STRUCTURAL TESTING AND CHARACTERIZATION OF SRI LANKAN YELLOW BAMBOO BAMBUSA VULGARIS

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ABSTRACT

Bamboo is a woody grass belonging to the sub family *Bambusoideae* of the family *Poaceae* (*Gramineae*). The increasing need for sustainable building construction and the use of natural local materials have made bamboo a popular material. Sri Lanka is an island nation located south of the Indian peninsula. It is a tropical country with distinct dry and wet seasons. Sri Lanka has nearly 5000 ha of natural bamboo forests and another 5000 ha of domestically cultivated land, scattered mainly in the South Western zone which amounts to 0.5% of the total forest cover in Sri Lanka. However, with the restoration of cascading reservoir systems in the Eastern Province, there is potential to have many marginal lands converted to bamboo plantations hence allowing for the growth and harvesting of bamboo in a sustainable manner for use in construction as a structural material.

Sri Lanka is home to ten endemic species of bamboo. In addition, several exotic species have been introduced to the country. The bamboo plant has a variety of uses. Industrial utilization of bamboo can be through primary or secondary value addition, which enhances the market value of bamboo. Bamboo in construction is found in either full-culm or engineered form. Bamboo is limited in its application through its durability and its tendency to split. Hence it needs to be processed and treated to ensure its long-term usage. Bamboo structures should be detailed appropriately for the full protection of treated bamboo. Bamboo used for construction has to undergo harvesting, grading, cleaning, preservative treatment, and storage. Determination of structural parameters of Sri Lankan bamboo could be based on ISO standards since other standards are often based on ISO standards themselves and are more suitable for bamboo species from those particular countries of those respective standards. To date, the mechanical characterization of Sri Lankan bamboo species has not been found in literature.

The widespread availability of *Bambusa Vulgaris* (Sri Lankan Yellow bamboo) led to it being chosen for investigation in this study. All bamboo culm sections in this study were obtained from a single supplier with initial moisture content and dimensions obtained on delivery. Once culm data was measured for all culms, a random selection of culms underwent preservation treatment prior to testing.

The mechanical characterization tests provided a set of structural parameters including; average strength values in compression, shear, flat ring flexure and tension for *Bambusa Vulgaris* (Sri Lankan Yellow bamboo). All Strength values tend to show gradual increase from bottom towards the top of the culm. Comparison of treated vs. untreated strength values across all four tests showed no significant increase in strength initially due to preservation treatment. Average densities of test samples tend to show a strong relationship with their respective strengths, whereas average diameter does not. Comparison of average strength values of *Bambusa Vulgaris* (Sri Lankan Yellow bamboo) with the same species from Kenya as well as relatable other species from Thailand revealed that the average strength values of *Bambusa Vulgaris* (Sri Lankan Yellow bamboo) to be lower compared to the respective average strength values of other species except in the case of tensile strength. Sri Lankan *Bambusa Vulgaris* showed characteristic strengths of 17.0N/mm^2, 2.0N/mm^2, 16.0N/mm^2 and 20.0N/mm^2 for compressive strength, shear strength, bending strength in flat ring flexure and tensile strength respectively.

Key words: Bambusa Vulgaris, flat ring flexure, compressive strength, shear strength,

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1. INTRODUCTION

1.1 General

The usage of sustainable construction materials is a popular trend in the construction industry at present due to the need to minimize the environmental footprint of development. Bamboo, a woody grass belonging to the sub family *Bambusoideae* of the family *Poaceae* (*Gramineae*), is one such sustainable construction material with high potential for varied uses.

The use of bamboo in construction is long established and still used extensively as a structural material in many regions (Mera & Xu, 2014). Bamboo can also be utilized in culinary and decorative areas. Bamboo is becoming popular as an excellent substitute for wood in paper industries, domestic commodities, cottage industries, board industry and charcoal industries (Lobovikov, et al. 2007).

Bamboo is an extremely versatile building material. Bamboo forest biomass stores a large quantity of carbon with nearly half of the total biomass being carbon. It has a great potential in removing heavy metal ions as a biological absorbent. The increasing need for sustainable building construction and the use of natural local materials have made bamboo a popular material. Bamboo is a strong, lightweight, fast-growing material which also has a very low embodied energy (Kaminski, et al. 2016).

The durability of bamboo limits its application and therefore needs to be treated to ensure its long-term usage. Untreated bamboo has a lower lifetime if in contact with the atmosphere and soil. Good detailed design such as keeping the culms away from the ground and under cover will help to increase its life span (Janssen, 1995). Stone foundations separating the bamboo from the soil and large overhangs on the roofs are a common detailing design practice. Traditional methods of bamboo treatment such as white washing and smoking are not expensive although long-term durability is still not ensured by them (Davies & Walker, 2008).

The natural tapering of bamboo and the varying structural properties make it a very hard material to categorize and development of standards is difficult because of the way bamboo's properties vary with geographical location and age. Irregular node spacing on the bamboo culms and varying thicknesses can cause considerable problems in design. When specifying bamboo, it is important to ensure that it comes from a sustainable source and is harvested, procured and visually graded by a reputable and experienced organization. There is a lack of structural data for Sri Lankan bamboo and there are no complete bamboo building codes for Sri Lanka. Unlike timber, bamboo has no knots or rays making the culms more evenly stressed across their length. The culms are hollow but split into chambers through diaphragms at the nodes. Bamboo generally has very good parallel-to-fibre structural properties, with allowable stresses in bending; tension and compression relatively high. A weak parenchyma matrix and typically thin section walls are reasons for bamboo's tendency to split resulting in low allowable shear stresses. Joints tend to be the most difficult aspect to design and also likely to be the weakest elements in the structure due to the hollow nature of bamboo as well as the above mentioned good parallel-to-fibre properties (Kaminski, et al. 2016).

Restoration of cascading reservoir systems in the Eastern Province enables many marginal lands to be converted to bamboo plantations for the supply of a sustainable construction material to be use in such structures as bridges and residential buildings. Such buildings would require very special shapes to ensure full protection of the treated bamboo, ensuring such structures potentially reach a lifespan of about 50 years or more.

1.2 Scope of research

There exist various challenges in using bamboo as a structural material to create a new architectural trend where a new breed of structural systems promoting sustainable construction of buildings and bridges that could merge well within the tourism industry could emerge in Sri Lanka. The variation of structural properties of bamboo makes it difficult categorize for usage. There is a lack of sufficient data on the structural parameters of bamboo species found in Sri Lanka. Hence the scope of this research lies in collection of data for the usage of bamboo as a structural material.

Bambusa Vulgaris (Sri Lankan Yellow bamboo) was chosen due to its widespread availability in Sri Lanka and known use as a construction material. Therefore, its potential uptake and acceptance of its use in construction could be considered.

1.3 Objectives

The aim of this research was to characterise Sri Lankan yellow bamboo through structural testing. It was intended to achieve the above objective through the following steps.

- Obtaining dimensional culm data of *Bambusa Vulgaris*
- Obtaining values for strength parameters of Bambusa Vulgaris culms through testing
- Checking for any correlation between dimensional and strength data

1.4 Methodology

The methodology of the research is as follows:

- Extensive literature review on Structural bamboo
- Fabrication of Test Apparatus for Structural Testing
- Obtaining culm data through measurements
- Treatment of limited number of culms
- Structural testing and determination of parameters based on test results
- Checking for correlation between strength data and dimensional data

1.5 Arrangement of the thesis

In this thesis, the research project has been presented in five chapters. The outline of this thesis is as follows.

Chapter 1: Introduction, Problem Identification, Aim and objectives, Methodology and Significance of the research.

Chapter 2: Details of past research and associated background studies

Chapter 3: Methodology of experimental work

Chapter 4: Results from experiments and analysis of experimental results.

Chapter 5: Conclusions and suggestions for future work relevant to the research topic.

2. LITERATURE REVIEW

2.1 Bamboo in Sri Lanka

Sri Lanka is an island nation located south of the Indian peninsula. It has an area of 66,000 sq. km, with a span of 433km from North to South (latitude 5°55 North to 9°51 North), and 244 km East to West at its widest point (longitude 79°41 East to 81°53 East). Sri Lanka is a tropical country with distinct dry and wet seasons.

The total forest cover of Sri Lanka is 1,933,000 ha. The total area of bamboo forests in Sri Lanka is reported to be 5166 ha. Total area cultivated domestically is 5000 ha. Hence total area covered is approximately 10000 ha, which is about 0.5% of the total forest cover in the country (Amunugoda, 2019). Forest cover is showing a significant decrease over the years. Sri Lanka is home to ten endemic species of bamboo in addition to several exotic species having been introduced to the country as shown in Table 2.1.

Table 2.1: Cultivation locations of bamboo species in Sri Lanka (Kariyawasam, 1998)

No	Species (Native)	Location
1	*Bambusa bambos*	Dry zone (Wasgamuwa) Intermediate and dry forests in low hills
2	*Ochlandra stridula*	Wet lowlands and in the low hills in the western and southern parts of the country
3	*Arundinaria densifolia*	High altitudinal montane areas
4	*A. debilis*	High altitudinal montane areas
5	*A. scandens*	High altitudinal montane areas
6	*A. floribunda*	High altitudinal montane areas
7	*A. walkeriana*	High altitudinal montane areas
8	*Pseudooxytenanthera monodelpha*	Wet and intermediate zone, mountains of Badulla and Nuwara Eliya districts
9	*Davidsea attenuata*	Wet and intermediate zone, mountains of Badulla and Nuwara Eliya districts
10	*Dendrocalamus cinctus*	Dry zone North Central Region, restricted distribution.
No	**Species (Introduced)**	**Location**
1	*Bambusa multiplex*	Cultivated in rural area
2	*Bambusa vulgaris*	Cultivated in the wet zone, common on riverbanks
3	*Dendrocalamus asper*	Cultivated in the intermediate zone

4	*Dendrocalamus giganteus*	Cultivated in the wet zone; common on riverbanks and home gardens
5	*Dendrocalamus membranaceus*	Cultivated in the intermediate hills
6	*Dendrocalamus strictus*	Planted by Forest Department in the dry zone
7	*Thyrsostachys siamensis*	Cultivated as an ornamental bamboo

2.2 Utilization of Bamboo

The bamboo plant has a variety of uses. One of the ways of classifying the uses is based on the species of bamboo. Most of the abovementioned bamboo species have many identified uses as given in Table 2.2 below.

Table 2.2: Known uses of Sri Lankan bamboo species (De Soyza & Vivekanandan, 1991)

No	**Species (Native)**	**Uses**
1	*Bambusa bambos*	Bridges; ladders; leaves for thatching
2	*Ochlandra stridula*	Storage boxes; winnowing fans; food covers; milk strainers; flutes; blinds; tea plucker's baskets
3	*Pseudoxytenanthera monodelpha*	tea plucker's baskets, fruit & vegetable baskets
4	*Davidsea attenuata*	tea plucker's baskets, fruit & vegetable baskets
No	**Species (Introduced)**	**Uses**
1	*Bambusa multiplex*	Ornamental
2	*Bambusa vulgaris*	House frames; walls; bridges; scaffolding; floor coverings; fences; ladders
3	*Dendrocalamus asper*	Multiple uses
4	*D. giganteus*	Bridges; house frames; walls; ladders; floor covering; scaffolding; lamp stands; vessels
5	*D. membranaceus*	Multiple uses
6	*D. strictus*	House frames; tent poles; concrete reinforcement; walls; scaffolding; fences; mats; thatching (leaves)
7	*Thyrsostachys siamensis*	Wattle and daub walls; scaffolding; ceilings

Industrial utilization of bamboo can be differentiated into two stages. First is primary value addition. In value addition of primary production, bamboo is utilized as an end product without much change from raw state. Examples of primary value addition provided by (Wei, 2019(a)) are listed below:

- Biomass for energy
- Pulp production
- Fodder & feed for farms
- Direct utilization of shoots
- Direct utilization of leaves, branches and other parts

Secondary value addition of bamboo is the complete utilization of bamboo biomass through various production techniques (Wei, 2019(b)). Table 2.3 provides some examples of secondary value addition for bamboo.

Table 2.3: Uses of parts of Bamboo plant (Wei, 2019(b))

Part of Plant	**Biomass percentage%**	**Products**
Rhizome/Roots		Handicrafts, brushes
Sheaths		Handicraft, fodder, feed, pulp
Shoots		Vegetable, edible fibre
Base part	5-10	Charcoal, handicrafts
Middle lower part	40-50	Laminated furniture, flooring
Middle upper part	30-40	Curtain, mat, carpet, handicraft, woven articles
Top part	5-10	Bamboo poles, scaffoldings, sticks, agricultural tools
Twigs		Brooms, clothes
Leaves		Manure, medicine, fodder, juices, pigments, beverage
Left over from processing		Charcoal, pulp, particle boards, fuel

2.3 Bamboo as a Construction Material

Bamboo is used in two different forms as a construction material. In full culm bamboo construction, bamboo is used in its harvested geometric shape without modifying. Full culm bamboo is popular in the construction of footbridges. Full culm bamboo is also a popular construction material in structures used for tourism purposes. It has been used in the construction of innovative architectural shapes such as Luum Temple in Mexico. Ease of fabrication of structure due to the lightweight nature of bamboo has been utilized at the

Sombra Verde pavilion in Singapore. Architectural shift towards dynamic movement and flexibility favors bamboo as a material. Figures 2.1 to 2.4 given below provide illustrations of the use of full culm bamboo in construction.

Figure 2.1: Full culm bamboo Bridge in Java, Indonesia (www.archdaily.com, 2017)

Figure 2.2: Bamboo used for a restaurant building, Elle, Sri Lanka (Photo: Kumara, 2019)

Figure 2.3: Luum Temple, Mexico (bamboo-construction, 2019)

Figure 2.4: Sombra Verde pavilion, Singapore (bamboo-construction, 2019)

Engineered bamboo which is the second form of bamboo as a construction material involves the use of pressed and laminated bamboo which is similar to timber in geometry through processing. Figure 2.5 below shows an engineered bamboo construction.

Figure 2.5: Engineered bamboo construction (Wei, 2019(b))

Full culm bamboo could be used to construct pedestrian bridges cost effectively in rural areas. Standard truss and arch designs are followed in practice in the construction of such bridges. Bridge designs used have typical spans from 6m to 30m and typical width varying from 2.9m to 3.9m (German development cooperation, Faculty of Environmental Sciences Pereira University of Technology, 2000).

Similarly, typical full culm bamboo roof frame designs are used for simple roof frames in practice. The choice of frame depends on purpose of structure. Frames are composed of separate structural elements fabricated in bamboo (Stamm, et al. 2014). Sri Lankan yellow bamboo is also used as a material for scaffoldings widely in Sri Lanka.

2.4 Preparation for Full Culm Bamboo Construction

Construction with full culm bamboo follows a set of procedures to ensure quality of the structure.

2.4.1 Harvesting and Grading

Matured bamboo of 3-5 years old is used for construction. Higher lichens and moss cover indicates the culm has been standing for long in the groove. If the culm has become grey, the culm might be too old, and the tissue would have started losing tensile strength.

Quality Grading is carried out through visual inspection according to length, diameter, and straightness to separate culms. It is recommended to separate the straighter poles from the much-curved culms. The zigzag poles are separated to form a third group that can be used for non-structural applications. The process of carrying out visual grading is indicated in Figure 2.6 below.

A-grade Poles are the strong and straight ones, rated according to their diameters.
B-grade Poles are the strong and curved one, also separated in diameters.
C-grade Poles: have more than one curve, cracks and are only useful in sections (Stamm, et al. 2014).

Figure 2.6: Checking straightness of pole

2.4.2 Preservation treatment methods

Preservation treatment ensures the durability of harvested bamboo. Treatment of harvested bamboo could be broadly categorized into two types. First one is oil-based chemicals which penetrate quicker and deeper than water. The ingredients in this method are usually more expensive. Oil based chemicals used in closed or air-conditioned rooms could harm the nervous system or cause allergies. The second type is water-based chemicals, where boron, copper or chrome containing salts are usually dissolved in water. Among this Borax treatment is considered most eco-friendly and perfectly suited for diffusion treatment of fresh bamboo poles (Stamm, et al. 2014).

Given below are the different techniques practiced in Borax treatment of bamboo poles. Selection of the suitable treatment technique depends on the size of bamboo, time allowed and labour availability.

a. Horizontal dip diffusion

This method is suitable for industrial treatment plants where large numbers of poles are to be treated at once. In this method the poles are drilled thorough both ends and immersed into tanks filled with the borax solution as shown in Figure 2.7. The suggested curing period for cold water solution is 1 week, for hot water solutions the curing period reduces to 3 days.

Figure 2.7: Horizontal dip diffusion (Stamm, et al. 2014)

Figure 2.8: Vertical sap diffusion (Stamm, et al. 2014)

b. Vertical sap diffusion

This is a smaller scale treatment method. The bamboo poles are kept vertically by forming a tripod among themselves or by placing slightly inclined along a tree as shown above in Figure 2.8. In this method the poles are drilled at only one end and filled with borax solution.

c. Treatment in trough

This method is suitable for short bamboo. The bamboo strips are immersed in a trough which is filled with borax solution and heated from below. Heating 2-3 hours at 70°C is enough to treat the strips. A set of strips undergoing treatment in a trough is portrayed in Figure 2.9 below.

Figure 2.9: Treatment in trough

d. Boucherie method

This can be done within one day of cutting the bamboo. The cut bamboo is placed in a bucket filled with borax solution with leaves and shoots intact so that the transpiration pulls the solution upwards. However, this may not be adequate for industrial usage.

e. Modified Boucherie method

In this method the pressure enabling the diffusion of the treatment solution is created artificially using pumps as shown in the below Figure 2.10. Treated poles are stored without direct exposure to atmosphere under a roof without placing directly on soil. If necessary, the treated poles must be bleached for aesthetic appearance.

Figure 2.10: Modified Boucherie method (Stamm, et al. 2014)

2.5 Design of Bamboo Structures

2.5.1 Design Standards

There exists no specific bamboo design code for Sri Lanka at present. Hence designers have to rely on standards. There are five different standards for full culm bamboo globally at present. The following Table 2.4 lists the respective codes and standards available for full culm bamboo design presently.

Table 2.4: Existing structural bamboo standards and codes (Gato´o, et al. 2014)

Country Standard	Code	Standard
China		JG/T 199: Testing method for physical and mechanical properties of bamboo used in building (PRC MoC, 2007)
Colombia	Reglamento Colombiano de Construccio´ n Sismoresistente – chapter G12 Estructuras de Guadua (Guadua structures) (ICONTEC, 2010)	NTC 5407: Uniones de Estructuras con Guadua angustifolia Kunth (Structural unions with Guadua angustifolia Kunth) (ICONTEC, 2006) NTC 5525: Me´ todos de Ensayo para Determinar las Propiedades Fı´sicas y Meca´ nicas de la Guadua angustifolia Kunth (Methods and tests to determine the physical and mechanical properties of Guadua angustifolia Kunth) (ICONTEC, 2007)
Ecuador	Norma Ecuatoriana de la Construccio´ n – chapter 17 Utilizacio´ n de la Guadua Angustifolia Kunth en la Construccio´ n (Use of Guadua angustifolia Kunth in construction) (INEN, 2011)	INEN 42: Bamboo Can˜ a Guadua (bamboo cane Guadua) (INEN, 1976)
India	National Building Code of India, section 3 Timber and bamboo: 3B (BIS, 2010)	IS 6874: Method of tests for round bamboos (BIS, 2008)

		IS 15912: Structural design using bamboo – code of practice (BIS, 2012)
Peru	Reglamento Nacional de Edificaciones, Section III. Code E100 – Disen˜ o y Construccio´ n con Bamboo (ICG 2012)	
USA		ASTM D5456: Standard specification for evaluation of structural composite lumber products (ASTM, 2013)
International		ISO 22156: Bamboo – structural design (ISO, 2004a) ISO 22157-1 Bamboo – determination of physical and mechanical properties – part 1: requirements (ISO, 2004b) ISO 22157-2: Bamboo – determination of physical and mechanical properties – part 2: laboratory manual (ISO, 2004c) ISO 22157: 2019 Bamboo structures — Determination of physical and mechanical properties of bamboo culms — Test methods (ISO, 2019)

Among them, ISO standards are the most suitable to conform for Sri Lankan full culm bamboo design. This is due to the other standards being suitable for their respective country's' bamboo species. Most of the other standards are also based on the guidelines provided by the ISO standard as well.

For full culm bamboo designs following standards could be referred:

- ISO 22156: 2004 Bamboo – structural design
- ISO 22157-1: 2004 Bamboo – determination of physical and mechanical properties – part 1: requirements

- ISO 22157-2: 2004 Bamboo – determination of physical and mechanical properties – part 2: laboratory manual
- ISO 22157: 2019 Bamboo structures — Determination of physical and mechanical properties of bamboo culms — Test methods

Design of structures using engineered bamboo could be based on the existing timber codes and standards since engineered bamboo is similar to timber in terms of geometry and significantly different from full culm bamboo in this regard. The following Figure 2.11 lists the timber codes and standards which could be used in engineered bamboo design.

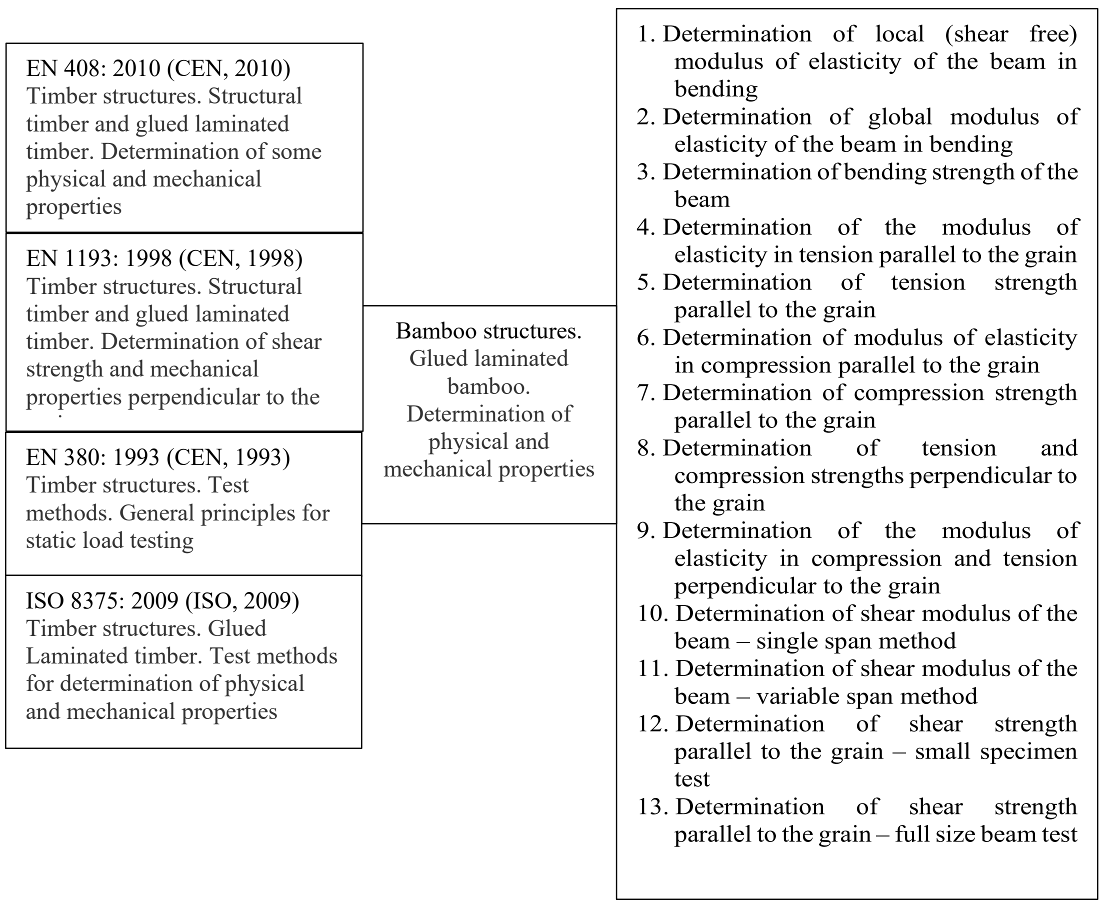

Figure 2.11: Relevant European norms and ISO timber standards and their application to bamboo (Gato´o, et al. 2014)

2.5.2 Design Values

Average strength values and characteristic strength values for different types of bamboos are available in literature as given in Table 2.5 below. However, neither average strength values nor characteristic strength values are available for Sri Lankan grown bamboo species yet.

Table 2.5: Average strengths of dry mature bamboo

	Flexure (*fm,k*) (N/mm^2)	**Shear (*fv,k*) (N/mm^2)**	**Tension parallel to fibre (*ft,0,k*) (N/mm^2)**	**Compression parallel to fibre (*fc,0,k*) (N/mm^2)**	**References**
Kenyan *Bambusa vulgaris*	137.7	-	94.3	51.7	(Mbuge, 2000)
Thai *Dendrocalamus asper*	83.7	9.6	96.0	68.7	(Sompoh, et al. 2013)
Thai *Bambusa blumeana*	92.0	12.2	120.0	66.5	
Thai *Dendrocalamus strictus*	83.0	13.0	106.3	56.0	
Thai *Bambusa bambos*	164.3	9.0	101.5	54.2	

Most Thai bamboos show a similar pattern among themselves in average strengths.

Characteristic strength of a Colombian bamboo species calculated using equations are available in literature along with the respective equations. Scheme design strengths for all species have also been suggested as given in the blow Table 2.6.

Table 2.6: Characteristic strength and design values for Colombian dry mature bamboo

	Flexure (*fm,k*) (N/mm^2)	**Shear (*fv,k*) (N/mm^2)**	**Tension parallel to fibre (*ft,0,k*) (N/mm^2)**	**Compression parallel to fibre (*fc,0,k*) (N/mm^2)**	**References**
Colombian grown *Guadua angustifolia Kunth*	35-50	3-5	40	20	(Kaminski, et al. 2016)
For scheme design, all species	30	2	40	20	

The characteristic strengths of Colombian bamboo suggested are much lower than the average strength values above. In addition to characteristic strength literature suggests typical values for modulus of elasticity of bamboo. These values are dependent on the moisture content as shown in Table 2.7.

