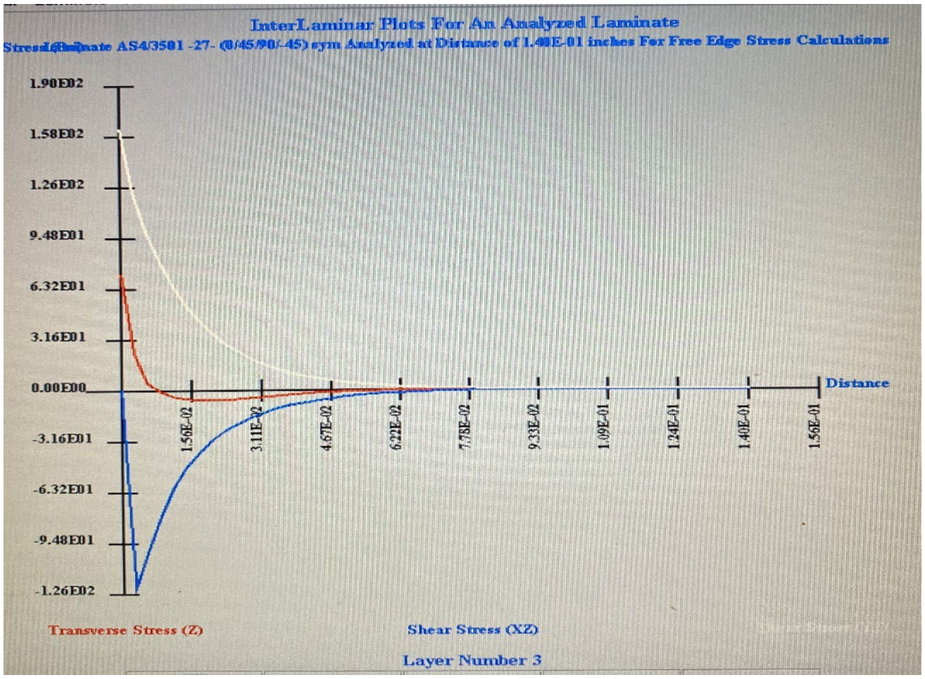

Figure 5. Interlaminar stress components at 90/-45 interface of $(0/45/90/-45)_s$ laminate.

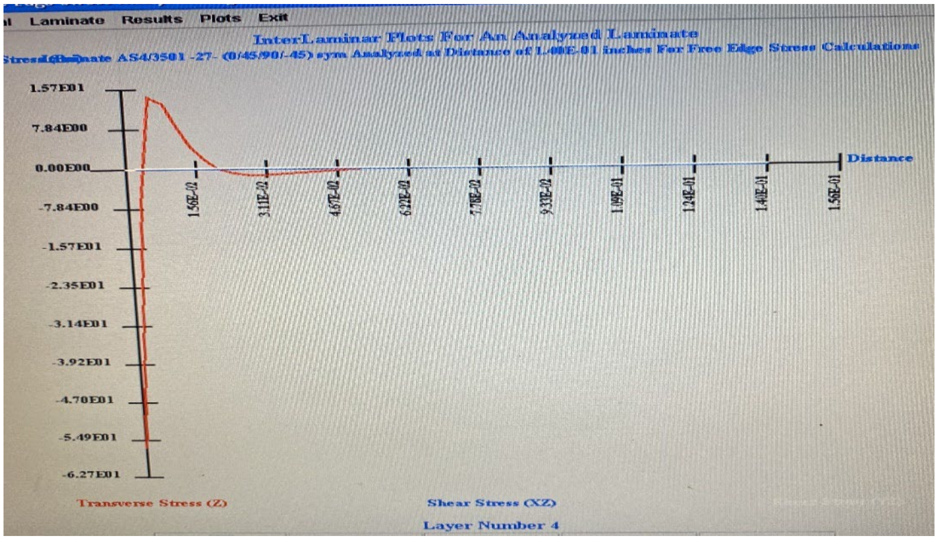

Figure 6. Interlaminar stress components at mid-surface of $(0/45/90/-45)_s$ laminate.

## 5.4 Discussion

Tables 1 and 2 show the variation in effective stiffness properties of the $(0/90)_s$ laminates made with the variation of hemp fiber properties 1): $E_A$=2.9 msi, $E_T$ =0.2 msi, $\nu_{AT}=\nu_{TA}$=.15, $G_{AT}$=1.01 msi; and 2): $E_A$=5.8 msi, $E_T$ =0.4 msi, $\nu_{AT}=\nu_{TA}$=.15, $G_{AT}$=2.02 msi; A stands for axial and T stands for transverse directions of the fiber; giving an idea as to how to design a composite for required applications.