Table 2.7: Typical values of modulus of elasticity (Kaminski, et al. 2016)

Moisture content (%)	**Average modulus E0.5 (N/mm^2)**	**5th percentile modulus E0.05 (N/mm^2)**
12	10,000-17000	7500-13,000
19	8500-15,000	6700-8000

The characteristic value of strength for a whole population, $f_{i,k}$ can be determined from the following Equation 2.1 (Kaminski, et al. 2016):

$$f_{i,k} = C_{mois} C_{lab} f_{i,0.05} \left[1 - \frac{2.7s}{m\sqrt{n_t}}\right] \qquad \text{Eq 2.1}$$

Where:

$f_{i,k}$ is the characteristic value of strength in N/mm^2

$f_{i,\,0.05}$ is the 5th percentile value of strength results from test data in N/mm^2

C_{mois} is the moisture content correction factor

C_{lab} is the laboratory correction factor

s is standard deviation of test data in N/mm^2

m is mean value of test data in N/mm^2

n_t is the number of tests

The fifth percentile value could be calculated from strength test results from Equation 2.2:

$$f_{i,0.05} = m - 1.645s \qquad \text{Eq. 2.2}$$

Moisture content correction factor and Laboratory test condition factor can be computed from the following Table 2.8 and Table 2.9 respectively.

Table 2.8: Moisture content correction factor C_{mois} as a function of the moisture content at time of testing (Kaminski, et al. 2016)

Moisture content (MC) %	Flexure	Shear	Tension parallel to fibre	Compression parallel to fibre
MC≤12	1.0	1.0	1.0	1.0
12<MC≤18	Interpolate between above and below			
MC<18	1.2	1.2	1.2	1.2

Table 2.9: Laboratory test correction factor C_{lab} (Kaminski, et al. 2016)

Flexure	Shear	Tension parallel to fibre	Compression parallel to fibre
0.7	0.5	0.5	0.7

Rules of thumb are also available to calculate the design values.

For most bamboos, the density (ρ) is about 700 − 800 kg/m^3, which varies with the quality of the site of growing, the species, the position of the culm. Strength increases with the density of bamboo (Burggräf , 2006). Increse in moisture content reduces the tensile strength of bamboo (Fattah, et al. 2014).

2.5.3 Flat ring flexural test of bamboo

Flat ring flexure is a test developed to assess the transverse tensile strength of bamboo. This test method presents significant advatages inorder to be used as a standard test for full culm bamboo (Virgo, et al. 2018).

They are the following:

- The test being simple in nature, which makes flexural testing less cumbersome and saves time
- The test being compression-based (in the field it can be run using free weights rather than a test machine)
- Could use a simple apparatus and specimen, which makes testing possible via the standard compression machine and saves test material for more tests.

2.6 Summary

Bamboo is a suitable material due to increase in demand for sustainable building construction and the promotion of use of natural local materials.

Bamboo forests occupy a very small portion of the exiting total forest cover in Sri Lanka. Creating bamboo forests and plantations is a suitable technique to counter the reducing forest cover of Sri Lanka. Native and exotic bamboo species in Sri Lanka have many known uses that can be tapped industrially. Bamboo is a suitable plant to face challenges and minimize impacts of climate change.

Bamboo for construction is of two types. One is full culm bamboo which can be used to fabricate structural elements. Full culm bamboo can be used to in construction of both typical and innovative structures. Typical structures include bridges and roof frame structures which follow typical designs used in practice. Other is engineered bamboo which is of similar geometrically and utilization wise to timber. Bamboo used for construction has to undergo a series of processes before being used. These processes are harvesting, grading, cleaning, preservative treatment, bleaching and storage. Preservative treatment is necessary to ensure durability of the structure.

Design of bamboo structures with structural bamboo can be based on ISO standards since there is no bamboo design code for Sri Lanka at present. Average strength values and characteristic strength values for different types of bamboos are available in literature. However, neither average strength values nor characteristic strength values are available for Sri Lankan grown bamboo species yet. Flat ring flexure is an efficient test method to determine transverse tensile strength of bamboo.

Hence, based on literature, there exists a need to determine the basic structural properties of Sri Lankan grown bamboo species to ensure their wider usage based on scientific principles. *Bambusa Vulgaris* (Sri Lankan Yellow bamboo); a species with widespread availability in Sri Lanka, makes it a species with potential for uptake and acceptance for use in construction. So, this research focused on characterization and determination of important structural parameters of Sri Lankan *Bambusa Vulgaris* to ensure its wider usage.

3. EXPERIMENTAL PROGRAMME

3.1 Introduction

Tests were conducted to determine four different structural parameters for Sri Lankan Yellow bamboo. The tested parameters are as follows:

- Compression parallel to fibres
- Tension parallel to fibres
- Shear parallel to fibres
- Bending strength perpendicular to fibres from Flat ring flexure test

In addition to structural testing, culm data was measured and recorded for each pole prior to testing. Some selected poles also underwent preservation treatment.

3.2 Fabrication of Test Apparatus

In order to measure culm data and to carry out structural testing, a few special apparatus have been fabricated.

3.2.1 Culm Data Measurement Frame

Pair of V-frames was developed in order to facilitate culm data measurements. Dimensions of the V-frames are given in Figure 3.1 below.

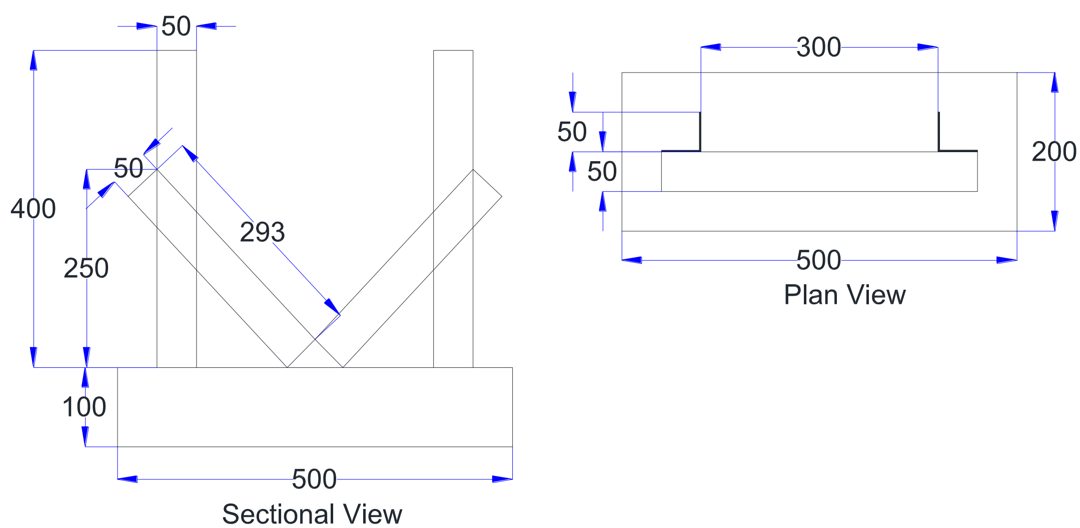

Figure 3.1: Dimensions of the fabricated V-frames in mm

The following Figure 3.2 gives a clear picture on the use of V-frames for culm data measurement

Figure 3.2: 3D view of a V-frame in use for culm data measurement

3.2.2 Compressive Strength Testing Plates

Plates for compressive strength testing parallel to fibres were designed according to ISO 22157: 2019 Bamboo structures — Determination of physical and mechanical properties of bamboo culms — Test methods, 2019. Dimensions of the plates developed is as given in Figure 3.3 below.

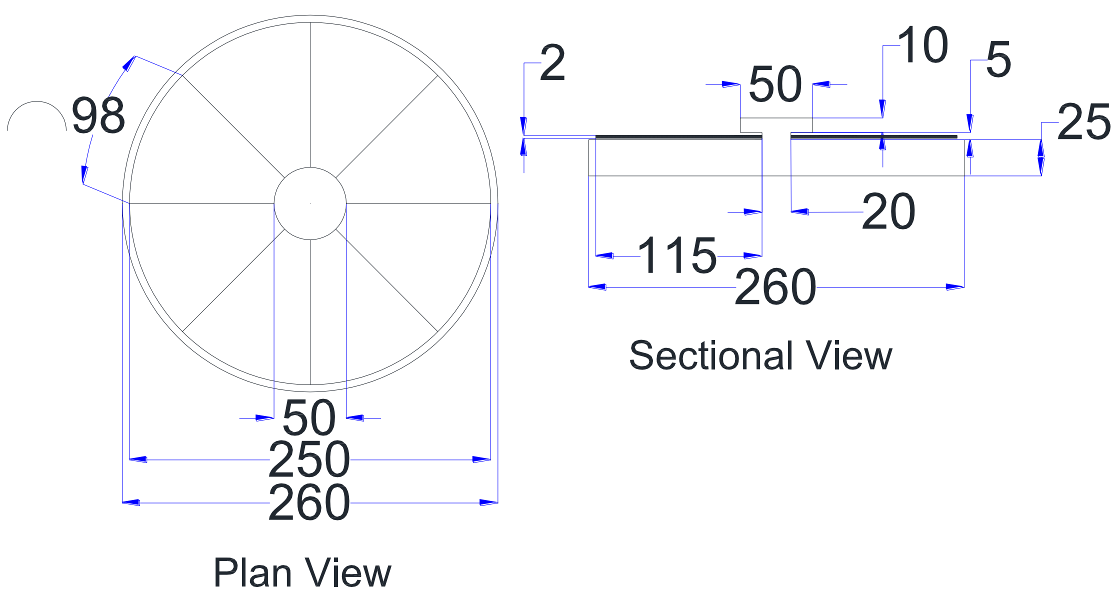

Figure 3.3: Dimensions of compressive strength testing plates in mm

A pair of thin steel plates was cut into equal parts and used in minimizing friction. Thin steel plates along with the base is shown clearly in Figure 3.4 below.

Figure 3.4: 3D view of compression testing plates

3.2.3 Shear Strength Testing Plates

Plates for shear strength testing parallel to fibres were designed according to ISO 22157: 2019 Bamboo structures — Determination of physical and mechanical properties of bamboo culms — Test methods, 2019. Dimensions of shear strength test plates are as given in below Figure 3.5.

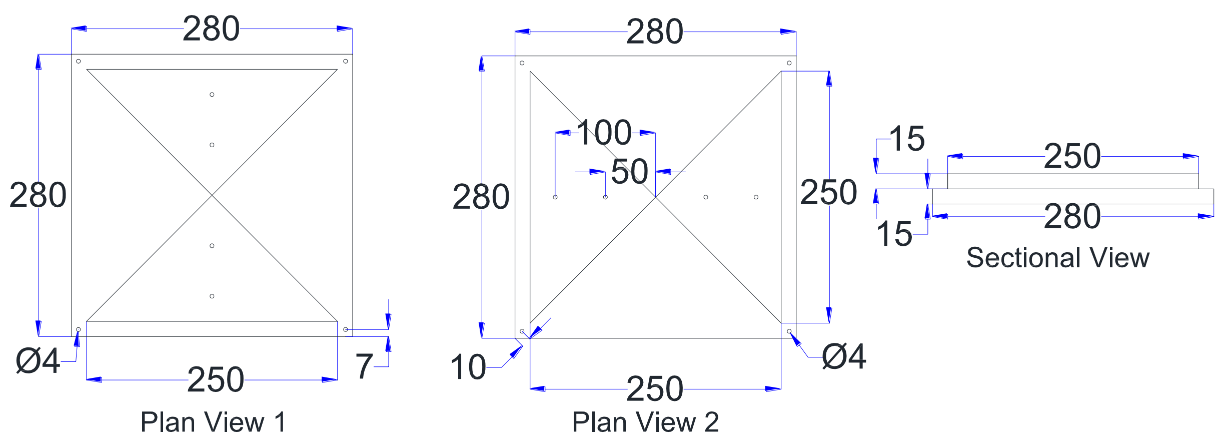

Figure 3.5: Dimensions of shear strength testing plates in mm

These ISO standards follow bow tie shear test for shear strength parallel to fibres. The fabricated test plates are shown in Figure 3.6 below.

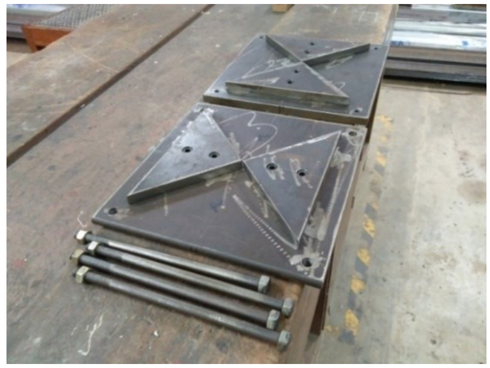

Figure 3.6: 3D view of shear test plates

3.2.4 Flat ring flexure plates

Flat ring flexure plates were designed according to the data available in the literature and the dimensions of the compressive strength testing machine available. Plate design was intended for four-point bending test. A further modification would be needed in case three-point bending test needed to be carried out. Plates were fabricated for flat ring flexure testing conforming to the dimensions given if Figure 3.7.

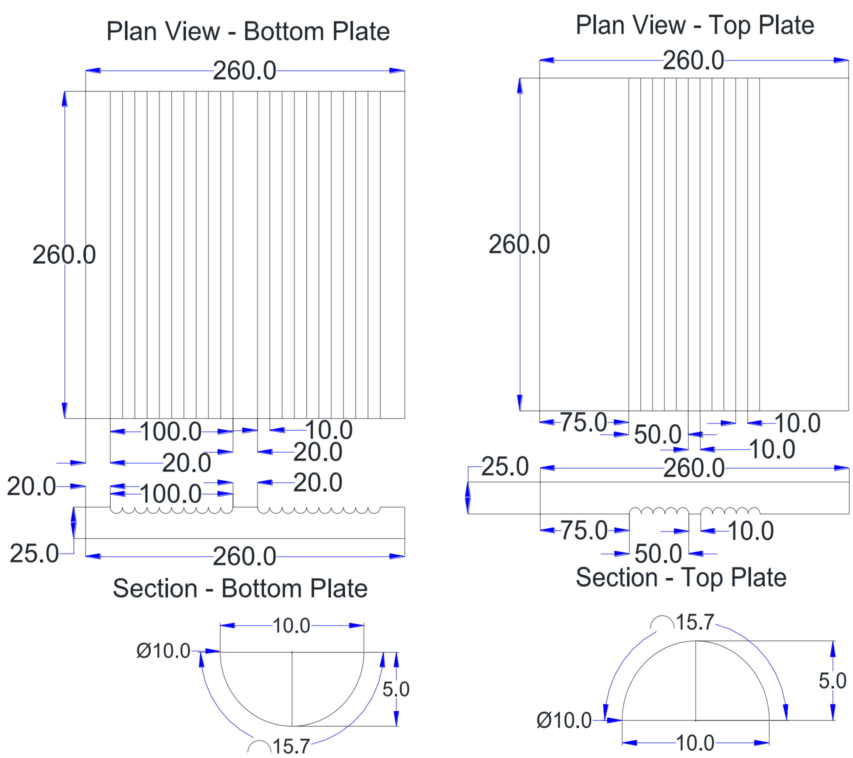

Figure 3.7: Dimensions of flat ring flexure test plates in mm

This test is done using standard compression machine. The fabricated plates are shown in the below Figure 3.8.

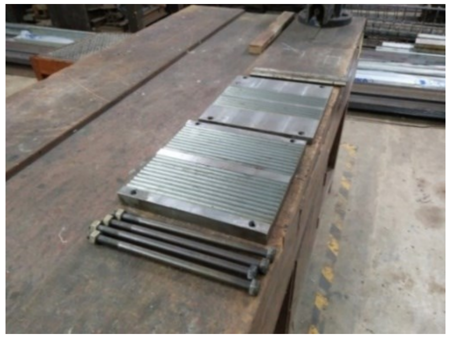

Figure 3.8: 3D view of flat ring flexure plates

3.3 Handling of Culms

Initially the provenance of acquired bamboo poles was recorded. Once the poles were transported to the laboratory, those were washed and cleaned to get rid of any growth and dirt. Once washed, the bamboo culms were kept indoors to dry. Those were kept slanted as shown in Figure 3.9 by allowing the top end of the poles to rest on the walls. This drying method was used to eliminate the possibility of fluctuation of moisture content due to outdoor dying and to ensure the moisture within the culms drops downwards.

Figure 3.9: Bamboo culms kept slanted on wall

The culms were allowed to dry in this manner for a period of one month. At the end of the period moisture content of five random culms were checked. Limiting moisture content was considered to be 20% since any value below 19%-20% is acceptable in tropical regions as a steady moisture content after drying in tropical environments. Since the moisture content of the tested culms was less than the limiting value they were considered to be adequately dry and to initiate culm data measurement.

3.4 Culm Data Measurement

Culm data was recorded to assess the geometric characterization of the bamboo culms. The setup was prepared by placing the pair of V-frames parallel and apart from each other along a straight line at a slightly shorter distance than the average length of culms. Then a pair of strings were tied to connect the respective edges of the pair of V-frames and made taut. The measurement procedure was as follows for all culms:

- Initially the weight of the culm was measured
- Then the culm was placed on the pair of V-frames such that the short span of the cross section of the culm was horizontal as shown in the below Figure 3.10.

Figure 3.10: Data measurement setup for a bamboo culm

- Then considering the initial node to be zero node at station zero, stations of other nodes was obtained by measuring the distance between each node

- Next the distance to the right side of the node was measured from the left string and vice versa was recorded for each node
- Then considering the initial node to be at station zero and distance between node zero and node one as first internode distance, the distance between each internode was measured and the station of each internode was obtained
- Next the distance to the right side of the node was measured from the left string and vice versa was recorded for each internode
- Finally, the above set of procedures were repeated for the same culm by rotating and ensuring that the long span of the cross section of the culm was horizontal

The cross section of each culm was typically detailed as shown if Figure 3.11 consisting of a short span and long span in the cross section.

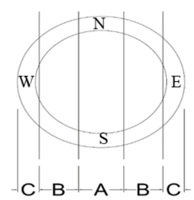

Figure 3.11: Detailing of a typical culm cross section

The legend for culm data measurement is as given below in Table 3.1:

Table 3.1: Legend for culm data measurement

Node	nodal number beginning from base node equal to 0
Station	distance from base node
XL	measured distance from left string to right side of culm
XR	measured distance from right string to left side of culm
D	Outer diameter measured at node or internode
Internode	internode number beginning from first node above base node equals to 1
Max D	Maximum outer diameter measured at Node or Station Marker
Min D	Minimum outer diameter measured at Node or Station Marker

The above terms that could be marked in a sample diagram as in following Figure 3.12:

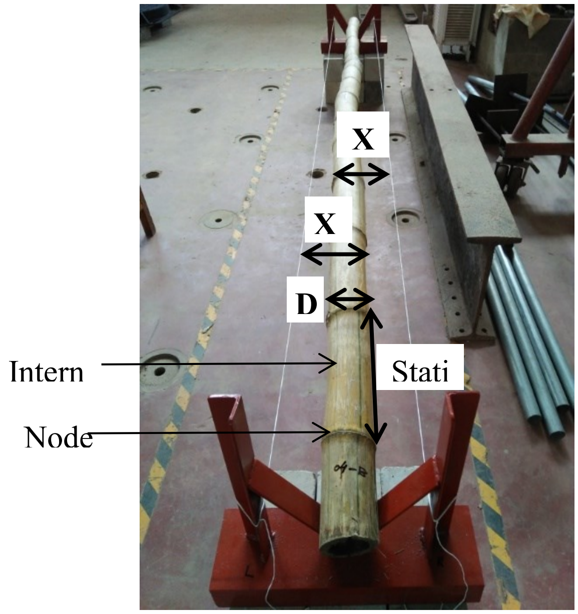

Figure 3.12: sample legend detail used for culm data measurement

3.5 Preservation Treatment of Poles

Preservation treatment was carried out for some eight selected poles before samples were cut for testing. Horizontal dip diffusion method was used to treat the poles. Part of the poles from which test samples would be cut was only treated due to limitation of available tank size. These treated parts were from top and bottom of each selected pole along with the test samples marked on them. All Node diaphragms were perforated by piercing through with a steel rebar for all selected pole parts. Nodes needed to be perforated to enable the solution to penetrate inner tissues of culms.

Borax treatment was selected because it is considered relatively ecofriendly and least toxic compared to other preservation treatment methods. Borax solution of 5% was prepared which comprised of the following:

- Borax powder (Borax Decahydrate) 2.5kg per 100 liters of solution
- Boric acid 2.5kg per 100 liters of solution

Total solution of 120 liters was prepared in this case.

The Poles were kept immersed in the treatment solution for 7 days. Replacement of sap in bamboo fibres with borax solution was confirmed due to the solution turning dark at the end of treatment period as shown in Figure 3.13 and Figure 3.14 depicting day 1 and day 7 of the immersion period respectively.

Figure 3.13: Preservation treatment of poles

(day 1)

Figure 3.14: Preservation treatment of poles

(day 7)

All treated poles were dried after preservation treatment was completed.

3.6 Structural Testing

3.6.1 Preparation of Samples

Test samples were prepared in accordance with ISO 22157:2019. In order to obtain representative values for this particular species of bamboo (*Bambusa Vulgaris*), samples were obtained from bottom and top of each pole respectively for each test as detailed in Table 3.2 and portrayed in Figure 3.15. Hence, a total of 8 samples were tested from each pole. A total of 58 poles were tested out of which 29 were classified as bottom poles and the rest classified as top poles.

Table 3.2: Distribution of number of samples per test

Tests	Tests per pole	Tested poles	Total samples tested
compressive strength	2	57.5	115
Shear strength	2	57.5	115
Flat ring flexure	2	57.5	115
Tensile strength	2	58	116
Total tests	8	58	461

Figure 3.15: Samples being marked on a pole prior to cutting

Dimensions and dry weight of samples were measured after preparing the samples as illustrated in Figure 3.16. Once tested, samples were oven dried for 24 hours, dry mass was recorded and moisture content was calculated.

Figure 3.16: A set of samples prepared for testing

The poles had been cut in such a manner due to the limitations in transportation. Hence in the context of results, values obtained from testing of bottom samples of bottom poles were considered to be representative of the bottom of bamboo plant. Values obtained from testing of top samples of bottom poles and bottom samples of top poles together were considered to be representative of the middle of bamboo plant. Values obtained from testing of the remaining top samples of top poles were considered to be representative of the top of bamboo plant. The number of tests based on position of test sample is clearly given in Table 3.3 below.

Table 3.3: Distribution of tests based on position of sample

	Bottom	Middle		Top	
Tests	**Bottom-Bottom**	**Bottom-Top**	**Top-Bottom**	**Top-Top**	**Total tests**
compressive strength	29	28	29	29	115
Shear strength	29	28	29	29	115
Flat ring flexure	29	28	29	29	115
Tensile strength	29	29	29	29	116
Total tests					461

Test results and specimen data from all four tests were recorded in accordance with the following legend given in Table 3.4:

Table 3.4: Legend for test results and specimen data

D1	Outer diameter at section 1
D2	Outer diameter at section 2
D	Average outer diameter of specimen
t1	Thickness at location 1 of specimen
t2	Thickness at location 2 of specimen
t3	Thickness at location 3 of specimen
t4	Thickness at location 4 of specimen
t	Average thickness of specimen
M	Bending moment at failure of specimen
Y	Distance to the neutral axis from outer most fibre of section
I	Second moment of area of the section of specimen about neutral axis
MoR	Modulus of Rupture of specimen
a	Shear span in four point flat ring flexure test
c	Distance between top supports in four point flat ring flexure test

δ1	Wall thickness at location 1 of specimen
δ2	Wall thickness at location 2 of specimen
b1	Width of specimen at location 1
b2	Width of specimen at location 2
A1	Cross sectional area at location1 of specimen
A2	Cross sectional area at location2 of specimen
A	Mean cross sectional area of specimen

3.6.2 Compressive Strength Testing

Compressive strength was tested using the ADR Touch 2000 standard compression machine. Test samples were prepared according to ISO 22157:2019. Then test samples were placed in between the compressive strength test plates in the machine and loaded as shown in Figure 3.17. Failure load was obtained. Compressive strength was calculated using average cross-sectional area of the samples according ISO 22157:2019. Average density was calculated assuming the samples to be cylindrical. Loading rate of 0.2 KN/s was maintained for compressive strength testing.

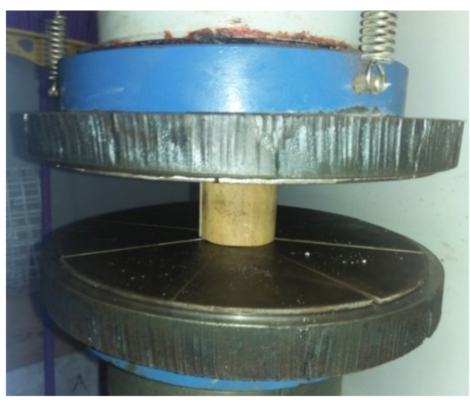

Figure 3.17: Compressive strength testing with standard compression machine

3.6.3 Shear Strength Testing

Shear strength was tested using the ADR Touch 2000 standard compression machine. Test samples were prepared according to ISO 22157:2019. Then test samples were placed in between the shear strength test plates in the machine and loaded as shown in Figure 3.18. Failure load was obtained. Shear strength was calculated using average area of shearing planes of the samples according ISO 22157:2019. A loading rate of 0.1 KN/s was maintained for shear strength testing.

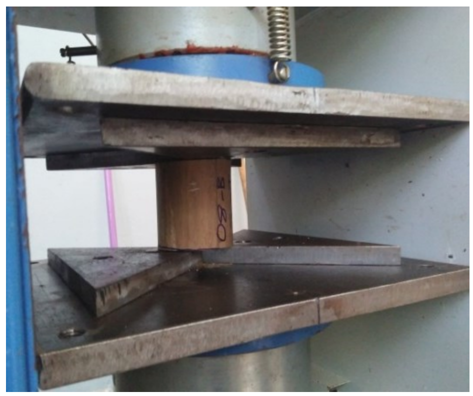

Figure 3.18: Shear strength testing with standard compression machine

3.6.4 Flat Ring Flexure Testing

Flexural strength was tested using the ADR Touch 2000 standard compression machine. Test samples were prepared with height of 0.2D-0.3D based on literature on the test. All samples were tested for four-point bending as illustrated in Figure3.20. Test samples were placed in between the flat ring flexure test plates with their supports kept at appropriate spans depending on the diameter of the sample. Finally, the test sample setup was kept in the machine and loaded as shown in Figure 3.19. Failure load was obtained. Bending strength and Modulus of Rupture were calculated using the equations developed for the four points bending flat ring flexure test. Loading rate of 0.05 KN/s was maintained for four-point bending testing.

Figure 3.19: Flat ring flexure testing with standard compression machine

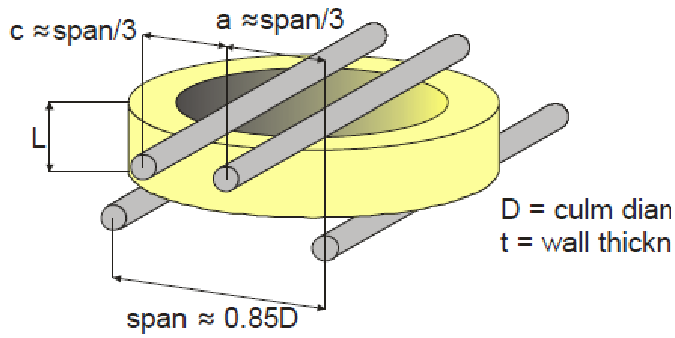

Figure 3.20: Four point bending flat ring flexure test geometry (Virgo, et al. 2018)

3.6.5 Tensile Testing

Tensile testing was carried out using the Hounsfield Tensometer. Test samples were prepared in accordance with ISO 22157:2019. Prepared samples were clamped at both ends and loaded as shown in Figure 3.21. Failure load of the samples were recorded and tensile strength of the samples were calculated using the average cross-sectional area of the respective samples according to ISO 22157:2019.

Figure 3.21: Tensile testing with Hounsfield Tensometer

3.7 Summary

In order to measure culm data and to carry out structural testing, a few special apparatus were fabricated. A pair of V-frames was developed in order to facilitate culm data measurements. Plates for testing of compressive strength parallel to fibres were designed according to ISO 22157: 2019 standard. The same ISO 22157: 2019 standard was followed in designing plates for bowtie shear test, to determine shear strength parallel to fibres. Flat ring flexure plates were designed according to the data available in the literature and the dimensions of the compressive strength testing machine available. Plate design was intended for four-point bending test.

Bamboo culms to be tested were handled systematically. They were cleaned and stored indoors to dry. Once their moisture content was below an acceptable threshold of 20%, they were subjected to culm data measurement. Culm data was recorded to assess the geometric characterization of the bamboo culms. The setup was prepared by using the pair of V-frames which had been developed earlier. Culm data was measured using a standard procedure and recorded for each and every culm.

Preservation treatment was carried out for eight selected poles before samples were cut for testing. Horizontal dip diffusion method was used to treat the poles. Part of the poles from which test samples would be cut was only treated due to limitation of available tank size. Borax treatment was selected for preservation because it is considered relatively ecofriendly and least toxic compared to other preservation treatment methods.

Test samples were prepared in accordance with ISO 22157:2019, except for flat ring flexure test for which samples were prepared according to recommendations from literature. In order to obtain representative values for this particular species of bamboo (*Bambusa Vulgaris*), samples were obtained from bottom and top of each pole respectively for each test. Dimensions and dry weight of samples were measured after preparing the samples. Once tested, samples were oven dried for 24 hours, dry mass was recorded and moisture content was calculated.

Compressive strength, Shear strength and flat ring flexure were tested using the ADR Touch 2000 standard compression machine. In each test, samples were placed in between the respective pair of test plates developed specifically for that test and loaded. Then failure load was obtained. Compressive strength and Shear strength were calculated according to ISO 22157:2019. Bending strength and Modulus of Rupture were calculated using the equations developed for the four points bending flat ring flexure test. Tensile testing was carried out using the Hounsfield Tensometer. Test samples were prepared in accordance with ISO 22157:2019. Failure load of the samples were recorded and tensile strength of the samples were calculated according to ISO 22157:2019.

Culm data and test result data recorded experimentally lead us to the next step of evaluating that data. Culm data has been evaluated to characterize the geometry of culms. Test results have been evaluated to determine key structural parameters of this species of bamboo (*Bambusa Vulgaris*) and effort has been made to observe underlying patterns in these test result data.

4. RESULTS AND DISCUSSION

4.1 Bamboo Provenance

Provenance of bamboo culms is an important part in ensuring the quality control of bamboo used for testing. Provenance of bamboo culms acquired from the supplier is presented in Table 4.1 as follows:

Table 4.1: Provenance of acquired bamboo culms

<table>
<tr><th colspan="5">Bamboo Provenance</th></tr>
<tr><td>Order date:</td><td colspan="4">15th November 2019</td></tr>
<tr><td>Receipt date:</td><td colspan="4">15th November 2019</td></tr>
<tr><td>Supplier:</td><td colspan="4">Asoka Saw Mills & Timber Depot</td></tr>
<tr><td>Address:</td><td colspan="4">No.601/1 Old Galle Rd, Moratuwa 10400</td></tr>
<tr><td colspan="5"></td></tr>
<tr><td>Species:</td><td colspan="4">Bambusa Vulgaris</td></tr>
<tr><td>Quantity:</td><td colspan="2">58</td><td>Age:</td><td>3-5 years</td></tr>
<tr><td>Date of harvest:</td><td colspan="4">7th to 10th October 2019</td></tr>
<tr><td colspan="5"></td></tr>
<tr><td>Location of harvest:</td><td colspan="4">Mathugama, Kalutara District, Sri Lanka</td></tr>
<tr><td>Coordinates</td><td>Longitude</td><td>80.1144</td><td>Latitude</td><td>6.5222</td></tr>
<tr><td>Altitude</td><td colspan="4">109m</td></tr>
<tr><td>Cut height</td><td colspan="4">3.5m-3.9m</td></tr>
<tr><td rowspan="2">Notes</td><td colspan="4">29 Bottom poles and 29 Top poles each</td></tr>
<tr><td colspan="4">Untreated</td></tr>
</table>

4.2 Moisture Content Check

Results of moisture content of five random culms checked at the end of the drying period of one month are given in Table 4.2 along with the image of a such random sample in Figure 4.1.

Figure 4.1: A sample checked for moisture content

Limiting moisture content was considered to be 20%, since any value below 19%-20% is acceptable in tropical regions as steady moisture content after drying in tropical environments (Kaminski, et al. 2016).

Table 4.2: Moisture content check of five random culms

Pole old No	Pole new No	Sample mass	Oven dry mass	M.C.%
26	44-T	41.3	34.6	19.36
28	42-T	73.5	62.4	17.79
27	37-T	90.6	76.1	19.05
29	51-T	153.1	128.5	19.14
30	52-T	75.3	63.9	17.84
			Average	18.64

Since the moisture content of the tested culms was less than the limiting value, they were considered to be adequately dry.

4.3 Culm Data Measurement

Culm data was measured for all 58 poles that were used for testing. An example of the data collected for all poles is provided below for pole 01-B (Tables 4.3 –4.6).

Table 4.3: Culm data of pole 01-B

Culm I.D		01-B			
Species		Bambusa Vulgaris			
Bottom Diameter(mm)			100.60	102.40	101.50
Top Diameter(mm)			80.60	82.12	81.36
Length(mm)					3785
Mass(kg)					7.25
Bottom Thickness(mm)	10.00	10.70	9.40	11.50	10.40
Top Thickness(mm)	8.82	8.42	7.67	7.30	8.05
Distance between demarcation strings(mm)					295

Culm data along short span and long span was measured and recorded for all 58 poles.

D (diameter at each node/internode) was calculated as follows from Equation 4.3:

$$D = (XR) - [295 - (XL)] \qquad \text{Eq. 4.3}$$

Following alternative Equation 4.4 could also be used instead of the above Equation 4.3.

$$D = (XL) - [295 - (XR)] \qquad \text{Eq. 4.4}$$

Culm data along short span for pole 01-B is given below.

Table 4.4: Culm data along short span of pole 01-B in mm

N-S (shorter span)										
Node	**Station**	**XL**	**XR**	**D**	**Internode**	**Station**	**Length**	**XL**	**XR**	**D**
0	0	218	205	**128**	-	-	-	-	-	-
1	314	195	210	**110**	1	157	314	193	200	**98**
2	644	191	203	**99**	2	479	330	188	197	**90**
3	937	195	213	**113**	3	791	293	188	200	**93**
4	1249	190	208	**103**	4	1093	312	189	202	**96**
5	1548	192	206	**103**	5	1399	299	188	200	**93**
6	1845	189	200	**94**	6	1697	297	190	198	**93**
7	2148	192	196	**93**	7	1997	303	192	200	**97**
8	2491	195	195	**95**	8	2320	343	190	200	**95**
9	2804	194	195	**94**	9	2648	313	192	195	**92**
10	3139	200	193	**98**	10	2972	335	190	189	**84**
11	3457	196	190	**91**	11	3298	318	195	190	**90**

When measurement of culm data along nodes with shorter span horizontal is considered, XL values do not show much variation along the nodes. They remain in low 190s mostly. XR values do show gradual drop. Hence the outer diameter too drops gradually. This kind of drop in outer diameter suggests that the pole is tapering progressively. When Internode measurements are considered, XL values remain fairly stable. XR shows a drop towards the end. Hence outer diameter too follows with a small relative drop towards the end. So, it could be stated that this pole shows progressive tapering when the short span is horizontal.

Culm data along long span for pole 01-B is given below.

Table 4.5: Culm data along long span of pole 01-B in mm

E-W (longer span)										
Node	**Station**	**XL**	**XR**	**D**	**Internode**	**Station**	**Length**	**XL**	**XR**	**D**
0	0	215	218	**138**	-	-	-	-	-	-
1	322	182	221	**108**	1	161	322	187	215	**107**
2	642	180	222	**107**	2	482	320	180	218	**103**
3	947	175	240	**120**	3	795	305	170	230	**105**
4	1252	173	225	**103**	4	1100	305	170	225	**100**
5	1560	165	231	**101**	5	1406	308	163	230	**98**
6	1878	175	220	**100**	6	1719	318	177	225	**107**
7	2196	170	223	**98**	7	2037	318	165	210	**80**
8	2534	180	213	**98**	8	2365	338	173	213	**91**
9	2856	180	210	**95**	9	2695	322	168	212	**85**
10	3177	188	195	**88**	10	3017	321	178	195	**78**
11	3499	188	191	**84**	11	3338	322	181	193	**79**

When measurement along nodes of pole 01-B is looked at with the longer span being horizontal, XL values decrease towards the middle and then increase gradually. The inverse of this pattern is visible in XR values where the highest values have been recorded in the middle. Outer diameter shows a decreasing trend. Measurements along internodes follow a pattern similar to measurements along nodes. XL decreases towards the middle and then increases. XR values are high in the middle. Outer diameter also shows a decreasing trend. Hence it could be stated that this pole shows a strong curvature towards the left in middle region when the long span is horizontal. Tapering is also observed based on the values.

Full culm data was summarized for each of the 58 poles. Full culm data of pole 01-B is given below. Maximum and minimum outer diameters have been classified by comparing the respective diameters for each node and internode. Summary of diameters verify the tapering trend found in this pole.

Table 4.6: Summary of full culm data of pole 01-B in mm

Full culm data					
Node	**Max D**	**Min D**	**Internode**	**Max D**	**Min D**
0	138	128	-	-	-
1	110	108	1	107	98
2	107	99	2	103	90
3	120	113	3	105	93
4	103	103	4	100	96
5	103	101	5	98	93
6	100	94	6	107	93
7	98	93	7	97	80
8	98	95	8	95	91
9	95	94	9	92	85
10	98	88	10	84	78
11	91	84	11	90	79

Culm data from other culms showed that most of them exhibit a degree of curvature. In certain poles high curvature was limited to a part of the pole. Hence curvature of Sri Lankan *Bambusa Vulgaris* would have to be accounted during design of structures. The culm data measured could be used for various purposes; one such use could be in the creation of detailed models.

4.4 Compressive Strength

4.4.1 Test Results

Compressive strength of test samples was calculated using the following Equation 4.5:

$$f_{c,0} = \frac{F_{ult}}{A} \qquad \text{Eq 4.5 (ISO, 2019)}$$

Where:

$f_{c,0}$ is compressive strength parallel to fibre in N/mm^2

F_{ult} is the maximum load at which specimen fails in N

A is the average cross-sectional area of culm in mm^2

Compressive strength of each sample was calculated using above equation and relevant data of each sample was recorded. Moisture content and average density were also calculated for each sample respectively. Compressive strength test result data for sample 06-B-Top is presented below in Table 4.7.

Table 4.7: Compression test data of 06-B-Top

Culm ID	06-B
Sample position	Top
D1(mm)	91.3
D2 (mm)	89.7
D(mm)	90.5
t1 (mm)	10.4
t2 (mm)	10.2
t3 (mm)	10.1
t4 (mm)	9.0
t(mm)	9.9
D-2t(mm)	70.7
Height (mm)	90
Failure Load(KN)	73.0
Area (mm^2)	2513.4
Compressive strength(N/mm^2)	29.1
mass(g)	142.38
dry mass(g)	124.14
Moisture content%	14.69
Density(kg/m^3)	629.44

Sample Calculations

Average outer diameter(D)$=\frac{D1+D2}{2}=\frac{91.3+89.7}{2}=$ 90.5mm

Average Thickness(t)$=\frac{t1+t2+t3+t4}{4}$

$=\frac{10.4+10.2+10.1+9.0}{4}=$ 9.9mm

D- 2t =90.5-(2×9.9)=70mm

Area $=\frac{\pi D^2}{4}-\frac{\pi (D\text{-}2t)^2}{4}=\frac{\pi\times 90.5^2}{4}-\frac{\pi\times 70.7^2}{4}=2513.4\text{mm}^2$

Compressive strength $=\frac{\text{Failure Load}}{\text{Area}}=\frac{73\times 1000}{2513.4}=$ 29.1N/mm^2

Moisture content% $=\frac{\text{mass-dry mass}}{\text{dry mass}}\times 100$

$=\frac{142.38\text{-}124.14}{124.14}\times 100=14.69\%$

Average volume=
Height ×Area=90×2513.4=235274.9mm^3

Density$=\frac{\text{mass}}{\text{volume}}=\frac{142.38\times 10^6}{235274.9}=629.44$ kg/m^3

Failure pattern was observed for each sample as given for 06-B-Top (Figures 4.2-4.4) below.

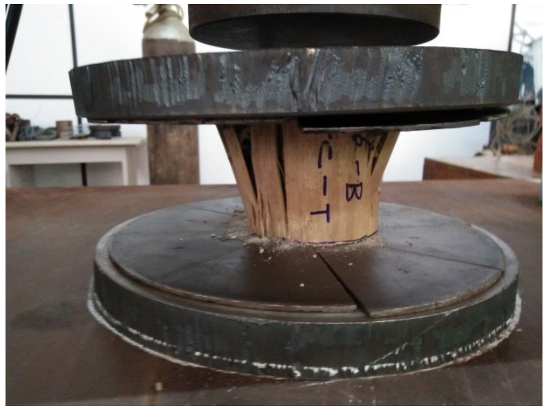

Figure 4.2: Failure of 06-B-Top during compression loading

Figure 4.3: Compressive failure pattern of 06-B-Top

Figure 4.4: Top view of compressive failure pattern of 06-B-Top

The common failure pattern observed was of crushing failure. Crushing failure was always close to one of the ends of the sample. When the failure pattern was observed closely, splits were seen along the lines of the movement of intermediate layer plates. These splits progressed in case the load was applied beyond failure.

Table 4.8: Average compressive strength values in N/mm^2 based on position of sample

Bottom-Bottom	**Bottom-Top**	**Top-Bottom**	**Top-Top**
38.3	38.7	43.2	46.8
Bottom	**Middle**		**Top**
38.3	41.0		46.8
Overall Average			
41.8			

Based on the above values from Table 4.8, it could be observed that compressive strength shows a gradual increase towards the top of the culm. Higher compressive strength towards top could be due to relatively higher maturity and lower moisture content. Moisture content could be lower due to the position of drying poles in the laboratory.

4.4.2 Relationship with Diameter

Variation of compressive strength of test samples with outer diameter was plotted and checked for simple linear relationship as given in the below Figure 4.5.

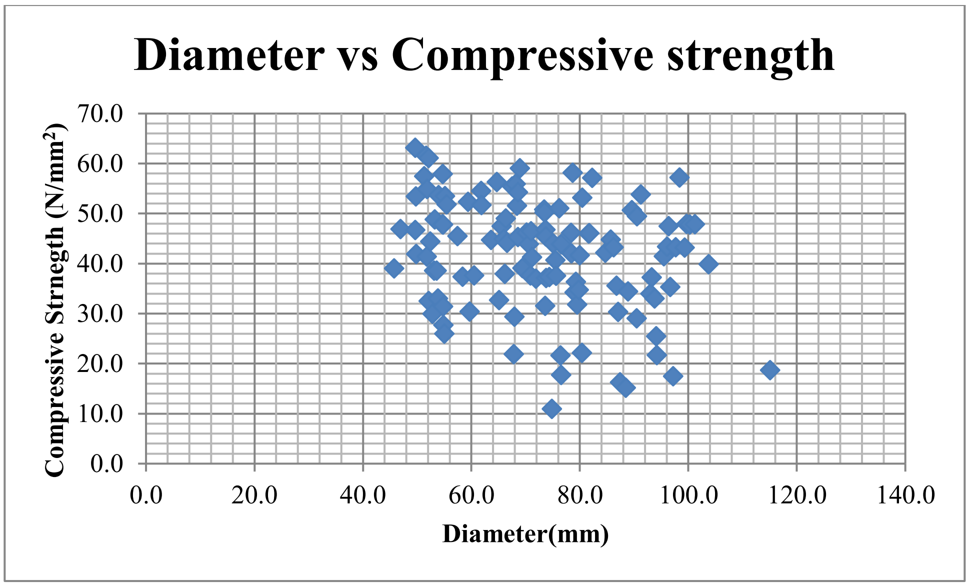

Figure 4.5: Diameter vs. Compressive strength plot

The above plot shows a scattered distribution of data points. Furthermore, the above set of data has a Correlation Coefficient of -0.27334 and Coefficient of Determination (R^2) of 7.4712%. Based on these values it could be stated that there exists a weak negative relationship between sample diameter and its respective compressive strength. In addition, it can be interpreted that the variability of compressive strength can be weakly explained by the variability of sample diameter. Hence, it can be concluded that compressive strength cannot be assessed based on the diameter of samples.

4.4.3 Relationship with Density

Variation of compressive strength of test samples with average density was plotted in Figure 4.6. This plot shows a linear distribution pattern of data points. On checking for linear relationship between variables, this set of data has a Correlation Coefficient of 0.884465 and Coefficient of Determination (R^2) of 78.2278%. Based on these values, it could be stated that there exists a strong positive relationship between sample average density and its respective compressive strength. In addition, it can be interpreted that the variability of compressive strength can be strongly explained by the variability of sample average density. Therefore, we could conclude that compressive strength shows a strong linear relationship with the average density of test samples.

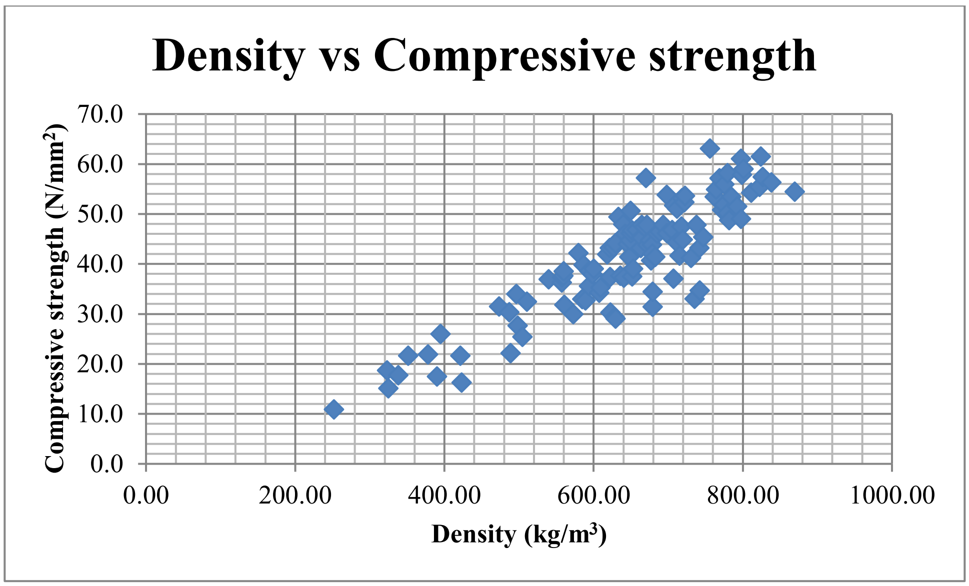

Figure 4.6: Average density vs. Compressive strength plot

4.4.4 Effect of Preservation Treatment

Effect of preservation treatment on the compressive strength was investigated as given in Table 4.9.

Table 4.9: Comparison of compressive strength in N/mm^2 of treated and untreated samples

Bottom-Bottom		Bottom-Top		Top-Bottom		Top-Top	
Treated	Not Treated	Treated	Not Treated	Treated	Not Treated	Treated	Not Treated
38.3	38.3	39.0	38.6	39.3	43.9	45.9	47.0
Bottom		**Middle**				**Top**	
Treated	Not Treated	Treated		Not Treated		Treated	Not Treated
38.3	38.3	39.1		41.3		45.9	47.0
Overall Average							
Treated				Not Treated			
40.6				42.0			

Treated poles showed slightly lower strength values compared to untreated poles. This could indicate that preservation treatment does not directly improve compressive strength. Marginally higher moisture content of treated poles though within the accepted range could be a reason for lower compressive strength values. The other is that for the Borax based treatment, bamboo samples have been immersed in the solution for 7 days. This also could have some effect on the fibers and hence could lead to a lower strength. Significantly higher compressive strength could be expected for treated poles compared to untreated poles after a longer period since preservation treatment improves durability of poles and durability would enable to maintain compressive strength over a longer period of time.

4.5 Shear Strength

4.5.1 Test Results

Shear strength parallel to fibre of test samples were calculated using Equation 4.6 given in ISO 2019:

$$f_v = \frac{F_{ult}}{\Sigma(\delta \times L)} \qquad \text{Eq 4.6}$$

Where:

f_v is shear strength parallel to fibre in N/mm^2

F_{ult} is the maximum load at which specimen fails in N

Σ ($\delta \times L$) is the sum of the four measured areas at the shear planes in mm^2

Shear strength of each sample was calculated using above equation and relevant data of each sample was recorded. Moisture content was also calculated for each sample respectively. Shear strength test result data for sample 07-B-Bottom is presented below in Table 4.10.

Table 4.10: Shear test data of 07-B-Bottom

Culm ID	07-B	**Sample Calculations** Average outer diameter(D)= $\frac{D1+D2}{2} = \frac{87.0+87.1}{2} = 87.1mm$ Average Thickness(t)= $\frac{t1+t2+t3+t4}{4}$ $= \frac{10.4+10.8+12.1+12.6}{4} = 11.5mm$ Shear strength $= \frac{\text{Failure Load}}{\Sigma(t \times \text{Height})} = \frac{37.4 \times 1000}{4 \times (11.5 \times 91)} = 8.9N/mm^2$ Moisture content% $= \frac{\text{mass-dry mass}}{\text{dry mass}} \times 100 = \frac{183.82-161.36}{161.36} \times 100 =$ 13.92%
Sample position	Bottom	
D1(mm)	87.0	
D2 (mm)	87.1	
D(mm)	87.1	
t1 (mm)	10.4	
t2 (mm)	10.8	
t3 (mm)	12.1	
t4 (mm)	12.6	
t(mm)	11.5	
Height (mm)	91	
Failure Load(KN)	37.4	
Shear strength(N/mm²)	8.9	
mass(g)	183.82	
dry mass(g)	161.36	
Moisture content%	13.92	

Failure pattern was observed for each sample as shown for two samples in Figure 4.7 and Figure 4.8.

Figure 4.7: Shear failure pattern of 58-T-Bottom sample

Figure 4.8: Shear failure pattern of 07-B-Bottom sample

Shear splitting was the most common form of failure observed. This type of failure was observed in both samples with and without nodes.

Table 4.11: Average shear strength values in N/mm^2 based on position of sample

Bottom-Bottom	Bottom-Top	Top-Bottom	Top-Top
7.7	7.9	9.3	9.4
Bottom	**Middle**		**Top**
7.7	8.6		9.4
Overall Average			
8.6			

Values from the above Table 4.11 show that shear strength similar to compressive strength exhibits a gradual increase towards the top of the culm. The higher shear strength towards top could be due to same reason as in the case compressive strength samples which are relatively higher maturity and lower moisture content. Lower moisture content could also be due to the position of drying poles in lab.

4.5.2 Relationship with Diameter

Variation of shear strength of test samples with outer diameter was plotted in Figure 4.9. This plot also shows a scattered distribution of data points. Hence on checking the linear relationship between variables, this set of data has a Correlation Coefficient of -0.24101 and Coefficient of Determination (R^2) of 5.8085%. Based on these values it could be stated that there exists a weak negative relationship between sample diameter and its respective shear strength. In addition, it can be interpreted that the variability of shear strength can be weakly explained by the variability of sample diameter. Hence, we can conclude that shear strength similar to compressive strength cannot be assessed based on the diameter of samples.

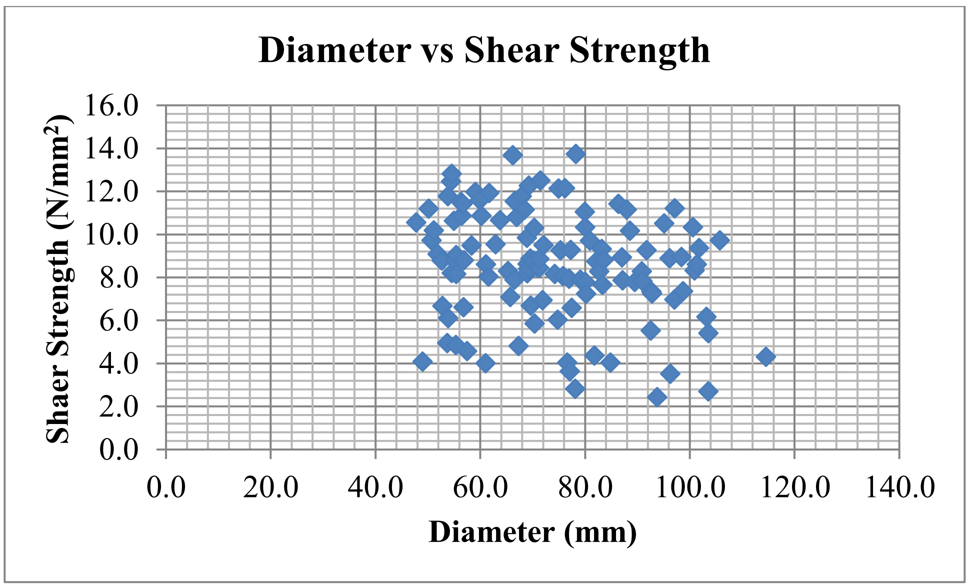

Figure 4.9: Diameter vs. Shear strength plot

4.5.3 Relationship with Density

Variation of shear strength of test samples with average density was plotted in Figure 4.10 and checked for simple linear relationship.