Table 3 shows the effective properties of AS4/3501, $V_f$=0.55, well known quasi-isotropic laminate $(0/45/90/-45)_s$, which shows a huge variability of lamina properties. This variability of directional properties stimulates interlaminar stresses in figures 3 through 6. These results provide an indication as to the variation in the stress components at different locations of the laminate near the free edge. Using these stress components, appropriate criteria can be applied to predict the failure.

## 5.5 Future Plans

Central State University will be producing hemp fiber to develop our own products. The hemp thus produced will be tested to determine the mechanical properties, such as Young's modulus, Poisson's ratio and tensile strength. A set of composite laminates will be identified, manufactured and tested. The composite analysis code, ASCA, will be used to analyze the laminates. A comparison of experimental and predicted response characteristics will be done to show the efficacy of models used.

## 6. Conclusion

A foundation is laid for doing mechanics-based research on hemp-fiber-reinforced composites. There has been increasing interest in this field. We have effectively used the mathematical models developed in ASCA for studying the response characteristics of Hemp/EPON 828 and AS4/H3501-6 laminates. Future studies will study and improve the hemp reinforced composites and products.

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## Biographies

**Dr. Soni** has PhD from University of Roorkee (renamed as IIT Roorkee) India, 1972. Dr. Soni has more than 40 years of experience in teaching and research related to systems engineering design, analytical and experimental mechanics of composite materials and structures. Dr. Soni retired from AFIT in December 2011. Before joining as an Associate Professor in the Air Force Institute of Technology in December 2005, Dr. Soni was involved in AdTech Systems Research Inc as President and CEO for more than 20 years (1984- 2005). He has worked as a senior Scientist for the University of Dayton Research Institute (1981- 1984) conducting research in composite materials and structures. Dr. Soni's recent studies include: a) Cost modeling of composite Aircrafts; b) Systems Engineering Approach to Integrated Health Monitoring System for Aging Aircrafts; and c) Ballistic response of co-cured adhesive bonded composite joints. Dr. Soni is author/ co-author of 100+ research publications in the field of mechanics of solids and structures with special emphasis on composites. Dr. Soni is a Fellow of the American Society for Composites. He has won numerous awards including Co-author of Air Force Materials Laboratory's Cleary Award publication, State of Ohio Edison Emerging Technology Award, Enterprise Spirit Award of Kettering Moraine and Oakwood Chamber of Commerce; and Engineering Science Foundation (Affiliate Society Council) Award for Outstanding Professional Achievement for his accomplishments. Dr. Soni is a Heartfulness meditation trainer for more than 30 years.

**Dr. Sritharan** has PhD Civil Engineering, Colorado State University, Fort Collins, CO; 1984. Dr. Sritharan is a Professor of Water Resources Management, C.J. McLin International Center for Water Resources Management, Central State University, Ohio. He is actively engaged in numerous areas of environmental engineering & water resources management research & education. His areas of research include Surface Hydraulics, Sub-surface Hydraulics, Water Resources Systems Analysis, Hydrology, Water Quality, and Environmental Engineering, and Irrigation and Drainage. He has worked on, a) Water Use and Stream-Aquifer-Phreatophyte Interaction Along a Tamarisk-Dominated Segment of the Lower Colorado River; b) Application of GIS in Evaluating the Potential Impacts of Land Application of Biosolids on Human Health, in Geospatial Technologies in Environmental Management, Geotechnologies and the Environment. Professor Sri has held various leadership positions such as, Dean of College of Science and Engineering and Founding Director of the Land Grant Program at Central State University.

**Dr. Schluttenhofer** has PhD from the Department of Plant & Soil Sciences, University of Kentucky, Lexington, KY; 2016. Dr. Schluttenhofer is a Research Assistant Professor of Natural Products at Central State University, Ohio. He is leading research and development efforts in hemp production and applications in Ohio. Current research activities focus on understanding production, processing, and new uses for hemp. He has worked on a) the chemistry of hemp cigarettes and vape products; b) using hemp grain as a feed ingredient for fish; c) elucidating impacts of manure application to hemp; and d) evaluating varieties and breeding new hemp cultivars.