The below plot shows a linear distribution pattern of data points. The above set of data has a Correlation Coefficient of 0.7505 and Coefficient of Determination (R^2) of 56.3264%. This shows that there exists a strong positive relationship between sample average density and its respective shear strength. In addition, it can also be stated that the variability of shear strength can be strongly explained by the variability of sample average density. Hence, we could state that shear strength shows a strong linear relationship with the average density of test samples.

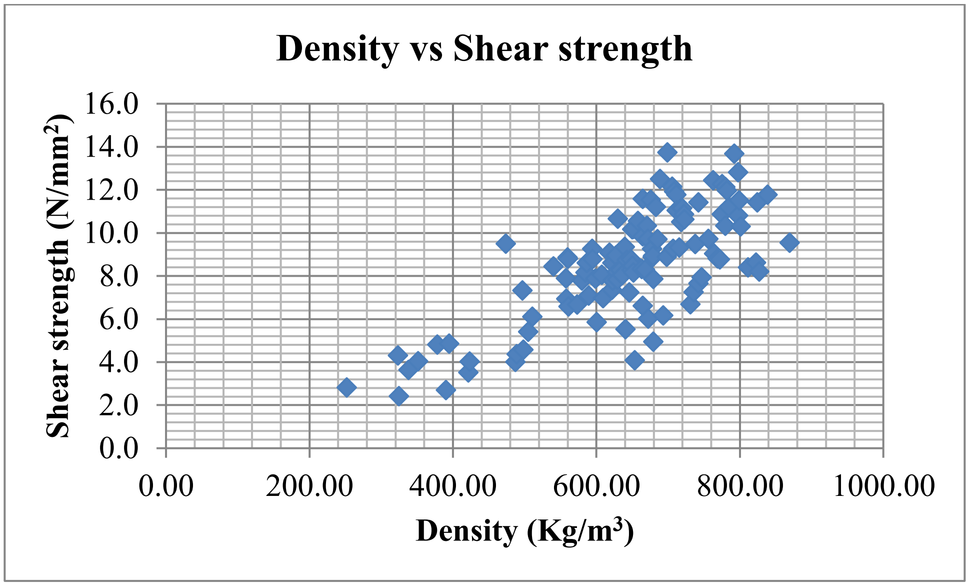

Figure 4.10: Average density vs. Shear strength plot

4.5.4 Effect of Preservation Treatment

Effect of preservation treatment on shear strength was investigated as shown in Table 4.12.

Table 4.12: Comparison of average shear strength in N/mm^2 of treated and untreated samples

Bottom-Bottom		**Bottom-Top**		**Top-Bottom**		**Top-Top**	
Treated	Not Treated	Treated	Not Treated	Treated	Not Treated	Treated	Not Treated
6.6	7.8	7.6	7.9	6.4	9.8	9.7	9.4
Bottom		**Middle**				**Top**	
Treated	Not Treated	Treated		Not Treated		Treated	Not Treated
6.6	7.8	7.0		8.9		9.7	9.4
Overall Average							
Treated				Not Treated			
7.6				8.7			

From the above results, treated poles showed slightly lower shear strength values compared to untreated poles. The reason for lower shear strength of treated poles compared to untreated poles corresponds to the same reason as in the case of compressive strength. Hence it could be stated that preservation treatment does not directly improve shear strength. Shear strength values could be explained by the marginally higher moisture content of treated poles. The 7 day immersion period for treatment could also be a reason for lower shear strength values.

4.6 Flat Ring Flexure

4.6.1 Test Results

Bending strength at failure of four point bending samples were calculated using regular bending formula given as Equation 4.7.

Bending stress= $\frac{M\times y}{I}$ Eq. 4.7

Where:

M is bending moment at failure of specimen

Y is distance to the neutral axis from outer most fibre of section

I is the second moment of area of the section of specimen about neutral axis

Modulus of rupture for each sample was calculated using the following Equation 4.8 for flat ring flexure testing

$f_r = \frac{3F_{ult}a}{(t_N+t_S)L^2}$ Eq. 4.8 (Virgo, et al. 2018)

Where:

f_r is modulus of rupture

F_{ult} is the maximum load at which specimen fails

a is the shear span

t_N and t_S are culm wall thicknesses at failure locations on either side of the culm

L length of culm section tested or specimen depth

Bending strength and Modulus of rupture of each sample was calculated using bending formula and the above equation respectively. Relevant data of each sample was recorded. Moisture content was also calculated for each sample respectively. Four point bending flat ring flexure test result data for sample 58-T-Top is presented below in Table 4.13:

Table 4.13: Flexural test data of 58-T-Top

Culm ID	58-T	**Sample Calculations** Average outer diameter(D)= $\frac{D1+D2}{2}=\frac{52.0+54.3}{2}$ $= 53.2$mm Average Thickness(t)= $\frac{t1+t2+t3+t4}{4}$ $=\frac{7.0+6.2+6.0+6.0}{4} = 6.3$mm
Sample position	Top	
D1(mm)	52.0	
D2 (mm)	54.3	
D(mm)	53.2	
t1 (mm)	7.0	
t2 (mm)	6.2	
t3 (mm)	6.0	

t4 (mm)	6.0
t(mm)	6.3
Height (mm)	18
C(mm)	20
a(mm)	5
Failure Load(KN)	4.8
M(Nmm)	23887.5
y(mm)	9.0
I(mm^3)	3061.8
Failure Zone	B
Bending stress(N/mm^2)	70.2
MoR(N/mm^2)	17.6
mass(g)	10.34
dry mass(g)	8.70
moisture content%	18.85

M =Failure load ×1000×a=4.8×1000×5=23887.5Nmm

$$y = \frac{\text{Height}}{2} = \frac{18}{2} = 9\text{mm}$$

$$I= \frac{1}{12}\times t\times \text{Height}^3=\frac{1}{12}\times 6.3\times 18^3=3061.8\text{mm}^3$$

$$\text{Bending stress}=\frac{M\times y}{I}=\frac{23887.5\times 9}{3061.8}=70.2\text{N/mm}^2$$

$$\text{MoR} =\frac{3\times \text{Failure Load}\times a}{2\times t\times \text{Height}^2}=\frac{3\times 4.8\times 1000\times 5}{2\times 6.3\times 18^2}=17.6\text{N/mm}^2$$

$$\text{Moisture content\%} =\frac{\text{mass-dry mass}}{\text{dry mass}}\times 100 = \frac{10.34\text{-}8.70}{8.70}\times 100 = 18.85\%$$

Failure pattern was observed for each sample as shown for two samples in Figures 4.11 and 4.12. Location of failure of each sample was recorded.

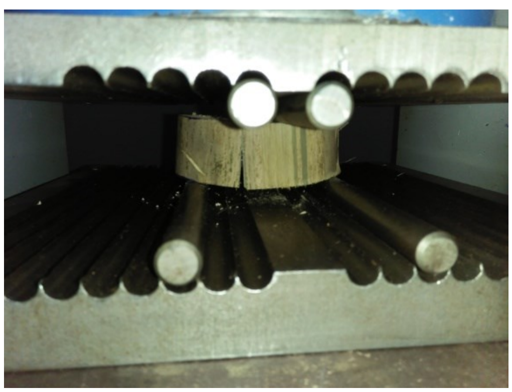

Figure 4.11: Failure in loading of a flat ring flexure test sample

Figure 4.12: Failure pattern 58-T-Top sample in flat ring flexure test

The common failure plane observed was close to top bars.

Table 4.14: Average bending strength values in N/mm^2 based on position of sample

Bottom-Bottom	Bottom-Top	Top-Bottom	Top-Top
58.3	64.2	73.5	65.8
Bottom	**Middle**		**Top**
58.3	68.9		65.8
Overall Average			
65.5			

Bending strength given in above Table 4.14 shows a gradual increase towards the middle of the culm. Then it shows a slight decline towards the top.

Table 4.15: Average modulus of rapture values in N/mm^2 based on position of sample

Bottom-Bottom	bottom-Top	Top-Bottom	Top-Top
14.6	16.1	18.4	16.4
Bottom	**Middle**		**Top**
14.6	17.2		16.4
Overall Average			
16.4			

Modulus of rupture given in above Table 4.15 also shows a gradual increase towards the middle of the culm and then it shows a slight decline towards the top of the culm. The gradual increase of both these values could be attributed to lower moisture content towards the top of culms due to the position of drying culms in lab and to the relatively higher maturity towards the top of culms. The slight drop in values from middle to top could be due to developments of crack that leads to flat ring flexural failure due to dropping moisture content.

4.6.2 Relationship with Diameter

Variation of bending strength and modulus of rupture of test samples with outer diameter was plotted in Figure 4.13. Both these plots show scattered distribution of data points. Both plots were checked for a simple linear relationship among variables independently.

The diameter vs. bending strength set of data has a Correlation Coefficient of -0.22436 and Coefficient of Determination (R^2) of 5.0337%. These coefficient values suggest that there exists a weak negative relationship between sample diameter and its respective bending strength. The coefficient of determination value could be used to interpret that the variability of bending strength can be weakly explained by the variability of sample diameter. So, we can state that bending strength cannot be assessed based on the diameter of samples.

Furthermore, the diameter vs. modulus of rupture set of data has a Correlation Coefficient of -0.22436 and Coefficient of Determination (R^2) of 5.0337%. These values too indicate that there exists a weak positive relationship between sample diameter and its respective modulus of rupture value. In addition, it can be interpreted that the variability of modulus of rupture can be weakly explained by the variability in sample diameter. Hence, we can also state that modulus of rupture also cannot be assessed based on the diameter of samples.

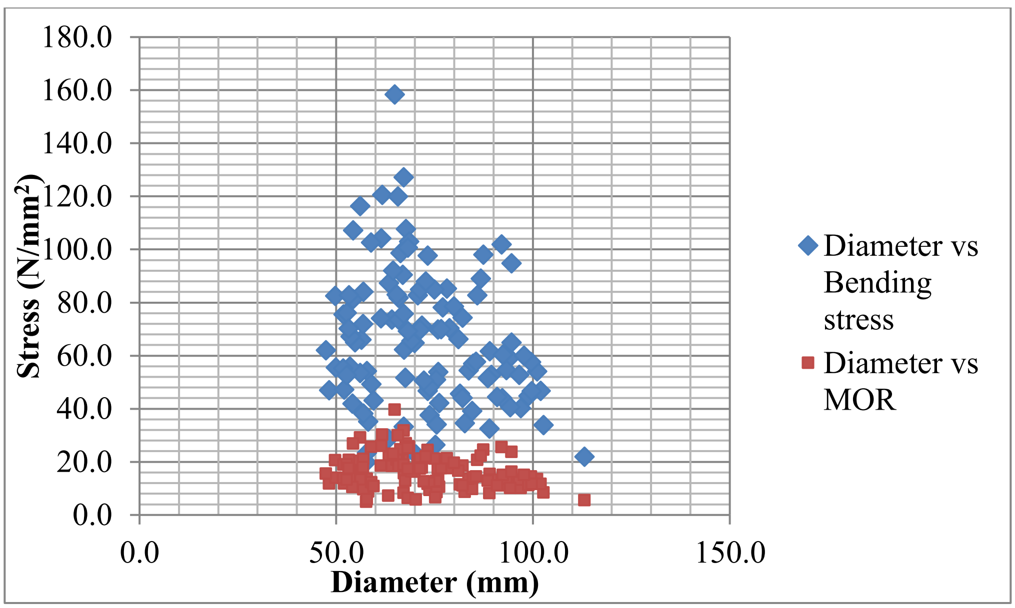

Figure 4.13: Diameter vs. bending strength plot and Diameter vs. MOR plot

4.6.3 Relationship with Density

Variation of bending strength and modulus of rupture of test samples with average density was plotted in Figure 4.14. Both these plots showed scattered distribution of data points. Both these plots were also checked for a simple linear relationship among variables independently.

The average density vs. bending strength data set has a Correlation Coefficient of 0.3769 and Coefficient of Determination (R^2) of 14.2067%. Both these values suggest of a weak positive relationship between average density and its respective bending strength. The coefficient of determination value could be used to interpret that the variability of bending strength can be weakly explained by the variability of average density. Hence, it is possible to conclude that bending strength obtained from flat ring flexure can be weakly assessed based on the average density.

The average density vs. modulus of rupture set of data has a Correlation Coefficient of 0.3769 and Coefficient of Determination (R^2) of 14.2067%. These values indicate that there exists a weak positive relationship between average density and its respective modulus of rupture value. In addition, it can be interpreted that the variability of modulus of rupture can be weakly explained by the variability in average density. So we could say that modulus of rupture obtained by flat ring flexure also can only be weakly assessed based on the average density. Therefore, the overall results obtained from flat ring flexural testing of samples seem to be loosely related with average density.

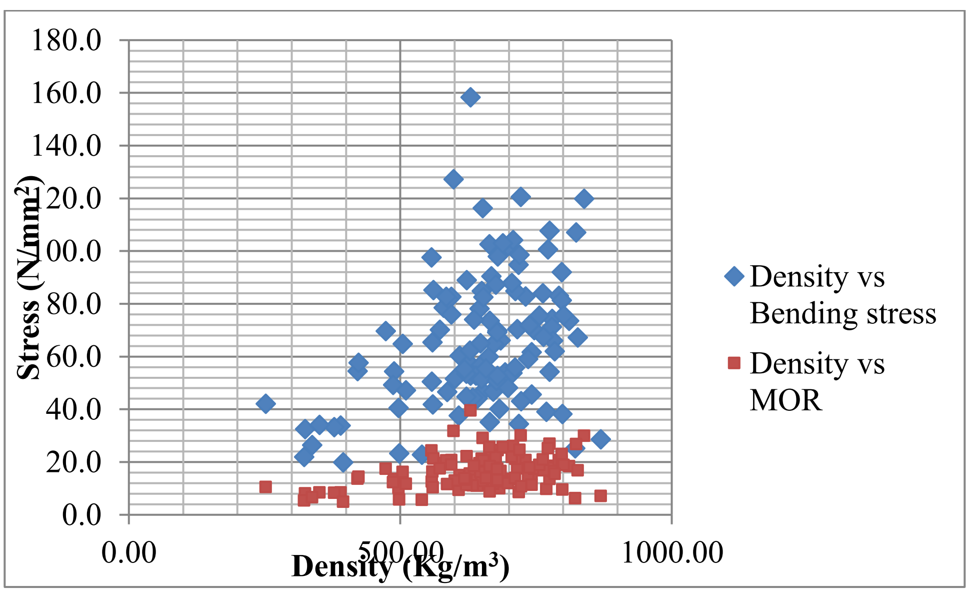

Figure 4.14: Average density vs. Bending strength plot and Average density vs. MOR plot

4.6.4 Effect of Preservation Treatment

Effect of preservation treatment on bending strength and modulus of rupture was investigated as given in the below Table 4.16.

Table 4.16 : Comparison of average bending strength in N/mm^2 of treated and untreated samples

Bottom-Bottom		**Bottom-Top**		**Top-Bottom**		**Top-Top**	
Treated	Not Treated	Treated	Not Treated	Treated	Not Treated	Treated	Not Treated
48.2	60.0	40.3	68.2	49.8	76.2	36.8	70.4
Bottom		**Middle**				**Top**	
Treated	Not Treated	Treated		Not Treated		Treated	Not Treated
48.2	60.0	44.4		72.4		36.8	70.4
Overall Average							
Treated				Not Treated			
43.4				68.8			

It could be observed from the above table that treated poles showed significantly lower bending strength values compared to untreated poles.

Table 4.17: Comparison of average modulus of rupture values in N/mm^2 of treated and untreated samples

Bottom-Bottom		**Bottom-Top**		**Top-Bottom**		**Top-Top**	
Treated	Not Treated	Treated	Not Treated	Treated	Not Treated	Treated	Not Treated
12.0	15.0	10.1	17.1	12.4	19.1	9.2	17.6
Bottom		**Middle**				**Top**	
Treated	Not Treated	Treated		Not Treated		Treated	Not Treated
12.0	15.0	11.1		18.1		9.2	17.6
Overall Average							
Treated				Not Treated			
10.8				17.2			

Modulus of rupture values presented in the above Table 4.17 also show a pattern similar to bending strength. Treated poles showed significantly lower modulus of rupture values compared to untreated poles. This significant reduction may not be due to slightly higher moisture content in the treated samples. As can be seen, keeping the samples immersed in the Borax solution for nearly one week has affected the flexural strength and modulus of rupture to a greater extent than the compressive and shear strengths. However, the pattern of variation of strength values from bottom to top is similar for treated and untreated poles.

4.7 Tensile Strength

4.7.1 Test Results

Tensile strength parallel to fibre of test samples were calculated using Equation 4.8 (ISO 2019):

$$f_{t,0} = \frac{F_{ult}}{A_g} \qquad \text{Eq 4.9}$$

Where:

$f_{t,0}$ is compressive strength parallel to fibre in N/mm^2

F_{ult} is the maximum load at which specimen fails in N

A_g is the mean cross-sectional area of the gauge portion of the sample in mm^2

Tensile strength of each sample was calculated using above equation and relevant data of each sample was recorded. Moisture content was also calculated for each sample respectively. Tensile strength test result data for sample 06-B-Top is presented below in Table 4.18.

Table 4.18: Tensile test data of 06-B-Top

Culm ID	06-B
Sample position	Top
δ1(mm)	10.5
b1(mm)	7.2
A1(mm^2)	75.6
δ2(mm)	11.5
b2(mm)	5.0
A2(mm^2)	57.5
A(mm^2)	66.6
Height (mm)	204
Gauge length(mm)	100
Rotations	570
Failure load(Kg)	400
Tensile strength(N/mm^2)	59.0
mass(g)	9.68
dry mass(g)	8.26
moisture%	17.2

Sample Calculations

Area1(A1) $=\delta1\times b1=10.5\times7.2=75.6\text{mm}^2$

Area2(A2) $=\delta2\times b2=11.5\times5.0=57.5\text{mm}^2$

Average Area (A)$=\frac{A1+A2}{2}=\frac{75.6+57.5}{2}=66.6\text{mm}^2$

Tensile strength

$=\frac{\text{Failure Load}}{A}=\frac{400\times9.81}{66.6}=59.0\text{N/mm}^2$

Moisture content% $=\frac{\text{mass-dry mass}}{\text{dry mass}}\times100$

$=\frac{9.68-8.26}{8.26}\times100=17.2\%$

Failure pattern was observed for each sample as shown in the below Figures 4.15 and 4.16.

Figure 4.15: Tensile failure between grip and node of 58-T-Top sample

Figure 4.16: Tensile failure at node of 02-B-Top sample

The most common type of failure observed was of the above shown type where failure occurred between grips and the middle node. A few samples showed failure close to node as shown in figure 4.16.

Table 4.19: Average tensile strength values in N/mm^2 based on position of sample

Bottom-Bottom	**Bottom-Top**	**Top-Bottom**	**Top-Top**
85.0	98.2	111.3	129.0
Bottom	**Middle**		**Top**
85.0	104.7		129.0
Overall Average			
106.2			

Tensile strength similar to compressive strength and shear strength shows increase towards the top of the culm as shown in the above Table 4.19. The increase of tensile strength could also be attributed to the same factors affecting the compressive and shear strengths. They are lower moisture content and relatively higher maturity towards the top of culms. Positioning of culms for drying in lab could have influenced moisture content distribution.

4.7.2 Relationship with Diameter

Variation of tensile strength of test samples with outer diameter was plotted and checked for simple linear relationship as given in Figure 4.17 below.

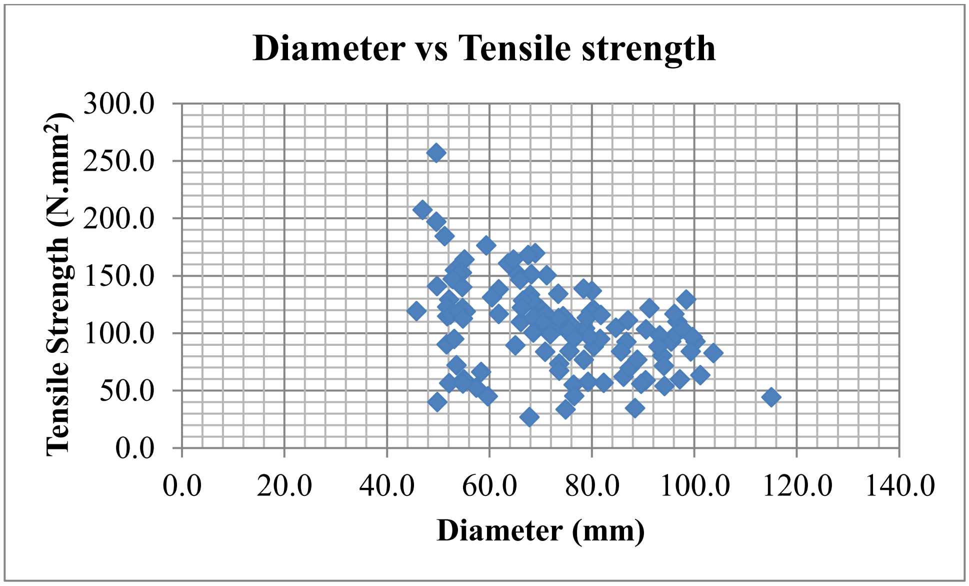

Figure 4.17: Average diameter vs. Tensile strength plot

The average diameter vs. tensile strength plot shows a scattered distribution of data points. These set of plot data have a Correlation Coefficient of -0.4197 and Coefficient of Determination (R^2) of 17.5945%. Therefore, the relationship between sample average diameter and its respective tensile strength could be considered weak. In addition, it can be stated that the variability of tensile strength cannot be strongly explained by the variability of sample diameter. Hence, we could conclude that tensile strength similar to shear strength and compressive strength cannot be assessed based on the diameter of samples.

4.7.3 Relationship with Density

Variation of tensile strength of test samples with average density was plotted as given in Figure 4.18. It was also checked if tensile strength and density showed linear relationship.

The average density vs. tensile strength plot shows a linear distribution pattern of data points. These set of data have a Correlation Coefficient of 0.6097 and Coefficient of Determination (R^2) of 37.1730%. Therefore, it could be interpreted that there exists a strong positive relationship between sample average density and its respective tensile strength. It can also be stated that the variability of tensile strength cannot be strongly explained by the variability of sample average density. Yet we could conclude that tensile strength shows a relatively strong linear relationship with the average density of test samples.

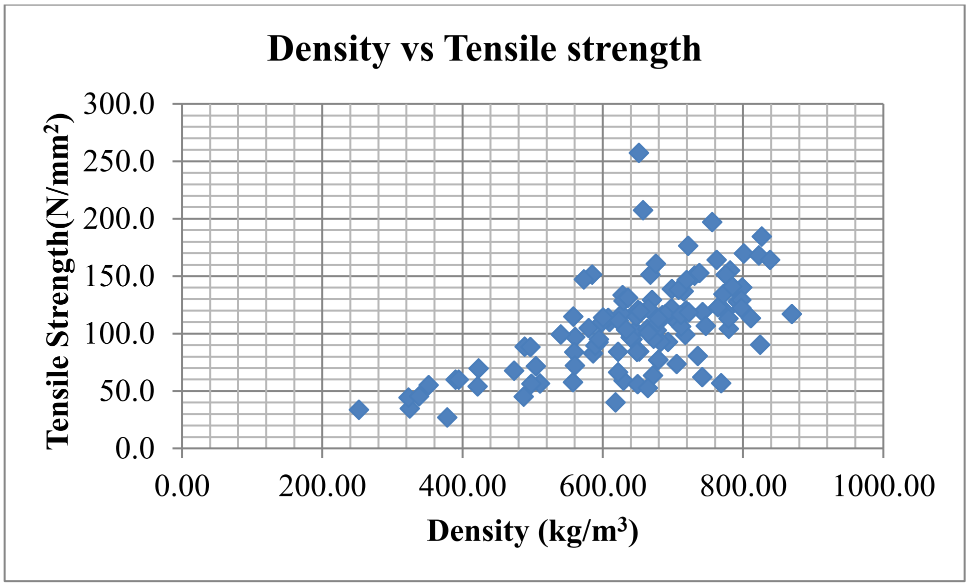

Figure 4.18: Average density vs. Tensile strength plot

4.7.4 Effect of Preservation Treatment

Effect of preservation treatment on tensile strength was investigated as presented in Table 4.20 below.

Table 4.20: Comparison of average tensile strength values in N/mm^2 of treated and untreated samples

Bottom-Bottom		**Bottom-Top**		**Top-Bottom**		**Top-Top**	
Treated	Not Treated	Treated	Not Treated	Treated	Not Treated	Treated	Not Treated
84.3	86.9	82.2	100.7	94.7	113.9	110.2	132.0
Bottom		**Middle**				**Top**	
Treated	Not Treated	Treated		Not Treated		Treated	Not Treated
84.3	86.9	88.4		107.3		110.2	132.0
Overall Average							
Treated				Not Treated			
92.8				108.4			

Values from the above table show that treated poles showed lower tensile strength values compared to untreated poles. This is not only due to slightly higher moisture content of treated poles compared to untreated ones but also due to the 7 day immersion period followed in treatment process. These results imply that preservation treatment does not immediately improve tensile strength of treated poles.

4.8 Comparison of Results

The average strength values obtained for compressive strength, shear strength and tensile strength for Sri Lankan *Bambusa Vulgaris* through testing has been compared with strength values of other relatable bamboo species from literature and presented in Table 4.21 below.

Table 4.21: Comparison of average strengths of different bamboo species from literature in N/mm^2

Species of bamboo	Compressive strength parallel to fibres	Shear strength parallel to fibres	Tensile strength parallel to fibres
Sri Lankan *Bambusa Vulgaris*	41.8	8.6	106.2
Kenyan *Bambusa vulgaris*	51.7	-	94.3
Thai *Dendrocalamus asper*	68.7	9.6	96.0
Thai *Bambusa blumeana*	66.5	12.2	120.0
Thai *Dendrocalamus strictus*	56.0	13.0	106.3
Thai *Bambusa bambos*	54.2	9.0	101.5

The above table shows us that average strength values of Sri Lankan *Bambusa Vulgaris* seems to be lower compared to the other species except in the case of tensile strength. These results also shows that the strength patterns of most Thai bamboos are similar to the pattern of values obtained for Sri Lankan *Bambusa Vulgaris*. Kenyan *Bambusa vulgaris* shows a significant deviation in average strength values despite being the same species as Sri Lankan *Bambusa Vulgaris.* In design purposes, it would be prudent to use a regional factor to account for the changes in average strength of *Bambusa Vulgaris* from region to region in case a global value is determined. Hence, we could conclude that different bamboo species grown in different parts of the world show different average strength values. Same species from different regions too tend to show different strength values.

Characteristic strengths of Sri Lankan *Bambusa Vulgaris* have been calculated using the following Equation 4.10 available in the literature.

$$f_{i,k} = C_{mois}C_{lab}f_{i,0.05}\left[1 - \frac{2.7s}{m\sqrt{n_t}}\right]$$ Eq 4.10 (Kaminski, et al. 2016)

Where:

$f_{i,k}$ is the characteristic value of strength in N/mm^2

$f_{i,\,0.05}$ is the 5th percentile value of strength results from test data in N/mm^2

C_{mois} is the moisture content correction factor

C_{lab} is the laboratory correction factor

s is standard deviation of test data in N/mm^2

m is mean value of test data in N/mm^2

n_t is the number of tests

Characteristic strengths for Sri Lankan *Bambusa Vulgaris* have been calculated as follows in Table 4.22. Finally, $f_{i,k}$ has been rounded off to the nearest whole number. Introducing density for characteristic strength calculation is not considered, since density varies longitudinally and radially.

Table 4.22: Calculation of characteristic strengths for Sri Lankan *Bambusa Vulgaris*

Term in equation	**Compressive strength parallel to fibres**	**Shear strength parallel to fibres**	**Bending strength perpendicular to fibres from four point flat ring flexure**	**Tensile strength parallel to fibres**
$f_{i,\,0.05}$	23.5	4.4	24.0	42.0
C_{mois}	1.1	1.1	1.1	1.1
C_{lab}	0.7	0.5	0.7	0.5
s	11.1	2.5	25.2	39.1
m	41.8	8.6	65.5	106.2
n_t	115.0	115.0	115.0	116.0
$f_{i,k}$	16.6	2.2	16.0	20.4
$f_{i,k}$ usable	17.0	2.0	16.0	20.0

Calculated values have been compared to other relatable characteristic strength values available in literature in Table 4.23.

Table 4.23: Comparison of characteristic strengths of Sri Lankan *Bambusa Vulgaris* with different bamboo species from literature and relatable softwood classes in N/mm^2

Species of bamboo/Design classification	**Compressive strength parallel to fibres**	**Shear strength parallel to fibres**	**Tensile strength parallel to fibres**
Sri Lankan *Bambusa Vulgaris*	17.0	2.0	20.0
Colombian *Guadua angustifolia Kunth*	20.0	3.0-5.0	40.0
For scheme design, all species	20.0	2.0	40.0
C16 softwood	17.0	3.2	10.0

Suggested scheme design value as well as strength of C16 softwood class has been compared. Scheme design value suggested for all species cannot be considered suitable for Sri Lankan *Bambusa Vulgaris*. Colombian *Guadua angustifolia Kunth* shows much similarity to the suggested scheme design values. However, its characteristic strength values are much higher than Sri Lankan *Bambusa Vulgaris*. Sri Lankan *Bambusa Vulgaris* shows characteristic strengths closest to C16 softwood purely on numerical grounds. Sri Lankan *Bambusa Vulgaris* has not been compared with any hardwood classes, since bamboo is not considered hard.

5. CONCLUSION AND FUTURE WORK

5.1 Conclusions

Bambusa Vulgaris (Sri Lankan Yellow bamboo) was chosen due to its widespread availability in Sri Lanka and therefore its potential uptake and acceptance of its use in construction. *Bambusa Vulgaris* (Sri Lankan Yellow bamboo) harvested from Mathugama, kaluatara which is in the wet zone of Sri Lanka was used for this experimental research. Apparatus necessary for testing structural properties of bamboos were developed in accordance with ISO 22157:2019 specifications. Then, the bamboo culms to be tested were brought to the lab and stored after necessary processing. Once the culms were ready, initial moisture content was checked randomly. Then culms were classified as top and bottom and culm data measurement was recorded for each culm separately. The recorded culm data serves as numerical interpretation of the geometry of each culm. Most of the measured culms show a degree of curvature. Once culm data had been recorded, some poles underwent preservation treatment. Testing of samples began after this stage.

Four tests were carried out to assess the structural properties of each culm. The four tests were:

- Compressive strength parallel to fibres
- Shear strength parallel to fibres
- Bending strength perpendicular to fibres from flat ring flexure test
- Tensile strength parallel o fibres

Two samples were tested from each culm per test. One sample tested was from bottom and the other from top. Test results were recorded and analyzed.

The most common form of failure in compressive strength testing was crushing failure. Results from compressive strength testing showed a pattern of increasing strength towards the top of culms. An overall average strength of 41.8N/mm^2 was obtained. It was not possible to identify any strong relationship between compressive strength of samples and their average diameter. However, a strong positive relationship was identified between compressive strength of samples and their respective average densities. Preservation treatment did not immediately improve the compressive strength of test samples.

Shear splitting was the most common form of failure in shear strength testing. Results from shear strength testing showed a pattern of increasing strength towards the top of culms. Overall average shear strength of 8.6N/mm^2 was obtained. The relationship between shear strength of samples and their average diameter was found to be weakly negative. However, a strong positive relationship was identified between shear strength and respective average densities of test samples. Treated samples did not show any immediate improvement in shear strength.

The location of failure was close to top bars in most cases in four point bending flat ring flexure testing. Results from flat ring flexure testing showed a pattern of gradual increase in bending strength as well as modulus of rupture from bottom until the middle of culms. Then, both values showed a gradual drop towards the top of culms. Overall average bending strength was 65.5N/mm^2 and overall average of modulus or rupture was 16.4N/mm^2. It was not possible to identify any strong relationship between bending strength or modulus of rupture with average diameter. It was also noted that only a weak relationship exists between bending strength and modulus of rupture with average density. Significant decrease was observed in bending strength and modulus of rupture of samples treated for preservation.

Failure of test sample between grip and node was seen most often in tensile test samples. Tensile strength test results showed a pattern of increasing strength towards the top of culms. Overall average tensile strength was 106.2 N/mm^2. Tensile strength results of test samples showed a weak correlation with their respective average diameters. However, tensile strength of samples showed a strong correlation with average density of those respective samples. Poles which had undergone preservation treatment showed lower tensile strengths compared to untreated poles.

Based on the overall results, it could be stated that strength values show strong correlation with density, whereas they do not show a strong relationship with average diameter. Average strength values generally tend to increase towards top as well. Preservation treatment method followed in the experimental programme did not yield any immediate advantage in terms of strength for treated samples compared to untreated samples in any of the four tests; compressive strength, shear strength, flat ring flexure and tensile strength.

Comparison of overall average strength values of Sri Lankan *Bambusa Vulgaris* with the same species from Kenya as well as other relatable species from Thailand showed that the average strengths of Sri Lankan *Bambusa Vulgaris* is lower except in the case of tensile strength. Scheme design value suggested in literature for all species cannot be considered suitable for Sri Lankan *Bambusa Vulgaris.* Sri Lankan *Bambusa Vulgaris* showed characteristic strengths of 17.0N/mm^2, 2.0N/mm^2, 16.0N/mm^2 and 20.0N/mm^2 for compressive strength, shear strength, four point bending strength in flat ring flexure and tensile strength respectively. Characteristic strength of Sri Lankan *Bambusa Vulgaris* is lower than characteristic strength Colombian *Guadua angustifolia Kunth,* which shows much similarity to the suggested scheme design values. Hence it becomes necessary to develop separate design values for Sri Lanka. Characteristic values calculated for Sri Lankan *Bambusa Vulgaris* could be used for design purposes in the case of Sri Lankan *Bambusa Vulgaris.* An alternative method would be to develop a regional factor for Sri Lanka, which could be used to derive design values from a global data base. It would make design more efficient if each species of bamboo could have its own regional factor.

5.2 Future Work

The tests carried out and the results which were obtained from these tests leave us with a number of options to continue research work within this area. They are as follows:

- Further testing of structural parameters parallel to and perpendicular to fibres. ISO 22157:2019 gives guidelines for other tests such as tensile strength perpendicular to fibres.

- Testing the same structural parameters of different species of bamboo
- Testing of samples of bamboo with different moisture contents and checking for correlation strength with moisture content
- Checking of strength of bamboo with time. In this case some samples could be treated for preservation and the influence of preservation treatment over time could be investigated
- Further investigations on different treatment methods of bamboo could be conducted
- Application of Digital image correlation to study strain distribution, the development and on-set of failure on test samples.
- Use finite element models to investigate the behaviour of bamboo structures. The experimental results can be used to validate the finite element models.

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APPENDICIES

APPENDIX A1

Table A1.1: Compressive strength test specimen dimensions

No	Culm ID	Sample position	D1 (mm)	D2 (mm)	D (mm)	t1 (mm)	t2 (mm)	t3 (mm)	t4 (mm)	t (mm)	Height (mm)
1	01-B	Bottom	98.7	98.1	98.4	9.0	9.6	8.8	9.5	9.2	91
2	01-B	Top	79.8	81.1	80.5	7.0	7.2	7.1	7.4	7.2	87
3	02-B	Bottom	99.0	101.5	100.3	8.3	8.9	8.7	9.1	8.8	79
4	02-B	Top	80.8	83.8	82.3	6.9	7.2	7.7	6.7	7.1	96
5	03-B	Bottom	89.2	87.7	88.5	6.6	6.1	7.0	5.4	6.3	86
6	03-B	Top	76.2	73.5	74.9	5.7	5.6	6.1	5.9	5.8	83
7	04-B	Bottom	95.1	95.9	95.5	9.5	10.5	9.5	9.0	9.6	95
8	04-B	Top	84.1	88.3	86.2	8.0	6.4	7.6	7.2	7.3	93
9	05-B	Bottom	94.1	93.4	93.8	8.8	8.2	9.4	9.1	8.9	90
10	05-B	Top	79.6	80.0	79.8	6.9	6.5	6.0	7.1	6.6	90
11	06-B	Bottom	93.3	93.2	93.3	20.7	17.6	19.2	17.5	18.8	95
12	06-B	Top	91.3	89.7	90.5	10.4	10.2	10.1	9.0	9.9	90
13	07-B	Bottom	79.7	77.2	78.5	10.3	12.4	11.7	12.0	11.6	93
14	07-B	Top	86.7	86.8	86.8	8.5	8.6	8.9	9.4	8.9	90
15	08-B	Bottom	74.5	76.7	75.6	11.0	12.2	11.6	13.6	12.1	80
16	08-B	Top	72.8	69.6	71.2	6.1	6.3	6.4	6.5	6.3	83
17	09-B	Bottom	92.3	96.1	94.2	6.8	7.5	9.2	6.5	7.5	95
18	09-B	Top	79.5	81.3	80.4	5.4	5.6	5.2	6.0	5.6	95
19	10-B	Bottom	95.0	97.7	96.4	8.7	8.8	8.3	8.6	8.6	85
20	10-B	Top	78.9	78.5	78.7	7.0	7.0	6.8	6.6	6.9	87
21	11-B	Bottom	97.0	96.3	96.7	16.8	17.1	16.0	15.3	16.3	102
22	11-B	Top	96.7	95.5	96.1	10.7	11.2	11.7	10.8	11.1	105
23	12-B	Bottom	81.4	81.8	81.6	10.2	10.8	12.0	10.2	10.8	81
24	12-B	Top	74.1	73.5	73.8	6.8	6.8	7.0	6.6	6.8	78
25	13-B	Bottom	85.6	85.8	85.7	7.3	8.9	8.7	7.4	8.1	78
26	13-B	Top	74.0	76.1	75.1	5.3	6.4	6.4	5.9	6.0	78
27	14-B	Bottom	78.0	80.0	79.0	10.9	13.0	11.1	9.6	11.2	79
28	14-B	Top	68.9	67.0	68.0	5.7	5.8	5.1	5.7	5.6	82
29	15-B	Bottom	77.6	82.4	80.0	8.1	8.4	7.7	7.7	8.0	82
30	15-B	Top	76.1	71.3	73.7	5.6	5.8	5.9	6.0	5.8	87
31	16-B	Bottom	94.4	100.0	97.2	8.0	9.7	9.0	11.0	9.4	96
32	16-B	Top	85.6	89.2	87.4	5.0	5.3	6.0	5.7	5.5	93
33	17-B	Bottom	87.6	90.2	88.9	14.0	16.0	17.0	14.7	15.4	94

34	17-B	Top	88.1	86.0	87.1	8.4	7.5	7.4	7.5	7.7	102
35	18-B	Bottom	71.5	68.8	70.2	9.3	10.0	9.8	8.1	9.3	68
36	18-B	Top	66.4	65.9	66.2	5.7	5.7	5.0	6.7	5.8	68
37	19-B	Bottom	79.1	79.4	79.3	14.8	13.3	14.2	15.8	14.5	84
39	20-B	Bottom	80.0	79.0	79.5	7.4	6.6	7.7	7.0	7.2	83
40	20-B	Top	70.4	68.4	69.4	13.0	12.3	11.5	11.7	12.1	84
41	21-B	Bottom	98.3	101.1	99.7	8.5	8.8	7.1	9.6	8.5	102
42	21-B	Top	93.5	89.0	91.3	7.7	7.1	6.4	7.7	7.2	105
43	22-B	Bottom	89.4	89.8	89.6	11.0	12.0	11.4	12.6	11.8	99
44	22-B	Top	89.8	91.3	90.6	7.7	9.0	8.0	7.5	8.1	99
45	23-B	Bottom	116.2	113.9	115.1	13.0	13.0	13.4	12.2	12.9	109
46	23-B	Top	97.1	91.0	94.1	6.5	6.4	6.0	6.1	6.3	108
47	24-B	Bottom	80.0	83.5	81.8	14.1	13.1	14.0	12.6	13.5	93
48	24-B	Top	94.9	91.1	93.0	10.9	11.9	10.5	12.1	11.4	90
49	25-B	Bottom	101.3	97.3	99.3	17.0	16.2	15.3	15.9	16.1	102
50	25-B	Top	95.9	106.5	101.2	9.7	9.4	8.8	10.3	9.6	105
51	26-B	Bottom	83.5	85.9	84.7	7.8	7.7	7.2	7.4	7.5	77
52	26-B	Top	65.0	66.2	65.6	5.5	6.2	5.2	5.2	5.5	73
53	27-B	Bottom	74.3	78.1	76.2	12.7	11.5	11.1	11.1	11.6	84
54	27-B	Top	74.7	76.3	75.5	7.3	7.4	7.5	7.0	7.3	84
55	28-B	Bottom	101.9	105.6	103.8	20.7	20.8	18.7	22.2	20.6	107
56	28-B	Top	98.0	97.3	97.7	9.4	10.6	10.0	9.5	9.9	113
57	29-B	Bottom	66.7	68.9	67.8	12.3	12.6	11.8	12.4	12.3	70
58	29-B	Top	64.3	65.9	65.1	4.3	4.8	4.3	4.8	4.6	73
59	30-T	Bottom	78.7	78.0	78.4	7.0	6.6	6.9	6.7	6.8	71
60	30-T	Top	58.6	60.2	59.4	5.4	5.1	5.2	5.1	5.2	74
61	31-T	Bottom	73.1	74.2	73.7	7.5	6.3	6.2	5.8	6.5	70
62	31-T	Top	62.2	65.1	63.7	4.7	4.7	5.6	5.1	5.0	74
63	32-T	Bottom	77.6	75.3	76.5	6.7	6.6	7.0	6.5	6.7	74
64	32-T	Top	54.4	55.6	55.0	5.2	5.6	5.3	5.3	5.4	64
65	33-T	Bottom	74.7	74.0	74.4	6.4	7.1	7.2	6.3	6.8	67
66	33-T	Top	55.0	54.5	54.8	5.4	4.9	5.5	5.0	5.2	60
67	34-T	Bottom	75.7	77.4	76.6	6.8	6.6	6.6	6.4	6.6	63
68	34-T	Top	55.8	55.0	55.4	6.0	5.4	5.1	5.6	5.5	56
69	35-T	Bottom	74.5	72.5	73.5	6.1	6.0	6.4	6.5	6.3	64
70	35-T	Top	54.0	52.5	53.3	5.1	4.5	4.7	4.9	4.8	70
71	36-T	Bottom	71.5	70.3	70.9	7.0	7.2	6.4	6.4	6.8	67
72	36-T	Top	51.2	52.3	51.8	5.3	5.1	5.0	5.0	5.1	59
73	37-T	Bottom	70.0	67.2	68.6	6.0	6.0	6.0	5.9	6.0	60

74	37-T	Top	54.3	55.1	54.7	5.1	5.1	5.1	5.1	5.1	66
75	38-T	Bottom	70.0	66.8	68.4	8.0	8.0	7.5	7.1	7.7	67
76	38-T	Top	52.6	51.7	52.2	6.0	6.0	6.0	5.8	6.0	66
77	39-T	Bottom	69.8	66.6	68.2	5.6	5.4	5.4	6.4	5.7	65
78	39-T	Top	52.0	51.6	51.8	5.0	4.7	5.2	4.5	4.9	64
79	40-T	Bottom	68.0	65.2	66.6	4.6	5.1	5.8	5.5	5.3	64
80	40-T	Top	50.9	48.4	49.7	4.6	5.0	4.8	5.0	4.9	62
81	41-T	Bottom	59.8	57.0	58.4	5.1	5.4	4.9	5.2	5.2	54
82	41-T	Top	45.6	45.9	45.8	3.9	4.4	3.7	4.1	4.0	50
83	42-T	Bottom	70.2	67.0	68.6	5.8	5.8	5.5	5.7	5.7	64
84	42-T	Top	51.2	48.1	49.7	5.0	4.4	4.7	3.9	4.5	59
85	43-T	Bottom	60.3	63.4	61.9	5.2	4.7	4.6	4.8	4.8	60
86	43-T	Top	46.0	47.9	47.0	4.6	5.2	4.6	4.8	4.8	55
87	44-T	Bottom	66.0	66.0	66.0	5.3	5.7	5.4	6.1	5.6	62
88	44-T	Top	57.4	57.5	57.5	4.9	5.0	4.5	4.5	4.7	63
89	45-T	Bottom	69.3	68.6	69.0	5.5	5.2	5.3	5.1	5.3	66
90	45-T	Top	50.6	52.0	51.3	4.8	5.3	4.9	4.8	5.0	64
91	46-T	Bottom	72.8	69.2	71.0	5.5	5.7	5.8	5.5	5.6	69
92	46-T	Top	54.8	55.5	55.2	4.5	4.7	4.5	4.3	4.5	69
93	47-T	Bottom	59.5	59.9	59.7	7.0	5.0	6.1	6.8	6.2	58
94	47-T	Top	52.0	52.3	52.2	5.1	5.4	5.0	5.2	5.2	57
95	48-T	Bottom	68.4	66.7	67.6	7.8	9.1	8.5	9.0	8.6	72
96	48-T	Top	61.7	61.9	61.8	5.9	6.1	5.7	6.1	6.0	64
97	49-T	Bottom	64.0	65.4	64.7	5.3	5.7	5.5	5.2	5.4	64
98	49-T	Top	51.6	51.7	51.7	5.1	5.0	5.0	5.1	5.1	60
99	50-T	Bottom	74.2	73.0	73.6	6.9	7.2	6.6	6.7	6.9	65
100	50-T	Top	53.5	51.3	52.4	6.0	5.6	5.1	4.9	5.4	65
101	51-T	Bottom	72.5	74.4	73.5	6.7	5.7	5.9	6.1	6.1	62
102	51-T	Top	53.2	56.1	54.7	5.0	5.0	4.2	4.6	4.7	59
103	52-T	Bottom	70.0	71.2	70.6	7.0	6.4	6.6	7.5	6.9	65
104	52-T	Top	53.8	54.1	54.0	5.7	5.9	6.0	6.4	6.0	60
105	53-T	Bottom	58.3	62.7	60.5	5.0	5.7	4.7	5.6	5.3	67
106	53-T	Top	55.4	52.3	53.9	4.1	3.9	4.1	4.6	4.2	62
107	54-T	Bottom	73.3	70.5	71.9	6.4	6.4	6.5	6.6	6.5	68
108	54-T	Top	53.0	54.2	53.6	5.9	5.5	5.5	5.6	5.6	65
109	55-T	Bottom	76.7	76.4	76.6	7.5	6.5	6.3	6.4	6.7	75
110	55-T	Top	56.2	53.5	54.9	4.1	4.2	4.6	4.2	4.3	69
111	56-T	Bottom	65.0	67.7	66.4	5.7	5.9	6.4	5.2	5.8	65
112	56-T	Top	49.0	50.5	49.8	4.9	5.4	5.3	5.2	5.2	65

113	57-T	Bottom	52.6	53.7	53.2	11.0	9.0	9.0	10.0	9.8	65
114	57-T	Top	49.4	50.3	49.9	5.4	5.1	5.0	5.0	5.1	59
115	58-T	Bottom	55.0	54.6	54.8	13.6	11.0	10.2	11.9	11.7	57
116	58-T	Top	54.1	51.6	52.9	5.0	5.9	5.4	6.0	5.6	58

Table A1.2: Compressive strength test result data

No	Culm ID	Sample position	Loading rate (KN/s)	Failure Load (KN)	Area (mm^2)	Compressive strength (N/mm^2)	mass(g)	dry mass(g)	moisture %	density (kg/m^3)
1	01-B	Bottom	0.2	148.0	2585.4	57.2	157.68	136.67	15.37	670.19
2	01-B	Top	0.2	87.9	1652.4	53.2	103.30	89.87	14.94	718.59
3	02-B	Bottom	0.2	120.3	2516.3	47.8	137.80	114.20	20.67	693.22
4	02-B	Top	0.2	96.2	1683.4	57.2	124.28	108.87	14.15	769.04
5	03-B	Bottom	0.2	24.6	1620.6	15.2	45.27	38.86	16.50	324.81
6	03-B	Top	0.2	13.8	1263.7	10.9	26.44	22.92	15.36	252.09
7	04-B	Bottom	0.5	107.7	2597.7	41.4	168.48	145.10	16.11	682.70
8	04-B	Top	0.5	78.3	1810.2	43.2	124.92	110.65	12.90	742.04
9	05-B	Bottom	0.2	78.2	2367.4	33.0	156.70	136.32	14.95	735.45
10	05-B	Top	0.2	52.9	1523.6	34.7	101.79	89.08	14.27	742.32
11	06-B	Bottom	0.5	163.5	4390.2	37.2	267.13	223.97	19.27	640.50
12	06-B	Top	0.5	73.0	2513.4	29.1	142.38	124.14	14.69	629.44
13	07-B	Bottom	0.5	102.5	2437.2	42.1	153.89	135.42	13.64	678.96
14	07-B	Top	0.5	77.1	2166.7	35.6	115.85	101.97	13.61	594.08
15	08-B	Bottom	0.1	90.7	2414.8	37.5	125.92	109.31	15.20	651.81
16	08-B	Top	0.1	53.2	1289.6	41.3	78.23	68.60	14.04	730.86
17	09-B	Bottom	0.2	44.3	2043.6	21.7	81.85	71.20	14.96	421.59
18	09-B	Top	0.2	28.9	1305.6	22.1	60.62	52.62	15.20	488.75
19	10-B	Bottom	0.2	112.6	2371.8	47.5	144.73	126.85	14.10	717.91
20	10-B	Top	0.2	90.0	1546.8	58.2	104.91	92.37	13.58	779.57
21	11-B	Bottom	0.1	145.3	4116.2	35.3	255.88	217.06	17.88	609.45
22	11-B	Top	0.1	128.6	2965.3	43.4	195.21	170.44	14.53	626.97
23	12-B	Bottom	0.2	110.6	2403.2	46.0	125.02	109.80	13.86	642.26
24	12-B	Top	0.2	53.1	1431.9	37.1	78.96	69.48	13.64	706.98
25	13-B	Bottom	0.2	88.2	1970.0	44.8	99.69	87.37	14.10	648.77
26	13-B	Top	0.2	57.3	1302.1	44.0	65.60	57.89	13.32	645.91
27	14-B	Bottom	0.2	81.4	2377.7	34.2	114.12	98.82	15.48	607.55
28	14-B	Top	0.2	32.1	1092.9	29.4	56.31	49.18	14.50	628.34
29	15-B	Bottom	0.2	75.2	1805.3	41.7	105.91	92.17	14.91	715.46

30	15-B	Top	0.2	56.4	1242.6	45.4	80.74	71.23	13.35	746.86
31	16-B	Bottom	0.2	45.4	2600.0	17.5	97.42	84.57	15.19	390.30
32	16-B	Top	0.2	23.0	1415.7	16.3	55.71	48.15	15.70	423.14
33	17-B	Bottom	0.2	122.6	3562.0	34.4	227.47	190.04	19.70	679.37
34	17-B	Top	0.2	58.2	1920.3	30.3	121.96	106.55	14.46	622.67
35	18-B	Bottom	0.2	82.1	1778.6	46.2	78.63	67.93	15.75	650.15
36	18-B	Top	0.2	41.6	1095.8	38.0	44.60	39.02	14.30	598.54
37	19-B	Bottom	0.2	107.3	2954.7	36.3	138.35	118.33	16.92	557.43
39	20-B	Bottom	0.2	51.9	1630.9	31.8	75.93	66.46	14.25	560.92
40	20-B	Top	0.2	85.3	2182.6	39.1	110.07	95.92	14.75	600.37
41	21-B	Bottom	0.2	116.8	2436.3	47.9	158.94	139.02	14.33	639.58
42	21-B	Top	0.2	102.7	1908.0	53.8	139.88	123.17	13.57	698.22
43	22-B	Bottom	0.2	145.6	2874.9	50.6	184.93	162.05	14.12	649.76
44	22-B	Top	0.2	103.2	2087.3	49.4	130.89	114.94	13.88	633.43
45	23-B	Bottom	0.2	77.4	4141.5	18.7	145.89	127.38	14.53	323.18
46	23-B	Top	0.2	43.9	1724.6	25.5	94.00	82.50	13.94	504.67
47	24-B	Bottom	0.2	133.0	2887.1	46.1	183.94	160.38	14.69	685.06
48	24-B	Top	0.2	99.0	2912.6	34.0	130.20	114.63	13.58	496.70
49	25-B	Bottom	0.2	181.9	4209.9	43.2	266.97	232.42	14.87	621.71
50	25-B	Top	0.2	131.6	2750.8	47.8	193.98	170.53	13.75	671.59
51	26-B	Bottom	0.2	77.0	1825.2	42.2	81.50	71.58	13.86	579.91
52	26-B	Top	0.2	49.5	1043.2	47.5	50.86	44.97	13.10	667.89
53	27-B	Bottom	0.2	120.3	2355.1	51.1	140.81	122.63	14.83	711.77
54	27-B	Top	0.2	63.7	1564.7	40.7	89.02	78.40	13.55	677.29
55	28-B	Bottom	0.2	214.4	5383.4	39.8	337.81	292.75	15.39	586.45
56	28-B	Top	0.2	117.8	2724.2	43.2	204.15	179.64	13.64	663.19
57	29-B	Bottom	0.2	46.9	2142.1	21.9	56.72	49.56	14.45	378.27
58	29-B	Top	0.2	28.3	865.9	32.7	37.25	32.69	13.95	589.32
59	30-T	Bottom	0.5	70.6	1529.1	46.1	75.86	67.59	12.24	698.73
60	30-T	Top	0.5	46.4	885.8	52.3	47.32	42.39	11.63	721.91
61	31-T	Bottom	0.5	63.7	1362.2	46.8	67.28	60.07	12.00	705.56
62	31-T	Top	0.5	41.4	925.9	44.7	46.31	41.53	11.51	675.93
63	32-T	Bottom	0.2	31.8	1468.7	21.6	38.21	33.35	14.57	351.56
64	32-T	Top	0.2	21.7	834.8	26.0	21.09	18.63	13.20	394.73
65	33-T	Bottom	0.2	53.5	1434.1	37.3	53.62	46.76	14.67	558.05
66	33-T	Top	0.2	38.7	809.8	47.8	32.30	28.56	13.10	664.78
67	34-T	Bottom	0.2	63.7	1451.0	43.9	61.46	53.48	14.92	672.35
68	34-T	Top	0.2	44.9	866.0	51.9	37.58	32.90	14.22	774.87
69	35-T	Bottom	0.5	66.3	1321.0	50.2	65.90	58.54	12.57	779.49

70	35-T	Top	0.5	35.7	730.9	48.8	40.00	35.72	11.98	781.81
71	36-T	Bottom	0.2	51.2	1360.9	37.6	51.02	44.97	13.45	559.55
72	36-T	Top	0.2	31.0	747.7	41.4	28.58	25.22	13.32	647.83
73	37-T	Bottom	0.2	63.8	1176.0	54.3	57.24	50.23	13.96	811.22
74	37-T	Top	0.2	46.0	795.0	57.9	41.91	36.58	14.57	798.72
75	38-T	Bottom	0.2	75.3	1460.6	51.6	77.54	68.29	13.55	792.35
76	38-T	Top	0.2	52.8	863.9	61.1	45.47	40.30	12.83	797.44
77	39-T	Bottom	0.2	62.6	1119.6	55.9	56.42	49.82	13.25	775.25
78	39-T	Top	0.2	39.3	715.7	54.9	35.00	31.09	12.58	764.16
79	40-T	Bottom	0.2	44.7	1012.3	44.2	40.79	36.07	13.09	629.62
80	40-T	Top	0.2	31.9	682.9	46.7	27.59	24.42	12.98	651.65
81	41-T	Bottom	0.2	32.2	861.9	37.4	28.95	25.39	14.02	622.02
82	41-T	Top	0.2	20.6	527.8	39.0	17.24	15.24	13.12	653.25
83	42-T	Bottom	0.2	51.0	1126.8	45.3	47.93	42.17	13.66	664.63
84	42-T	Top	0.2	40.3	638.6	63.1	28.49	25.21	13.01	756.22
85	43-T	Bottom	0.2	44.7	864.7	51.7	36.74	32.44	13.26	708.11
86	43-T	Top	0.2	29.8	635.9	46.9	23.00	20.39	12.80	657.66
87	44-T	Bottom	0.2	47.9	1067.3	44.9	47.61	41.84	13.79	719.45
88	44-T	Top	0.2	35.6	783.0	45.5	32.77	29.02	12.92	664.34
89	45-T	Bottom	0.2	62.3	1055.6	59.0	55.81	49.33	13.14	801.04
90	45-T	Top	0.2	41.4	721.1	57.4	38.16	33.87	12.67	826.89
91	46-T	Bottom	0.2	53.7	1155.7	46.5	54.93	48.37	13.56	688.81
92	46-T	Top	0.2	38.3	716.3	53.5	37.69	33.44	12.71	762.54
93	47-T	Bottom	0.2	31.8	1046.2	30.4	29.56	25.98	13.78	487.15
94	47-T	Top	0.2	24.8	764.0	32.5	22.24	19.62	13.35	510.69
95	48-T	Bottom	0.2	88.3	1593.3	55.4	94.35	82.83	13.91	822.44
96	48-T	Top	0.2	56.9	1044.4	54.5	58.12	51.26	13.38	869.52
97	49-T	Bottom	0.2	56.9	1010.6	56.3	54.24	47.93	13.17	838.58
98	49-T	Top	0.2	45.5	739.6	61.5	36.58	32.36	13.04	824.31
99	50-T	Bottom	0.2	45.3	1437.0	31.5	44.23	38.59	14.62	473.52
100	50-T	Top	0.2	35.4	797.7	44.4	36.89	32.51	13.47	711.51
101	51-T	Bottom	0.2	65.6	1291.2	50.8	61.82	54.82	12.77	772.23
102	51-T	Top	0.2	35.3	737.8	47.9	32.12	28.38	13.18	737.85
103	52-T	Bottom	0.2	60.4	1376.9	43.9	60.71	53.60	13.26	678.33
104	52-T	Top	0.2	48.5	904.2	53.6	39.21	34.80	12.67	722.74
105	53-T	Bottom	0.2	34.3	911.6	37.6	38.84	34.29	13.27	635.90
106	53-T	Top	0.2	21.5	651.8	33.0	23.63	20.92	12.95	584.73
107	54-T	Bottom	0.2	49.2	1331.4	37.0	48.89	43.00	13.70	540.01
108	54-T	Top	0.2	32.7	848.1	38.6	30.88	27.20	13.53	560.15

109	55-T	Bottom	0.2	26.0	1465.9	17.7	37.16	32.58	14.06	338.00
110	55-T	Top	0.2	18.8	679.5	27.7	23.36	20.57	13.56	498.23
111	56-T	Bottom	0.2	54.1	1103.7	49.0	57.21	50.31	13.71	797.43
112	56-T	Top	0.2	38.9	728.1	53.4	37.13	32.77	13.30	784.58
113	57-T	Bottom	0.2	51.3	1329.9	38.6	51.38	45.08	13.98	594.38
114	57-T	Top	0.2	30.2	720.4	41.9	26.28	23.24	13.08	618.31
115	58-T	Bottom	0.1	49.7	1582.4	31.4	61.27	45.60	34.36	679.30
116	58-T	Top	0.1	24.8	828.3	29.9	27.53	21.20	29.86	573.03

APPENDIX A2

Table A2.1: Shear strength test specimen dimensions

No	Culm ID	Sample position	D1 (mm)	D2 (mm)	D (mm)	t1 (mm)	t2 (mm)	t3 (mm)	t4 (mm)	t (mm)	Height (mm)
1	01-B	Bottom	101.4	99.8	100.6	8.5	9.0	9.8	9.4	9.2	95
2	01-B	Top	87.4	88.5	88.0	7.2	7.6	8.2	8.1	7.8	91
3	02-B	Bottom	102.4	104.0	103.2	8.3	8.3	8.3	9.5	8.6	93
4	02-B	Top	85.6	81.6	83.6	7.8	7.6	6.9	7.4	7.4	90
5	03-B	Bottom	93.0	94.5	93.8	7.7	8.3	6.6	5.9	7.1	86
6	03-B	Top	79.2	77.1	78.2	5.7	5.9	5.9	6.2	5.9	86
7	04-B	Bottom	96.8	97.5	97.2	9.8	9.3	10.0	8.7	9.5	90
8	04-B	Top	87.8	85.0	86.4	7.7	7.6	6.4	7.4	7.3	98
9	05-B	Bottom	94.6	91.0	92.8	7.7	8.9	9.3	8.8	8.7	90
10	05-B	Top	84.0	82.6	83.3	6.4	7.3	6.8	7.7	7.1	91
11	06-B	Bottom	91.5	93.6	92.6	15.7	19.5	17.2	18.4	17.7	93
12	06-B	Top	89.8	92.1	91.0	9.8	9.7	11.4	9.1	10.0	92
13	07-B	Bottom	87.0	87.1	87.1	10.4	10.8	12.1	12.6	11.5	91
14	07-B	Top	93.6	89.9	91.8	10.3	11.3	9.9	10.5	10.5	95
15	08-B	Bottom	74.5	73.9	74.2	11.7	12.3	11.6	10.6	11.6	81
16	08-B	Top	67.8	71.5	69.7	6.8	6.9	6.1	7.4	6.8	81
17	09-B	Bottom	96.6	95.9	96.3	7.3	8.3	6.9	8.1	7.7	98
18	09-B	Top	81.4	82.2	81.8	5.5	5.4	5.2	7.9	6.0	93
19	10-B	Bottom	96.9	93.3	95.1	8.6	9.0	8.1	8.2	8.5	91
20	10-B	Top	79.2	80.9	80.1	7.8	7.9	7.1	7.2	7.5	95
21	11-B	Bottom	97.2	97.0	97.1	13.3	16.8	14.2	16.9	15.3	109
22	11-B	Top	99.3	97.5	98.4	11.0	11.0	10.9	10.3	10.8	109
23	12-B	Bottom	81.7	82.6	82.2	11.0	10.0	10.0	10.3	10.3	81

24	12-B	Top	74.4	76.2	75.3	6.6	6.7	7.3	6.2	6.7	82
25	13-B	Bottom	81.7	83.7	82.7	6.8	8.0	9.3	10.2	8.6	84
26	13-B	Top	80.8	79.6	80.2	6.3	9.2	8.4	7.4	7.8	81
27	14-B	Bottom	75.6	76.0	75.8	11.3	11.9	9.7	9.5	10.6	80
28	14-B	Top	67.9	70.0	69.0	5.5	6.0	5.5	5.4	5.6	82
29	15-B	Bottom	79.7	86.7	83.2	7.8	7.9	8.3	8.6	8.2	88
30	15-B	Top	78.9	75.0	77.0	6.5	6.4	6.7	6.8	6.6	88
31	16-B	Bottom	106.4	100.7	103.6	9.3	10.7	8.6	9.9	9.6	103
32	16-B	Top	83.2	86.5	84.9	5.5	5.6	5.6	6.0	5.7	101
33	17-B	Bottom	85.0	89.3	87.2	14.9	13.4	15.1	16.2	14.9	101
34	17-B	Top	90.0	89.0	89.5	8.7	10.2	8.4	9.3	9.2	97
35	18-B	Bottom	68.3	73.6	71.0	10.0	8.5	9.7	8.4	9.2	72
36	18-B	Top	68.4	64.7	66.6	5.7	6.6	6.5	5.0	6.0	69
37	19-B	Bottom	78.7	79.5	79.1	14.0	15.4	14.8	12.0	14.1	99
39	20-B	Bottom	79.0	75.9	77.5	7.0	7.3	7.5	7.0	7.2	83
40	20-B	Top	70.2	70.5	70.4	11.9	13.3	11.1	13.0	12.3	83
41	21-B	Bottom	103.6	99.9	101.8	9.3	8.9	9.0	9.3	9.1	102
42	21-B	Top	96.0	96.3	96.2	7.3	9.3	8.0	7.8	8.1	106
43	22-B	Bottom	87.1	90.1	88.6	11.5	12.5	10.8	11.0	11.5	98
44	22-B	Top	91.7	90.0	90.9	8.8	9.3	7.8	9.4	8.8	97
45	23-B	Bottom	116.0	113.1	114.6	10.4	11.9	10.8	10.2	10.8	111
46	23-B	Top	103.0	104.1	103.6	9.0	7.7	7.4	9.5	8.4	101
47	24-B	Bottom	77.8	84.1	81.0	12.1	13.1	11.8	12.0	12.3	93
48	24-B	Top	93.4	91.9	92.7	11.6	11.0	11.8	12.6	11.8	88
49	25-B	Bottom	100.0	97.5	98.8	13.9	15.4	15.8	13.8	14.7	107
50	25-B	Top	106.6	104.9	105.8	9.0	11.0	9.3	11.4	10.2	102
51	26-B	Bottom	79.2	80.8	80.0	7.4	6.7	6.5	6.7	6.8	74
52	26-B	Top	64.2	66.4	65.3	5.3	5.5	6.1	5.3	5.6	73
53	27-B	Bottom	80.4	79.5	80.0	11.0	11.6	11.5	12.7	11.7	79
54	27-B	Top	76.4	78.1	77.3	7.0	7.5	7.6	8.4	7.6	84
55	28-B	Bottom	100.6	102.1	101.4	17.6	20.0	17.5	17.1	18.1	104
56	28-B	Top	103.1	98.7	100.9	11.0	10.4	11.0	10.7	10.8	110
57	29-B	Bottom	66.5	68.2	67.4	12.0	11.7	12.1	13.1	12.2	69
58	29-B	Top	66.5	65.0	65.8	5.5	5.3	5.8	5.1	5.4	75
59	30-T	Bottom	78.0	78.5	78.3	7.0	5.5	6.0	5.9	6.1	67
60	30-T	Top	60.2	60.3	60.3	5.6	5.6	5.2	4.8	5.3	71
61	31-T	Bottom	77.2	75.2	76.2	6.7	6.5	7.0	7.0	6.8	74
62	31-T	Top	64.5	68.7	66.6	6.1	5.8	5.8	5.0	5.7	75
63	32-T	Bottom	75.3	77.9	76.6	6.6	6.5	6.2	6.0	6.3	65

64	32-T	Top	55.4	55.3	55.4	5.3	5.3	5.6	5.8	5.5	65
65	33-T	Bottom	69.7	74.1	71.9	8.0	7.5	6.5	6.0	7.0	64
66	33-T	Top	60.2	59.7	60.0	7.3	6.0	5.4	5.5	6.1	64
67	34-T	Bottom	75.6	74.0	74.8	6.3	5.9	6.7	6.9	6.5	64
68	34-T	Top	56.0	56.9	56.5	5.5	5.7	6.0	6.4	5.9	61
69	35-T	Bottom	75.5	74.4	75.0	5.9	6.3	6.7	6.8	6.4	73
70	35-T	Top	59.8	58.4	59.1	5.5	5.6	5.4	5.8	5.6	65
71	36-T	Bottom	71.6	71.0	71.3	5.8	6.7	6.1	6.4	6.3	67
72	36-T	Top	53.0	52.3	52.7	5.5	5.5	4.9	5.3	5.3	61
73	37-T	Bottom	68.6	69.7	69.2	6.3	6.9	6.1	5.9	6.3	65
74	37-T	Top	57.8	54.8	56.3	6.4	6.0	5.1	5.3	5.7	60
75	38-T	Bottom	68.3	64.1	66.2	7.2	8.1	7.1	7.0	7.4	68
76	38-T	Top	54.2	54.9	54.6	5.7	6.2	5.6	6.1	5.9	61
77	39-T	Bottom	69.2	69.4	69.3	6.1	6.0	5.8	6.0	6.0	66
78	39-T	Top	55.7	55.1	55.4	5.5	5.0	5.3	5.4	5.3	65
79	40-T	Bottom	63.9	63.7	63.8	5.5	5.7	5.2	5.1	5.4	60
80	40-T	Top	50.9	51.3	51.1	5.0	4.5	4.8	4.8	4.8	63
81	41-T	Bottom	61.6	60.6	61.1	6.3	6.3	6.7	6.4	6.4	54
82	41-T	Top	49.0	49.0	49.0	4.7	5.3	5.7	4.7	5.1	51
83	42-T	Bottom	69.9	67.9	68.9	5.0	5.3	4.9	5.9	5.3	60
84	42-T	Top	50.0	51.4	50.7	4.5	5.0	4.5	4.9	4.7	65
85	43-T	Bottom	62.0	61.4	61.7	5.2	5.6	5.9	5.5	5.6	58
86	43-T	Top	47.9	47.6	47.8	4.7	4.9	5.8	6.2	5.4	59
87	44-T	Bottom	68.3	68.7	68.5	4.9	5.1	5.4	5.1	5.1	61
88	44-T	Top	57.8	55.8	56.8	4.7	4.6	5.0	4.6	4.7	62
89	45-T	Bottom	70.0	70.6	70.3	5.4	5.7	6.3	6.4	6.0	61
90	45-T	Top	55.3	53.8	54.6	4.9	5.1	6.3	5.4	5.4	66
91	46-T	Bottom	72.5	70.4	71.5	5.5	5.1	5.4	5.5	5.4	72
92	46-T	Top	55.0	53.8	54.4	4.6	5.1	4.3	4.8	4.7	66
93	47-T	Bottom	60.5	61.6	61.1	6.6	7.7	7.3	6.3	7.0	55
94	47-T	Top	53.7	54.0	53.9	5.5	5.9	5.4	6.7	5.9	54
95	48-T	Bottom	70.0	68.1	69.1	7.1	8.2	7.9	8.0	7.8	66
96	48-T	Top	64.8	61.1	63.0	5.5	6.2	5.7	6.7	6.0	72
97	49-T	Bottom	67.0	68.9	68.0	5.7	6.1	6.1	6.0	6.0	62
98	49-T	Top	56.3	56.9	56.6	5.3	5.4	5.9	5.3	5.5	67
99	50-T	Bottom	72.0	72.2	72.1	6.4	6.3	6.3	6.3	6.3	68
100	50-T	Top	54.0	53.6	53.8	5.2	5.1	5.0	4.7	5.0	66
101	51-T	Bottom	70.0	70.5	70.3	5.2	5.7	6.4	6.7	6.0	62
102	51-T	Top	58.2	58.5	58.4	5.7	4.8	4.9	5.4	5.2	57

103	52-T	Bottom	69.4	69.8	69.6	7.0	6.1	6.8	6.7	6.7	65
104	52-T	Top	54.9	55.1	55.0	5.7	6.1	6.1	6.9	6.2	62
105	53-T	Bottom	61.0	62.2	61.6	5.5	5.4	5.4	5.7	5.5	63
106	53-T	Top	55.3	55.5	55.4	4.0	4.6	4.3	4.7	4.4	63
107	54-T	Bottom	72.0	70.4	71.2	6.1	6.2	6.0	6.0	6.1	66
108	54-T	Top	56.3	57.4	56.9	5.5	5.3	5.8	5.7	5.6	65
109	55-T	Bottom	76.6	77.6	77.1	6.1	6.5	6.7	6.8	6.5	72
110	55-T	Top	57.3	57.7	57.5	4.4	4.3	5.4	5.1	4.8	70
111	56-T	Bottom	68.8	65.1	67.0	5.0	5.8	5.9	5.2	5.5	64
112	56-T	Top	50.7	49.6	50.2	4.8	5.2	5.0	4.8	5.0	62
113	57-T	Bottom	55.1	55.1	55.1	10.4	9.2	9.2	10.7	9.9	54
114	57-T	Top	51.4	52.3	51.9	6.4	5.3	5.3	5.8	5.7	63
115	58-T	Bottom	53.6	53.8	53.7	10.0	10.9	11.0	10.4	10.6	60
116	58-T	Top	53.4	52.2	52.8	6.0	6.7	5.8	6.5	6.3	56

Table A2.2: Shear strength test result data

No	Culm ID	Sample position	Failure Load (KN)	Shear strength (N/mm^2)	mass (g)	dry mass (g)	moisture %
1	01-B	Bottom	36.1	10.3	214.32	180.21	18.93
2	01-B	Top	31.6	11.2	168.90	136.31	23.91
3	02-B	Bottom	19.8	6.2	158.81	133.53	18.93
4	02-B	Top	23.6	8.8	121.47	105.34	15.31
5	03-B	Bottom	6.0	2.4	58.97	50.63	16.47
6	03-B	Top	5.8	2.8	41.55	36.15	14.94
7	04-B	Bottom	38.2	11.2	157.57	136.55	15.39
8	04-B	Top	32.6	11.4	134.41	118.36	13.56
9	05-B	Bottom	22.7	7.3	187.68	160.53	16.91
10	05-B	Top	19.7	7.7	151.46	130.42	16.13
11	06-B	Bottom	36.5	5.5	242.07	204.89	18.15
12	06-B	Top	28.9	7.8	148.92	132.48	12.41
13	07-B	Bottom	37.4	8.9	183.82	161.36	13.92
14	07-B	Top	37.0	9.3	158.63	139.71	13.54
15	08-B	Bottom	30.6	8.2	120.41	103.87	15.92
16	08-B	Top	14.8	6.7	78.67	69.20	13.68
17	09-B	Bottom	10.6	3.5	117.00	101.60	15.16
18	09-B	Top	9.8	4.4	85.43	74.10	15.29
19	10-B	Bottom	32.5	10.5	152.85	133.32	14.65

20	10-B	Top	29.5	10.3	117.81	103.48	13.85
21	11-B	Bottom	46.6	7.0	309.23	262.19	17.94
22	11-B	Top	42.2	9.0	246.83	214.43	15.11
23	12-B	Bottom	29.3	8.7	120.65	105.83	14.00
24	12-B	Top	20.4	9.3	84.24	74.09	13.70
25	13-B	Bottom	23.9	8.3	127.12	111.02	14.50
26	13-B	Top	18.4	7.2	110.80	97.20	13.99
27	14-B	Bottom	27.4	8.1	113.28	97.24	16.50
28	14-B	Top	15.1	8.2	61.41	53.80	14.14
29	15-B	Bottom	26.8	9.3	151.95	129.78	17.08
30	15-B	Top	18.5	7.9	115.20	101.00	14.06
31	16-B	Bottom	10.8	2.7	98.98	85.78	15.39
32	16-B	Top	9.3	4.0	61.79	53.14	16.28
33	17-B	Bottom	47.4	7.9	276.18	227.19	21.56
34	17-B	Top	27.7	7.8	178.55	154.15	15.83
35	18-B	Bottom	22.4	8.5	78.78	68.24	15.45
36	18-B	Top	13.0	7.9	47.76	41.92	13.93
37	19-B	Bottom	44.0	7.9	194.20	163.83	18.54
39	20-B	Bottom	15.8	6.6	79.15	69.02	14.68
40	20-B	Top	24.0	5.9	108.00	93.94	14.97
41	21-B	Bottom	34.9	9.4	203.19	178.24	14.00
42	21-B	Top	30.6	8.9	196.60	171.99	14.31
43	22-B	Bottom	45.7	10.2	176.17	154.26	14.20
44	22-B	Top	28.4	8.3	135.33	118.57	14.14
45	23-B	Bottom	20.8	4.3	185.05	160.74	15.12
46	23-B	Top	18.4	5.4	141.48	123.12	14.91
47	24-B	Bottom	44.3	9.7	174.78	152.09	14.92
48	24-B	Top	30.4	7.3	128.67	112.79	14.08
49	25-B	Bottom	46.4	7.4	302.28	263.27	14.82
50	25-B	Top	40.4	9.7	246.98	216.17	14.25
51	26-B	Bottom	15.8	7.8	71.26	62.68	13.69
52	26-B	Top	13.5	8.3	51.89	45.88	13.10
53	27-B	Bottom	40.9	11.1	169.35	147.38	14.91
54	27-B	Top	23.8	9.3	134.39	117.86	14.03
55	28-B	Bottom	64.7	8.6	305.22	265.76	14.85
56	28-B	Top	39.5	8.3	214.76	188.41	13.99
57	29-B	Bottom	16.3	4.8	68.29	59.75	14.29
58	29-B	Top	11.6	7.1	56.43	49.31	14.44
59	30-T	Bottom	22.5	13.7	67.84	60.06	12.95

60	30-T	Top	16.4	10.9	48.28	42.79	12.83
61	31-T	Bottom	24.5	12.2	91.08	80.42	13.26
62	31-T	Top	19.7	11.5	69.09	61.16	12.97
63	32-T	Bottom	6.7	4.0	34.03	29.87	13.93
64	32-T	Top	7.0	4.9	22.44	19.65	14.20
65	33-T	Bottom	12.5	7.0	72.99	63.51	14.93
66	33-T	Top	18.0	11.6	56.66	49.34	14.84
67	34-T	Bottom	10.0	6.0	61.41	53.43	14.94
68	34-T	Top	15.7	10.9	44.16	38.41	14.97
69	35-T	Bottom	22.8	12.1	95.74	84.07	13.88
70	35-T	Top	17.4	12.0	57.15	50.42	13.35
71	36-T	Bottom	14.9	8.9	47.33	41.65	13.64
72	36-T	Top	11.4	8.8	29.61	26.16	13.19
73	37-T	Bottom	13.8	8.4	80.09	69.27	15.62
74	37-T	Top	15.8	11.5	59.19	50.36	17.53
75	38-T	Bottom	27.4	13.7	75.57	66.57	13.52
76	38-T	Top	18.5	12.8	44.76	39.61	13.00
77	39-T	Bottom	19.4	12.3	80.72	70.90	13.85
78	39-T	Top	12.5	9.0	55.25	48.79	13.24
79	40-T	Bottom	13.8	10.7	39.45	34.77	13.46
80	40-T	Top	12.3	10.2	28.53	25.27	12.90
81	41-T	Bottom	12.0	8.6	45.87	40.38	13.60
82	41-T	Top	4.3	4.1	31.86	27.95	13.99
83	42-T	Bottom	12.5	9.8	42.55	37.37	13.86
84	42-T	Top	12.0	9.7	32.41	28.58	13.40
85	43-T	Bottom	15.4	11.9	52.08	45.77	13.79
86	43-T	Top	13.5	10.6	37.04	32.58	13.69
87	44-T	Bottom	14.0	11.2	44.36	39.06	13.57
88	44-T	Top	7.8	6.6	34.42	30.34	13.45
89	45-T	Bottom	15.0	10.3	73.50	64.83	13.37
90	45-T	Top	11.8	8.2	57.57	50.91	13.08
91	46-T	Bottom	19.4	12.5	58.03	51.35	13.01
92	46-T	Top	15.5	12.5	36.91	32.78	12.60
93	47-T	Bottom	6.2	4.0	41.00	35.91	14.17
94	47-T	Top	7.8	6.1	33.83	29.65	14.10
95	48-T	Bottom	17.8	8.6	87.26	76.81	13.60
96	48-T	Top	16.6	9.5	68.70	60.65	13.27
97	49-T	Bottom	17.5	11.8	74.24	65.47	13.40
98	49-T	Top	16.8	11.4	59.04	52.21	13.08

99	50-T	Bottom	16.4	9.5	43.88	38.43	14.18
100	50-T	Top	15.6	11.8	34.49	30.53	12.97
101	51-T	Bottom	13.1	8.8	72.89	64.44	13.11
102	51-T	Top	11.3	9.5	48.41	42.73	13.29
103	52-T	Bottom	15.4	8.9	58.91	51.94	13.42
104	52-T	Top	16.4	10.6	43.00	38.07	12.95
105	53-T	Bottom	11.2	8.0	51.14	44.96	13.75
106	53-T	Top	9.1	8.2	37.39	33.03	13.20
107	54-T	Bottom	13.6	8.5	46.57	40.86	13.97
108	54-T	Top	12.8	8.8	33.11	29.06	13.94
109	55-T	Bottom	6.9	3.6	51.84	45.26	14.54
110	55-T	Top	6.2	4.6	35.67	31.26	14.11
111	56-T	Bottom	15.2	10.8	52.89	46.62	13.45
112	56-T	Top	13.8	11.2	34.12	30.26	12.76
113	57-T	Bottom	18.8	8.8	59.21	51.88	14.13
114	57-T	Top	13.1	9.1	46.76	41.12	13.72
115	58-T	Bottom	12.6	4.9	50.92	42.00	21.24
116	58-T	Top	9.4	6.7	28.99	24.20	19.79

APPENDIX A3

Table A3.1: Flat ring flexure test specimen dimensions

No	Culm ID	Sample position	D1 (mm)	D2 (mm)	D (mm)	t1 (mm)	t2 (mm)	t3 (mm)	t4 (mm)	t (mm)	Height (mm)
1	01-B	Bottom	97.3	95.5	48.2	9.0	8.9	8.1	8.6	8.7	29
2	01-B	Top	82.7	82.6	82.7	6.9	7.9	7.2	7.5	7.4	29
3	02-B	Bottom	101.6	100.4	101.0	9.1	9.1	9.5	9.0	9.2	31
4	02-B	Top	81.6	87.4	84.5	7.1	7.3	7.3	7.6	7.3	29
5	03-B	Bottom	86.4	91.4	88.9	7.6	7.4	8.1	7.1	7.6	29
6	03-B	Top	77.7	74.6	76.2	5.3	5.8	5.8	5.6	5.6	26
7	04-B	Bottom	98.2	95.5	96.9	8.6	8.4	9.5	9.6	9.0	30
8	04-B	Top	91.2	86.8	89.0	7.7	7.8	6.9	6.8	7.3	35
9	05-B	Bottom	94.5	93.6	94.1	8.2	7.6	7.7	8.6	8.0	25
10	05-B	Top	81.5	81.3	81.4	6.3	7.4	6.5	7.5	6.9	31
11	06-B	Bottom	94.5	89.9	92.2	15.1	16.8	15.1	16.6	15.9	33
12	06-B	Top	89.4	89.4	89.4	9.5	9.3	9.7	10.3	9.7	35
13	07-B	Bottom	72.4	79.3	75.9	14.0	12.5	12.9	14.9	13.6	32

14	07-B	Top	82.7	89.0	85.9	9.7	8.7	9.7	9.2	9.3	32
15	08-B	Bottom	71.4	75.1	73.3	10.5	10.6	11.0	12.2	11.1	30
16	08-B	Top	69.3	72.1	70.7	5.5	5.6	6.6	7.7	6.4	28
17	09-B	Bottom	94.3	92.1	93.2	6.0	7.2	9.0	6.3	7.1	29
18	09-B	Top	82.1	85.2	83.7	6.2	6.3	5.6	5.8	6.0	34
19	10-B	Bottom	95.6	93.5	94.6	8.0	9.4	8.2	8.7	8.6	30
20	10-B	Top	82.3	81.8	82.1	6.8	7.4	7.1	6.8	7.0	29
21	11-B	Bottom	91.8	92.9	92.4	12.5	14.0	14.0	13.2	13.4	33
22	11-B	Top	100.3	98.7	99.5	11.4	11.5	11.2	10.5	11.2	32
23	12-B	Bottom	82.6	81.5	82.1	9.0	8.9	9.2	9.1	9.1	28
24	12-B	Top	76.3	75.5	75.9	7.2	6.9	7.0	7.4	7.1	26
25	13-B	Bottom	86.8	82.8	84.8	7.8	8.2	7.3	8.6	8.0	27
26	13-B	Top	77.4	76.7	77.1	6.2	7.2	7.0	6.0	6.6	27
27	14-B	Bottom	72.2	75.3	73.8	10.2	10.4	9.2	8.7	9.6	33
28	14-B	Top	67.7	66.7	67.2	5.6	5.9	6.0	6.4	6.0	29
29	15-B	Bottom	84.0	73.5	78.8	7.1	7.0	7.0	7.2	7.1	30
30	15-B	Top	78.3	74.9	76.6	6.0	6.8	5.0	5.5	5.8	30
31	16-B	Bottom	112.8	92.5	102.7	10.7	9.6	10.0	10.8	10.3	34
32	16-B	Top	89.0	82.0	85.5	5.2	6.0	5.5	6.0	5.7	33
33	17-B	Bottom	89.4	85.3	87.4	12.1	15.0	13.2	16.0	14.1	30
34	17-B	Top	88.4	85.0	86.7	8.0	7.8	6.9	7.6	7.6	29
35	18-B	Bottom	70.8	71.7	71.3	7.2	9.5	8.6	7.8	8.3	22
36	18-B	Top	68.1	66.2	67.2	6.0	5.6	6.0	6.0	5.9	21
37	19-B	Bottom	72.0	74.5	73.3	11.1	12.4	11.5	11.6	11.7	24
38	20-B	Bottom	77.9	78.3	78.1	7.7	7.2	6.7	7.0	7.2	22
39	20-B	Top	68.5	66.6	67.6	11.1	11.2	10.0	12.3	11.2	29
40	21-B	Bottom	97.1	95.8	96.5	8.0	8.0	8.0	7.7	7.9	31
41	21-B	Top	90.0	94.0	92.0	6.5	6.8	6.4	7.2	6.7	32
42	22-B	Bottom	88.0	89.0	88.5	11.7	13.0	12.2	12.0	12.2	30
43	22-B	Top	92.5	89.2	90.9	8.4	8.3	8.1	7.9	8.2	32
44	23-B	Bottom	112.1	114.1	113.1	11.2	10.7	12.4	10.6	11.2	31
45	23-B	Top	95.6	93.4	94.5	6.9	7.1	7.6	6.8	7.1	36
46	24-B	Bottom	81.0	81.1	81.1	13.0	14.0	13.2	12.7	13.2	29
47	24-B	Top	93.1	95.3	94.2	12.0	12.7	13.0	11.7	12.4	29
48	25-B	Bottom	98.0	99.7	98.9	15.0	15.4	15.7	14.6	15.2	36
49	25-B	Top	97.9	105.9	101.9	10.5	9.7	10.4	9.2	10.0	33
50	26-B	Bottom	81.1	78.7	79.9	6.6	5.9	6.1	7.2	6.5	23
51	26-B	Top	67.1	66.7	66.9	6.0	5.5	5.6	5.3	5.6	23
52	27-B	Bottom	76.0	73.9	75.0	10.7	12.0	11.0	10.7	11.1	26

53	27-B	Top	75.1	75.5	75.3	7.4	7.2	7.0	7.3	7.2	30
54	28-B	Bottom	100.2	99.1	99.7	17.2	17.6	16.4	18.2	17.4	31
55	28-B	Top	99.4	96.0	97.7	11.6	10.6	10.0	10.6	10.7	32
56	29-B	Bottom	68.7	65.5	67.1	9.7	10.5	9.9	11.2	10.3	26
57	29-B	Top	67.2	64.4	65.8	4.7	5.3	4.9	4.9	5.0	23
58	30-T	Bottom	74.2	73.0	73.6	6.4	4.9	6.3	6.1	5.9	23
59	30-T	Top	61.0	62.3	61.7	5.0	4.1	4.4	5.0	4.6	23
60	31-T	Bottom	74.3	71.1	72.7	6.2	5.3	5.6	6.4	5.9	22
61	31-T	Top	61.3	65.5	63.4	4.8	4.8	5.3	5.0	5.0	24
62	32-T	Bottom	78.2	72.8	75.5	6.7	6.8	6.6	6.6	6.7	25
63	32-T	Top	57.4	57.8	57.6	5.6	5.7	5.4	5.5	5.6	22
64	33-T	Bottom	74.0	70.5	72.3	6.9	5.5	6.3	6.0	6.2	22
65	33-T	Top	57.6	58.6	58.1	5.3	4.8	4.9	6.0	5.3	22
66	34-T	Bottom	70.1	69.6	69.9	6.0	5.7	6.2	5.4	5.8	20
67	34-T	Top	57.5	58.1	57.8	5.8	5.3	5.6	5.7	5.6	18
68	35-T	Bottom	71.8	71.7	71.8	6.0	6.0	5.4	6.1	5.9	24
69	35-T	Top	57.3	55.4	56.4	4.8	5.3	4.9	4.9	5.0	27
70	36-T	Bottom	68.5	69.7	69.1	6.3	6.2	5.8	6.3	6.2	24
71	36-T	Top	54.0	55.5	54.8	4.8	4.7	5.1	5.6	5.1	20
72	37-T	Bottom	63.0	65.3	64.2	4.9	5.3	5.1	4.7	5.0	22
73	37-T	Top	55.9	57.8	56.9	5.2	4.9	5.1	5.3	5.1	21
74	38-T	Bottom	65.7	65.0	65.4	7.0	7.0	7.4	6.9	7.1	21
75	38-T	Top	54.2	54.3	54.3	5.5	5.4	5.8	6.1	5.7	20
76	39-T	Bottom	67.6	67.8	67.7	4.7	5.3	4.8	5.5	5.1	21
77	39-T	Top	53.0	54.8	53.9	4.9	4.7	5.3	4.5	4.9	22
78	40-T	Bottom	63.6	66.1	64.9	5.0	4.6	5.0	5.5	5.0	22
79	40-T	Top	57.4	54.7	56.1	4.8	4.9	4.6	4.2	4.6	22
80	41-T	Bottom	58.5	53.7	56.1	4.5	4.9	5.6	5.3	5.1	22
81	41-T	Top	50.5	49.0	49.8	4.3	3.6	4.3	4.8	4.3	17
82	42-T	Bottom	64.5	67.1	65.8	4.6	5.4	5.8	5.2	5.3	22
83	42-T	Top	52.7	50.9	51.8	4.5	4.7	4.3	5.0	4.6	25
84	43-T	Bottom	59.9	62.9	61.4	4.5	4.4	4.5	4.5	4.5	18
85	43-T	Top	49.0	50.8	49.9	4.8	4.6	5.0	4.7	4.8	22
86	44-T	Bottom	62.2	70.5	66.4	5.0	4.7	4.7	4.5	4.7	18
87	44-T	Top	59.0	58.7	58.9	4.1	4.5	4.3	4.7	4.4	18
88	45-T	Bottom	66.3	67.9	67.1	5.4	4.7	5.6	5.7	5.4	22
89	45-T	Top	54.3	52.9	53.6	4.4	4.9	5.0	4.8	4.8	22
90	46-T	Bottom	69.7	67.3	68.5	5.2	5.3	5.2	5.4	5.3	26
91	46-T	Top	57.2	56.6	56.9	4.6	4.1	4.6	4.5	4.5	24

92	47-T	Bottom	58.8	59.0	58.9	5.8	6.2	6.8	5.1	6.0	18
93	47-T	Top	52.1	51.9	52.0	5.5	5.9	5.7	4.7	5.5	17
94	48-T	Bottom	67.6	68.8	68.2	7.4	6.9	7.2	7.7	7.3	24
95	48-T	Top	62.6	63.9	63.3	6.6	5.5	5.7	5.7	5.9	24
96	49-T	Bottom	66.3	65.0	65.7	5.6	5.4	5.5	5.1	5.4	20
97	49-T	Top	55.0	53.5	54.3	5.1	5.2	5.0	4.8	5.0	19
98	50-T	Bottom	70.5	72.0	71.3	6.1	6.1	6.3	7.0	6.4	21
99	50-T	Top	53.4	53.5	53.5	5.4	5.0	5.3	5.0	5.2	19
100	51-T	Bottom	70.9	65.5	68.2	5.4	5.0	5.2	5.2	5.2	23
101	51-T	Top	57.8	55.8	56.8	4.5	4.6	4.6	5.0	4.7	20
102	52-T	Bottom	67.2	69.1	68.2	6.4	6.6	6.0	6.6	6.4	19
103	52-T	Top	59.1	59.9	59.5	6.3	5.6	5.6	6.1	5.9	23
104	53-T	Bottom	61.0	61.7	61.4	5.1	4.8	5.7	5.1	5.2	26
105	53-T	Top	51.0	55.5	53.3	4.1	4.4	4.0	4.3	4.2	19
106	54-T	Bottom	68.5	71.9	70.2	6.6	6.4	6.0	6.2	6.3	26
107	54-T	Top	53.6	54.7	54.2	5.5	5.8	5.4	6.1	5.7	24
108	55-T	Bottom	76.0	74.3	75.2	6.4	6.2	6.4	6.2	6.3	23
109	55-T	Top	58.6	57.0	57.8	4.4	4.5	4.1	4.7	4.4	24
110	56-T	Bottom	62.8	66.0	64.4	5.5	5.6	6.0	5.3	5.6	25
111	56-T	Top	47.7	47.1	47.4	5.5	4.7	5.1	4.6	5.0	22
112	57-T	Bottom	52.0	53.3	52.7	8.1	9.3	7.9	8.7	8.5	19
113	57-T	Top	51.8	51.7	51.8	5.3	5.2	5.7	4.9	5.3	21
114	58-T	Bottom	53.0	52.3	52.7	8.7	9.0	7.7	9.4	8.7	23
115	58-T	Top	52.0	54.3	53.2	7.0	6.2	6.0	6.0	6.3	18

Table A3.2: Flat ring flexure test results data part I

No	Culm ID	Sample position	C (mm)	a (mm)	Failure Load+Plate(KN)	M (Nmm)	y (mm)	I (mm^3)
1	01-B	Bottom	20	25	2.3	56937.5	14.5	17580.4
2	01-B	Top	20	15	2.4	35662.5	14.5	14989.1
3	02-B	Bottom	20	25	3.2	79437.5	15.5	22777.7
4	02-B	Top	20	15	2.7	40162.5	14.5	14887.5
5	03-B	Bottom	20	25	1.4	34437.5	14.5	15344.7
6	03-B	Top	20	15	1.8	26662.5	13.0	8238.8
7	04-B	Bottom	20	25	2.2	54437.5	15.0	20306.3
8	04-B	Top	20	25	3.7	91937.5	17.5	26082.3
9	05-B	Bottom	20	25	2.0	49437.5	12.5	10449.2
10	05-B	Top	20	15	3.4	50662.5	15.5	17191.9

11	06-B	Bottom	20	25	5.1	126937.5	16.5	47616.5
12	06-B	Top	20	25	4.2	104437.5	17.5	34657.3
13	07-B	Bottom	20	15	10.8	161662.5	16.0	37068.8
14	07-B	Top	20	15	8.8	131662.5	16.0	25463.5
15	08-B	Bottom	20	15	5.2	77662.5	15.0	24918.8
16	08-B	Top	20	15	4.6	68662.5	14.0	11616.3
17	09-B	Bottom	20	25	2.2	54437.5	14.5	14481.0
18	09-B	Top	20	15	4.2	62662.5	17.0	19570.1
19	10-B	Bottom	20	25	4.9	121937.5	15.0	19293.8
20	10-B	Top	20	15	4.9	73162.5	14.5	14277.7
21	11-B	Bottom	20	25	5.9	146937.5	16.5	40204.5
22	11-B	Top	20	25	4.4	109437.5	16.0	30446.9
23	12-B	Bottom	20	15	3.5	52162.5	14.0	16555.5
24	12-B	Top	20	15	2.9	43162.5	13.0	10435.8
25	13-B	Bottom	20	15	3.7	55162.5	13.5	13081.0
26	13-B	Top	20	15	4.2	62662.5	13.5	10825.7
27	14-B	Bottom	20	15	4.4	65662.5	16.5	28824.5
28	14-B	Top	20	15	3.5	52162.5	14.5	12143.7
29	15-B	Bottom	20	15	5.0	74662.5	15.0	15918.8
30	15-B	Top	20	15	4.1	61162.5	15.0	13106.3
31	16-B	Bottom	20	25	2.7	66937.5	17.0	33654.1
32	16-B	Top	20	25	2.4	59437.5	16.5	16995.2
33	17-B	Bottom	20	25	8.3	206937.5	15.0	31668.8
34	17-B	Top	20	25	3.8	94437.5	14.5	15395.6
35	18-B	Bottom	20	15	3.8	56662.5	11.0	7342.7
36	18-B	Top	20	15	3.7	55162.5	10.5	4553.3
37	19-B	Bottom	20	15	7.3	109162.5	12.0	13420.8
38	20-B	Bottom	20	15	3.3	49162.5	11.0	6344.4
39	20-B	Top	20	15	5.4	80662.5	14.5	22661.4
40	21-B	Bottom	20	25	2.7	66937.5	15.5	19674.5
41	21-B	Top	20	25	4.7	116937.5	16.0	18363.7
42	22-B	Bottom	20	25	3.8	94437.5	15.0	27506.3
43	22-B	Top	20	25	2.5	61937.5	16.0	22323.2
44	23-B	Bottom	20	25	1.6	39437.5	15.5	27867.0
45	23-B	Top	20	25	4.0	99437.5	18.0	27604.8
46	24-B	Bottom	20	15	8.2	122662.5	14.5	26878.7
47	24-B	Top	20	15	4.7	70162.5	14.5	25100.3
48	25-B	Bottom	20	25	5.9	146937.5	18.0	59000.4
49	25-B	Top	20	25	3.4	84437.5	16.5	29797.8

50	26-B	Bottom	20	15	3.0	44662.5	11.5	6539.8
51	26-B	Top	20	15	3.0	44662.5	11.5	5677.9
52	27-B	Bottom	20	15	7.1	106162.5	13.0	16257.8
53	27-B	Top	20	15	3.7	55162.5	15.0	16256.3
54	28-B	Bottom	20	25	5.2	129437.5	15.5	43072.8
55	28-B	Top	20	25	4.4	109437.5	16.0	29218.1
56	29-B	Bottom	20	15	2.6	38662.5	13.0	15122.7
57	29-B	Top	20	15	2.4	35662.5	11.5	5018.9
58	30-T	Bottom	20	15	1.7	25162.5	11.5	6007.5
59	30-T	Top	20	15	3.3	49162.5	11.5	4689.4
60	31-T	Bottom	20	15	2.8	41662.5	11.0	5213.1
61	31-T	Top	20	15	2.8	41662.5	12.0	5731.2
62	32-T	Bottom	20	15	1.6	23662.5	12.5	8691.4
63	32-T	Top	20	5	1.8	8887.5	11.0	4924.7
64	33-T	Bottom	20	15	1.7	25162.5	11.0	5479.3
65	33-T	Top	20	5	3.0	14887.5	11.0	4658.5
66	34-T	Bottom	20	15	1.7	25162.5	10.0	3883.3
67	34-T	Top	20	5	3.3	16387.5	9.0	2721.6
68	35-T	Bottom	20	15	2.7	40162.5	12.0	6768.0
69	35-T	Top	20	5	8.0	39887.5	13.5	8160.2
70	36-T	Bottom	20	15	2.6	38662.5	12.0	7084.8
71	36-T	Top	20	5	4.4	21887.5	10.0	3366.7
72	37-T	Bottom	20	15	2.0	29662.5	11.0	4436.7
73	37-T	Top	20	5	2.9	14387.5	10.5	3955.2
74	38-T	Bottom	20	15	2.9	43162.5	10.5	5460.1
75	38-T	Top	20	5	6.2	30887.5	10.0	3800.0
76	39-T	Bottom	20	15	2.7	40162.5	10.5	3916.6
77	39-T	Top	20	5	5.3	26387.5	11.0	4303.6
78	40-T	Bottom	20	15	4.3	64162.5	11.0	4458.9
79	40-T	Top	20	5	8.7	43387.5	11.0	4103.9
80	41-T	Bottom	20	5	4.4	21887.5	11.0	4503.2
81	41-T	Top	20	5	3.4	16887.5	8.5	1740.0
82	42-T	Bottom	20	15	2.1	31162.5	11.0	4658.5
83	42-T	Top	20	5	7.3	36387.5	12.5	6022.1
84	43-T	Bottom	20	15	1.7	25162.5	9.0	2174.9
85	43-T	Top	20	5	4.3	21387.5	11.0	4237.0
86	44-T	Bottom	20	15	1.7	25162.5	9.0	2296.4
87	44-T	Top	20	5	4.9	24387.5	9.0	2138.4
88	45-T	Bottom	20	15	2.2	32662.5	11.0	4747.2

89	45-T	Top	20	5	5.2	25887.5	11.0	4237.0
90	46-T	Bottom	20	15	4.1	61162.5	13.0	7726.1
91	46-T	Top	20	5	7.2	35887.5	12.0	5126.4
92	47-T	Bottom	20	5	3.2	15887.5	9.0	2903.9
93	47-T	Top	20	5	2.5	12387.5	8.5	2231.3
94	48-T	Bottom	20	15	1.2	17662.5	12.0	8409.6
95	48-T	Top	20	15	1.1	16162.5	12.0	6768.0
96	49-T	Bottom	20	15	2.9	43162.5	10.0	3600.0
97	49-T	Top	20	5	6.5	32387.5	9.5	2872.2
98	50-T	Bottom	20	15	2.2	32662.5	10.5	4919.9
99	50-T	Top	20	5	3.5	17387.5	9.5	2957.9
100	51-T	Bottom	20	15	3.1	46162.5	11.5	5272.4
101	51-T	Top	20	5	4.5	22387.5	10.0	3116.7
102	52-T	Bottom	20	15	1.8	26662.5	9.5	3658.1
103	52-T	Top	20	5	4.5	22387.5	11.5	5982.1
104	53-T	Bottom	20	15	2.9	43162.5	13.0	7579.7
105	53-T	Top	20	5	4.2	20887.5	9.5	2400.7
106	54-T	Bottom	20	15	1.1	16162.5	13.0	9227.4
107	54-T	Top	20	5	4.6	22887.5	12.0	6566.4
108	55-T	Bottom	20	15	1.0	14662.5	11.5	6387.7
109	55-T	Top	20	5	2.0	9887.5	12.0	5097.6
110	56-T	Bottom	20	15	3.6	53662.5	12.5	7291.7
111	56-T	Top	20	5	5.0	24887.5	11.0	4414.5
112	57-T	Bottom	20	5	7.8	38887.5	9.5	4858.5
113	57-T	Top	20	5	4.3	21387.5	10.5	4071.0
114	58-T	Bottom	20	5	8.1	40387.5	11.5	8821.1
115	58-T	Top	20	5	4.8	23887.5	9.0	3061.8

Table A3.3: Flat ring flexure test results data part II

No	Culm ID	Sample position	Failure Zone	Bending stress (N/mm^2)	MOR (N/mm^2)	mass (g)	dry mass (g)	moisture %
1	01-B	Bottom	B	47.0	11.7	47.14	41.08	14.75
2	01-B	Top	A	34.5	8.6	37.57	32.65	15.07
3	02-B	Bottom	B	54.1	13.5	53.60	46.04	16.42
4	02-B	Top	B	39.1	9.8	39.02	33.75	15.61
5	03-B	Bottom	B	32.5	8.1	14.08	12.22	15.22
6	03-B	Top	A	42.1	10.5	8.86	7.69	15.21
7	04-B	Bottom	B	40.2	10.1	53.40	46.99	13.64

8	04-B	Top	B	61.7	15.4	49.07	43.54	12.70
9	05-B	Bottom	B	59.1	14.8	39.50	34.55	14.33
10	05-B	Top	B	45.7	11.4	37.83	33.07	14.39
11	06-B	Bottom	B	44.0	11.0	83.90	72.55	15.64
12	06-B	Top	B	52.7	13.2	59.14	52.38	12.91
13	07-B	Bottom	B	69.8	17.4	59.66	52.02	14.69
14	07-B	Top	B	82.7	20.7	40.99	36.26	13.04
15	08-B	Bottom	B	46.7	11.7	43.11	37.61	14.62
16	08-B	Top	B	82.8	20.7	27.90	24.63	13.28
17	09-B	Bottom	B	54.5	13.6	25.53	22.36	14.18
18	09-B	Top	B	54.4	13.6	23.44	20.52	14.23
19	10-B	Bottom	B	94.8	23.7	50.21	43.91	14.35
20	10-B	Top	B	74.3	18.6	35.83	31.70	13.03
21	11-B	Bottom	B	60.3	15.1	79.69	68.75	15.91
22	11-B	Top	B	57.5	14.4	55.60	48.65	14.29
23	12-B	Bottom	B	44.1	11.0	39.71	35.13	13.04
24	12-B	Top	B	53.8	13.4	27.86	24.58	13.34
25	13-B	Bottom	B	56.9	14.2	34.53	30.38	13.66
26	13-B	Top	B	78.1	19.5	24.71	21.78	13.45
27	14-B	Bottom	B	37.6	9.4	46.64	40.28	15.79
28	14-B	Top	B	62.3	15.6	21.87	19.15	14.20
29	15-B	Bottom	B	70.4	17.6	37.85	33.24	13.87
30	15-B	Top	B	70.0	17.5	29.90	26.42	13.17
31	16-B	Bottom	B	33.8	8.5	35.24	30.69	14.83
32	16-B	Top	B	57.7	14.4	20.60	17.81	15.67
33	17-B	Bottom	B	98.0	24.5	69.60	58.90	18.17
34	17-B	Top	B	88.9	22.2	37.57	32.79	14.58
35	18-B	Bottom	B	84.9	21.2	23.52	20.47	14.90
36	18-B	Top	B	127.2	31.8	14.80	13.03	13.58
37	19-B	Bottom	B	97.6	24.4	42.39	35.71	18.71
38	20-B	Bottom	B	85.2	21.3	21.52	18.79	14.53
39	20-B	Top	B	51.6	12.9	31.73	27.63	14.84
40	21-B	Bottom	B	52.7	13.2	45.33	39.72	14.12
41	21-B	Top	B	101.9	25.5	43.82	38.48	13.88
42	22-B	Bottom	B	51.5	12.9	58.81	51.34	14.55
43	22-B	Top	B	44.4	11.1	43.57	38.29	13.79
44	23-B	Bottom	B	21.9	5.5	42.71	37.45	14.05
45	23-B	Top	B	64.8	16.2	35.03	30.82	13.66
46	24-B	Bottom	B	66.2	16.5	54.19	47.42	14.28

47	24-B	Top	B	40.5	10.1	42.48	37.36	13.70
48	25-B	Bottom	B	44.8	11.2	94.51	82.48	14.59
49	25-B	Top	B	46.8	11.7	65.44	57.47	13.87
50	26-B	Bottom	B	78.5	19.6	22.19	19.54	13.56
51	26-B	Top	B	90.5	22.6	17.47	15.49	12.78
52	27-B	Bottom	B	84.9	21.2	43.16	37.74	14.36
53	27-B	Top	B	50.9	12.7	33.13	29.21	13.42
54	28-B	Bottom	B	46.6	11.6	88.76	77.12	15.09
55	28-B	Top	B	59.9	15.0	63.31	55.48	14.11
56	29-B	Bottom	B	33.2	8.3	20.13	17.64	14.12
57	29-B	Top	B	81.7	20.4	12.49	10.98	13.75
58	30-T	Bottom	B	48.2	12.0	21.58	19.13	12.81
59	30-T	Top	B	120.6	30.1	15.38	13.70	12.26
60	31-T	Bottom	B	87.9	22.0	19.39	17.21	12.67
61	31-T	Top	B	87.2	21.8	14.73	13.12	12.27
62	32-T	Bottom	B	34.0	8.5	12.22	10.69	14.31
63	32-T	Top	B	19.9	5.0	7.62	6.71	13.56
64	33-T	Bottom	B	50.5	12.6	16.40	14.38	14.05
65	33-T	Top	B	35.2	8.8	12.81	11.26	13.77
66	34-T	Bottom	A	64.8	16.2	16.53	14.53	13.76
67	34-T	Top	B	54.2	13.5	12.09	10.63	13.73
68	35-T	Bottom	B	71.2	17.8	24.20	21.43	12.93
69	35-T	Top	B	66.0	16.5	17.08	15.18	12.52
70	36-T	Bottom	B	65.5	16.4	16.81	14.80	13.58
71	36-T	Top	B	65.0	16.3	10.15	8.99	12.90
72	37-T	Bottom	B	73.5	18.4	16.50	14.72	12.09
73	37-T	Top	B	38.2	9.5	13.53	11.88	13.89
74	38-T	Bottom	B	83.0	20.8	22.54	19.86	13.49
75	38-T	Top	B	81.3	20.3	15.13	13.41	12.83
76	39-T	Bottom	B	107.7	26.9	16.86	14.91	13.08
77	39-T	Top	B	67.4	16.9	12.64	11.21	12.76
78	40-T	Bottom	B	158.3	39.6	13.73	12.14	13.10
79	40-T	Top	B	116.3	29.1	11.16	9.92	12.50
80	41-T	Bottom	B	53.5	13.4	11.16	9.81	13.76
81	41-T	Top	B	82.5	20.6	6.45	5.71	12.96
82	42-T	Bottom	B	73.6	18.4	15.61	13.82	12.95
83	42-T	Top	B	75.5	18.9	12.73	11.30	12.65
84	43-T	Bottom	B	104.1	26.0	11.31	10.01	12.99
85	43-T	Top	B	55.5	13.9	10.50	9.36	12.18

86	44-T	Bottom	B	98.6	24.7	12.44	11.04	12.68
87	44-T	Top	B	102.6	25.7	9.81	8.69	12.89
88	45-T	Bottom	B	75.7	18.9	17.56	15.58	12.71
89	45-T	Top	B	67.2	16.8	12.97	11.54	12.39
90	46-T	Bottom	B	102.9	25.7	18.48	16.40	12.68
91	46-T	Top	B	84.0	21.0	12.91	11.48	12.46
92	47-T	Bottom	B	49.2	12.3	9.37	8.25	13.58
93	47-T	Top	B	47.2	11.8	6.11	5.39	13.36
94	48-T	Bottom	B	25.2	6.3	28.66	25.37	12.97
95	48-T	Top	B	28.7	7.2	22.91	20.28	12.97
96	49-T	Bottom	A	119.9	30.0	16.85	14.98	12.48
97	49-T	Top	B	107.1	26.8	12.97	11.54	12.39
98	50-T	Bottom	B	69.7	17.4	13.68	12.02	13.81
99	50-T	Top	B	55.8	14.0	10.37	9.21	12.60
100	51-T	Bottom	A	100.7	25.2	18.30	16.27	12.48
101	51-T	Top	B	71.8	18.0	11.50	10.26	12.09
102	52-T	Bottom	B	69.2	17.3	15.75	14.00	12.50
103	52-T	Top	B	43.0	10.8	17.52	15.56	12.60
104	53-T	Bottom	B	74.0	18.5	14.63	13.02	12.37
105	53-T	Top	B	82.7	20.7	7.24	6.47	11.90
106	54-T	Bottom	B	22.8	5.7	16.68	14.74	13.16
107	54-T	Top	B	41.8	10.5	11.88	10.50	13.14
108	55-T	Bottom	B	26.4	6.6	11.02	9.69	13.73
109	55-T	Top	B	23.3	5.8	8.27	7.31	13.13
110	56-T	Bottom	B	92.0	23.0	20.65	18.07	14.28
111	56-T	Top	B	62.0	15.5	10.75	9.45	13.76
112	57-T	Bottom	B	76.0	19.0	15.62	13.71	13.93
113	57-T	Top	A	55.2	13.8	10.15	8.93	13.66
114	58-T	Bottom	B	52.7	13.2	17.38	14.70	18.23
115	58-T	Top	B	70.2	17.6	10.34	8.70	18.85

APPENDIX A4

Table A4.1: Tensile strength test specimen dimensions

No	Culm ID	Sample position	δ1 (mm)	b1 (mm)	A1 (mm^2)	δ2 (mm)	b2 (mm)	A2 (mm^2)	A (mm^2)	Height (mm)
1	01-B	Bottom	7.1	2.9	20.6	7.3	2.9	21.2	20.9	205
2	01-B	Top	7.5	3.4	25.5	7.0	2.9	20.3	22.9	212
3	02-B	Bottom	8.2	5.7	46.7	9.6	4.6	44.2	45.5	207
4	02-B	Top	7.7	4.2	32.3	8.8	3.8	33.4	32.9	200
5	03-B	Bottom	5.5	4.3	23.7	5.1	3.1	15.8	19.7	202
6	03-B	Top	6.0	4.6	27.6	5.2	3.7	19.2	23.4	202
7	04-B	Bottom	9.1	5.1	46.4	11.1	4.4	48.8	47.6	187
8	04-B	Top	8.7	3.6	31.3	8.4	3.8	31.9	31.6	207
9	05-B	Bottom	8.2	6.5	53.3	8.7	5.1	44.4	48.8	197
10	05-B	Top	6.3	5.1	32.1	5.6	4.3	24.1	28.1	206
11	06-B	Bottom	13.7	5.6	76.7	15.3	4.0	61.2	69.0	205
12	06-B	Top	10.5	7.2	75.6	11.5	5.0	57.5	66.6	204
13	07-B	Bottom	11.4	7.4	84.4	14.0	6.4	89.6	87.0	200
14	07-B	Top	10.8	3.0	32.4	10.8	2.7	29.2	30.8	199
15	08-B	Bottom	9.4	6.1	57.3	10.5	5.6	58.8	58.1	198
16	08-B	Top	6.6	2.9	19.1	7.4	2.7	20.0	19.6	204
17	09-B	Bottom	6.6	4.1	27.1	6.9	4.0	27.6	27.3	202
18	09-B	Top	5.6	3.4	19.0	5.5	3.4	18.7	18.9	197
19	10-B	Bottom	8.1	4.7	38.1	9.6	4.3	41.3	39.7	203
20	10-B	Top	7.7	4.0	30.8	9.8	3.2	31.4	31.1	209
21	11-B	Bottom	13.0	7.4	96.2	15.3	5.6	85.7	90.9	201
22	11-B	Top	11.5	4.2	48.3	12.3	2.9	35.7	42.0	203
23	12-B	Bottom	8.7	4.5	39.2	9.7	3.2	31.0	35.1	207
24	12-B	Top	7.0	4.6	32.2	9.0	3.2	28.8	30.5	202
25	13-B	Bottom	7.5	6.0	45.0	10.0	4.6	46.0	45.5	205
26	13-B	Top	5.8	5.3	30.7	10.3	3.9	40.2	35.5	208
27	14-B	Bottom	8.1	5.5	44.6	12.0	4.5	54.0	49.3	202
28	14-B	Top	6.4	4.1	26.2	9.5	2.5	23.8	25.0	204
29	15-B	Bottom	6.4	4.3	27.5	8.0	3.2	25.6	26.6	207
30	15-B	Top	6.6	5.3	35.0	10.2	2.7	27.5	31.3	210
31	16-B	Bottom	7.1	6.5	46.2	8.6	3.4	29.2	37.7	209
32	16-B	Top	4.5	5.3	23.9	8.2	2.6	21.3	22.6	206
33	17-B	Bottom	11.2	5.6	62.7	13.0	4.0	52.0	57.4	206

34	17-B	Top	6.7	3.4	22.8	8.5	2.3	19.6	21.2	203
35	18-B	Bottom	8.2	5.2	42.6	11.6	3.2	37.1	39.9	201
36	18-B	Top	6.0	5.5	33.0	8.0	3.7	29.6	31.3	200
37	19-B	Bottom	13.0	5.0	65.0	10.1	3.7	37.4	51.2	208
38	19-B	Top	7.7	5.0	38.5	12.0	3.3	39.6	39.1	200
39	20-B	Bottom	9.2	3.9	35.9	11.7	2.3	26.9	31.4	203
40	20-B	Top	10.9	6.1	66.5	13.1	4.4	57.6	62.1	205
41	21-B	Bottom	8.0	5.5	44.0	9.1	4.1	37.3	40.7	201
42	21-B	Top	6.8	5.0	34.0	7.6	4.0	30.4	32.2	203
43	22-B	Bottom	12.7	8.0	101.6	15.6	5.4	84.2	92.9	202
44	22-B	Top	7.9	4.7	37.1	10.7	3.1	33.2	35.2	202
45	23-B	Bottom	7.9	4.3	34.0	10.9	2.6	28.3	31.2	209
46	23-B	Top	7.3	6.1	44.5	9.5	3.4	32.3	38.4	202
47	24-B	Bottom	14.3	6.5	93.0	16.6	4.6	76.4	84.7	200
48	24-B	Top	12.8	4.8	61.4	15.5	3.2	49.6	55.5	206
49	25-B	Bottom	13.1	5.5	72.1	14.5	4.2	60.9	66.5	204
50	25-B	Top	10.6	3.6	38.2	14.4	2.5	36.0	37.1	212
51	26-B	Bottom	6.6	3.3	21.8	7.2	2.7	19.4	20.6	200
52	26-B	Top	5.5	2.2	12.1	6.6	1.9	12.5	12.3	204
53	27-B	Bottom	10.7	3.6	38.5	12.2	2.9	35.4	37.0	208
54	27-B	Top	7.0	6.3	44.1	10.5	4.9	51.5	47.8	200
55	28-B	Bottom	16.7	5.8	96.9	18.3	4.3	78.7	87.8	201
56	28-B	Top	9.4	4.4	41.4	11.8	2.9	34.2	37.8	202
57	29-B	Bottom	8.5	5.2	44.2	10.2	2.8	28.6	36.4	204
58	29-B	Top	5.2	4.5	23.4	7.0	2.3	16.1	19.8	210
59	30-T	Bottom	6.0	3.7	22.2	7.4	3.5	25.9	24.1	206
60	30-T	Top	5.0	3.1	15.5	6.1	2.2	13.4	14.5	203
61	31-T	Bottom	5.6	4.2	23.5	5.6	3.9	21.8	22.7	203
62	31-T	Top	5.6	3.0	16.8	9.0	2.2	19.8	18.3	206
63	32-T	Bottom	6.2	2.8	17.4	9.8	1.5	14.7	16.0	196
64	32-T	Top	5.7	2.0	11.4	5.5	1.5	8.3	9.8	200
65	33-T	Bottom	6.3	3.5	22.1	7.3	2.6	19.0	20.5	199
66	33-T	Top	5.3	4.2	22.3	6.0	2.2	13.2	17.7	208
67	34-T	Bottom	6.7	4.4	29.5	8.0	3.0	24.0	26.7	200
68	34-T	Top	5.7	3.0	17.1	8.0	2.6	20.8	19.0	202
69	35-T	Bottom	5.6	3.1	17.4	6.5	3.2	20.8	19.1	207
70	35-T	Top	5.0	3.3	16.5	6.1	2.9	17.7	17.1	204
71	36-T	Bottom	5.7	2.6	14.8	8.5	1.7	14.5	14.6	208
72	36-T	Top	4.7	2.9	13.6	8.0	1.5	12.0	12.8	204

73	37-T	Bottom	5.3	3.6	19.1	7.4	3.5	25.9	22.5	202
74	37-T	Top	5.0	3.2	16.0	6.1	2.2	13.4	14.7	201
75	38-T	Bottom	7.0	5.3	37.1	7.6	3.7	28.1	32.6	199
76	38-T	Top	5.8	4.0	23.2	8.0	2.6	20.8	22.0	204
77	39-T	Bottom	5.1	3.0	15.3	6.6	2.4	15.8	15.6	208
78	39-T	Top	4.8	4.1	19.7	6.0	4.3	25.8	22.7	206
79	40-T	Bottom	5.0	4.2	21.0	7.5	2.5	18.8	19.9	201
80	40-T	Top	3.9	2.1	8.2	5.2	1.8	9.4	8.8	204
81	41-T	Bottom	5.0	4.1	20.5	7.5	3.6	27.0	23.8	205
82	41-T	Top	4.1	4.5	18.5	5.4	3.9	21.1	19.8	203
83	42-T	Bottom	5.3	4.2	22.3	10.3	2.2	22.7	22.5	198
84	42-T	Top	4.5	2.4	10.8	7.0	2.3	16.1	13.5	201
85	43-T	Bottom	4.7	3.3	15.5	10.0	2.0	20.0	17.8	200
86	43-T	Top	4.5	5.0	22.5	7.7	3.1	23.9	23.2	205
87	44-T	Bottom	5.0	4.0	20.0	10.1	2.0	20.2	20.1	203
88	44-T	Top	4.7	4.1	19.3	5.3	3.4	18.0	18.6	204
89	45-T	Bottom	5.6	4.1	23.0	9.0	2.2	19.8	21.4	207
90	45-T	Top	4.5	3.1	14.0	5.9	2.5	14.8	14.4	203
91	46-T	Bottom	5.1	3.7	18.9	6.2	3.2	19.8	19.4	197
92	46-T	Top	4.9	4.7	23.0	10.0	2.0	20.0	21.5	200
93	47-T	Bottom	5.2	2.2	11.4	4.5	2.3	10.4	10.9	202
94	47-T	Top	5.3	3.5	18.6	6.0	2.7	16.2	17.4	203
95	48-T	Bottom	6.3	3.1	19.5	7.9	3.0	23.7	21.6	210
96	48-T	Top	5.7	5.3	30.2	7.2	4.2	30.2	30.2	197
97	49-T	Bottom	5.3	4.8	25.4	6.3	4.5	28.4	26.9	207
98	49-T	Top	5.0	5.4	27.0	7.2	4.1	29.5	28.3	207
99	50-T	Bottom	6.1	4.0	24.4	6.2	3.1	19.2	21.8	207
100	50-T	Top	5.5	4.4	24.2	5.5	3.9	21.5	22.8	200
101	51-T	Bottom	5.3	3.5	18.6	5.8	2.6	15.1	16.8	200
102	51-T	Top	4.8	3.0	14.4	6.6	2.3	15.2	14.8	205
103	52-T	Bottom	6.1	3.4	20.7	7.6	2.7	20.5	20.6	203
104	52-T	Top	6.0	4.0	24.0	6.6	3.4	22.4	23.2	206
105	53-T	Bottom	5.4	4.0	21.6	7.5	2.3	17.3	19.4	203
106	53-T	Top	4.0	3.0	12.0	7.1	1.6	11.4	11.7	205
107	54-T	Bottom	6.0	4.6	27.6	7.4	3.5	25.9	26.8	208
108	54-T	Top	5.7	4.5	25.7	5.9	2.8	16.5	21.1	204
109	55-T	Bottom	6.0	4.5	27.0	8.1	2.0	16.2	21.6	205
110	55-T	Top	5.0	4.0	20.0	5.0	2.3	11.5	15.8	207
111	56-T	Bottom	5.0	4.0	20.0	12.4	2.4	29.8	24.9	203

112	56-T	Top	4.8	5.1	24.5	11.0	2.2	24.2	24.3	202
113	57-T	Bottom	8.8	4.4	38.7	10.2	3.3	33.7	36.2	200
114	57-T	Top	5.4	6.0	32.4	6.0	4.4	26.4	29.4	202
115	58-T	Bottom	10.0	4.0	40.0	10.0	4.0	40.0	40.0	200
116	58-T	Top	6.0	2.0	12.0	6.0	2.0	12.0	12.0	200

Table A4.2: Tensile strength test result data

No	Culm ID	Sample position	Rotations	Failure load (Kg)	Tensile strength (N/mm^2)	mass (g)	dry mass (g)	moisture%
1	01-B	Bottom	338	275	129.2	4.63	4.03	14.9
2	01-B	Top	403	280	119.9	4.94	4.31	14.6
3	02-B	Bottom	592	430	92.8	6.47	5.62	15.1
4	02-B	Top	323	190	56.7	5.37	4.70	14.3
5	03-B	Bottom	325	70	34.8	2.55	2.20	15.9
6	03-B	Top	432	80	33.5	2.29	1.98	15.7
7	04-B	Bottom	546	450	92.7	7.47	6.59	13.4
8	04-B	Top	260	200	62.0	6.73	5.97	12.7
9	05-B	Bottom	456	400	80.4	9.99	8.70	14.8
10	05-B	Top	408	340	118.7	6.16	5.42	13.7
11	06-B	Bottom	579	690	98.2	13.16	11.21	17.4
12	06-B	Top	570	400	59.0	9.68	8.26	17.2
13	07-B	Bottom	610	680	76.7	12.96	11.33	14.4
14	07-B	Top	383	290	92.4	5.07	4.48	13.2
15	08-B	Bottom	620	500	84.5	9.84	8.63	14.0
16	08-B	Top	352	300	150.5	4.55	4.00	13.8
17	09-B	Bottom	440	150	53.8	3.42	3.01	13.6
18	09-B	Top	454	170	88.4	2.67	2.32	15.1
19	10-B	Bottom	513	400	98.9	7.50	6.55	14.5
20	10-B	Top	360	330	104.2	5.68	5.04	12.7
21	11-B	Bottom	712	1020	110.0	14.12	12.33	14.5
22	11-B	Top	517	500	116.8	7.82	6.84	14.3
23	12-B	Bottom	480	340	95.0	6.14	5.89	4.2
24	12-B	Top	522	340	109.4	5.34	4.67	14.3
25	13-B	Bottom	624	390	84.1	6.97	6.06	15.0
26	13-B	Top	625	370	102.4	5.68	5.01	13.4
27	14-B	Bottom	622	570	113.5	9.23	8.00	15.4
28	14-B	Top	511	340	133.4	4.72	3.97	18.9
29	15-B	Bottom	440	370	136.7	5.20	4.53	14.8

30	15-B	Top	548	340	106.7	5.03	4.38	14.8
31	16-B	Bottom	619	230	59.9	4.47	3.91	14.3
32	16-B	Top	412	160	69.5	3.10	2.71	14.4
33	17-B	Bottom	431	450	77.0	11.00	9.45	16.4
34	17-B	Top	290	240	111.2	4.06	3.48	16.7
35	18-B	Bottom	541	490	120.5	6.45	5.66	14.0
36	18-B	Top	544	350	109.7	4.34	3.83	13.3
37	19-B	Bottom	561	300	57.5	10.53	9.23	14.1
38	19-B	Top	590	370	93.0	6.46	5.65	14.3
39	20-B	Bottom	379	310	96.9	4.88	4.21	15.9
40	20-B	Top	671	720	113.8	10.48	9.11	15.0
41	21-B	Bottom	425	400	96.5	6.19	5.94	4.2
42	21-B	Top	565	400	121.9	7.40	6.74	9.8
43	22-B	Bottom	443	530	56.0	14.38	12.65	13.7
44	22-B	Top	480	370	103.3	7.86	7.00	12.3
45	23-B	Bottom	433	140	44.1	4.90	4.39	11.6
46	23-B	Top	360	280	71.5	4.88	4.24	15.1
47	24-B	Bottom	630	1000	115.9	14.67	12.90	13.7
48	24-B	Top	507	500	88.3	7.77	6.99	11.2
49	25-B	Bottom	473	570	84.1	11.46	10.20	12.4
50	25-B	Top	435	240	63.5	6.37	5.56	14.6
51	26-B	Bottom	433	220	104.7	3.80	3.35	13.4
52	26-B	Top	266	190	151.3	2.87	2.56	12.1
53	27-B	Bottom	490	400	106.2	8.18	7.33	11.6
54	27-B	Top	613	500	102.7	7.40	6.64	11.4
55	28-B	Bottom	445	740	82.7	15.48	13.66	13.3
56	28-B	Top	488	400	103.8	8.26	7.43	11.2
57	29-B	Bottom	442	100	27.0	4.52	3.87	16.8
58	29-B	Top	324	180	89.4	3.19	2.77	15.2
59	30-T	Bottom	434	340	138.7	5.75	5.11	12.5
60	30-T	Top	303	260	176.4	3.49	3.06	14.1
61	31-T	Bottom	307	170	73.5	4.94	4.37	13.0
62	31-T	Top	308	300	160.8	3.53	3.12	13.1
63	32-T	Bottom	286	90	55.1	2.10	1.86	12.9
64	32-T	Top	245	60	59.9	1.54	1.34	14.9
65	33-T	Bottom	492	240	114.8	4.55	4.02	13.2
66	33-T	Top	369	220	121.7	3.25	2.85	14.0
67	34-T	Bottom	449	260	95.4	4.30	3.73	15.3
68	34-T	Top	398	230	119.1	4.23	3.68	14.9

69	35-T	Bottom	375	220	113.1	4.33	3.73	16.1
70	35-T	Top	368	270	154.9	3.64	3.20	13.8
71	36-T	Bottom	318	125	83.8	2.45	2.22	10.4
72	36-T	Top	236	150	114.8	2.51	2.22	13.1
73	37-T	Bottom	368	260	113.4	4.19	3.73	12.3
74	37-T	Top	271	210	140.0	3.37	3.01	12.0
75	38-T	Bottom	613	425	127.9	6.49	5.71	13.7
76	38-T	Top	347	290	129.3	4.58	3.94	16.2
77	39-T	Bottom	322	240	151.2	3.73	3.28	13.7
78	39-T	Top	325	285	122.9	4.39	3.88	13.1
79	40-T	Bottom	383	260	128.3	3.08	2.69	14.5
80	40-T	Top	355	230	257.1	2.30	2.01	14.4
81	41-T	Bottom	486	160	66.1	4.46	3.96	12.6
82	41-T	Top	430	240	119.2	3.67	3.19	15.0
83	42-T	Bottom	325	230	100.5	4.38	3.87	13.2
84	42-T	Top	363	270	196.9	2.97	2.58	15.1
85	43-T	Bottom	429	250	138.1	3.45	3.01	14.6
86	43-T	Top	578	490	207.3	4.45	3.88	14.7
87	44-T	Bottom	408	300	146.4	4.52	3.94	14.7
88	44-T	Top	240	100	52.6	3.34	2.96	12.8
89	45-T	Bottom	469	370	169.8	4.70	4.10	14.6
90	45-T	Top	318	270	184.6	3.32	2.91	14.1
91	46-T	Bottom	347	230	116.6	3.51	3.10	13.2
92	46-T	Top	356	360	164.1	4.75	4.13	15.0
93	47-T	Bottom	214	50	45.0	1.94	1.75	10.9
94	47-T	Top	351	100	56.5	2.70	2.38	13.4
95	48-T	Bottom	374	370	167.9	6.07	4.87	24.6
96	48-T	Top	440	360	116.8	6.59	5.59	17.9
97	49-T	Bottom	456	450	164.1	5.62	4.92	14.2
98	49-T	Top	422	260	90.3	5.78	5.09	13.6
99	50-T	Bottom	445	150	67.5	4.29	3.71	15.6
100	50-T	Top	439	270	116.0	4.19	3.66	14.5
101	51-T	Bottom	338	230	134.2	3.46	3.03	14.2
102	51-T	Top	431	230	152.6	3.40	2.95	15.3
103	52-T	Bottom	397	230	109.4	4.82	4.22	14.2
104	52-T	Top	473	280	118.3	5.04	4.40	14.5
105	53-T	Bottom	541	260	131.3	4.04	3.53	14.4
106	53-T	Top	355	180	151.2	2.46	2.13	15.5
107	54-T	Bottom	530	270	99.0	5.20	4.56	14.0

108	54-T	Top	455	155	72.1	3.79	3.36	12.8
109	55-T	Bottom	340	100	45.4	2.48	2.15	15.3
110	55-T	Top	445	90	56.1	2.18	1.98	10.1
111	56-T	Bottom	397	310	122.2	5.16	4.54	13.7
112	56-T	Top	408	350	141.1	4.93	4.30	14.7
113	57-T	Bottom	454	350	94.9	5.86	5.17	13.3
114	57-T	Top	320	120	40.0	5.20	4.58	13.5
115	58-T	Bottom	600	460	112.8	8.61	7.20	19.6
116	58-T	Top	180	180	147.2	2.65	2.20	20.5

Rows highlighted in indicate the respective samples have undergone preservation treatment in all the above tables

APPENDIX B1

Coefficient of correlation

$$\text{Coefficient of correaltion}(r) = \frac{n(\Sigma xy) - (\Sigma x)(\Sigma y)}{\sqrt{[n\Sigma x^2 - (\Sigma x)^2][n\Sigma y^2 - (\Sigma y)^2]}} \qquad \text{Eq B1.1}$$

Coefficient of determination expressed in percentage

$$\text{R squared} = (r^2) \times 100 \qquad \text{Eq B1.2}$$