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RESEARCH ARTICLE

Analysis of mechanical and anatomical properties of two bamboo species – *Thyrostachys siamensis* Gamble and *Dendrocalamus strictus* (Roxb.) Nees (Poaceae)

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Abstract: Bamboos are treated to boost their shelf life from the degrading activity of fungal microbes and other insects and to increase their longevity in use and durability by using various chemicals. The present study is vis-a-vis the standardization of two bamboo species *Dendrocalamus strictus* and *Thyrostachys siamensis* for a comparative analysis of the mechanical and anatomical properties of samples treated with CCB (Copper Chrome Boron), and BBA (Borax Boric Acid) as well as untreated samples. Samples were tested for both bending and compression; and the parameters such as MOE (Modulus of Elasticity), MOI (Moment of Inertia), Maximum compressive strength, and ultimate strength were analyzed. The anatomical variations arising in the top and bottom sections were also investigated and it has found that the mechanical properties of the species treated with CCB solutions yield a better result in maximum compressive strength and high value of MOI as compared to BBA whereas the samples treated with BBA provides superior performance with respect to MOE. Anatomical examination revealed that the cellular structure and arrangement of vascular bundles are responsible for the increase in time taken for the rate of penetration of chemicals in *D.strictus* i.e one-half hour as compared to *T.siamensis* which got treated in 20 minutes. In *D.strictus* the density of vascular bundles is high so it takes time to get it treated completely as compared to *T. siamensis.*

Keywords: bamboo, mechanical tests, vascular bundle, anatomy

Introduction

Bamboo, the magnificent grass species (Poaceae) growing in the tropics and subtropics region, has many uses, providing a vast range of sustainable products, livelihood options, and ecosystem services. Bamboo is a quickly regenerated material that is widely available and has the strength of structural materials. The inherent variety in bamboo's geometric and mechanical qualities and the lack of standardization limit its broad usage in the building industry. Engineered bamboo is treated and moulded into laminated composites to decrease the unpredictability of the natural material (Sharma *et al*., 2005). The role of bamboo in biodiversity conservation and land restoration is well recognized, and it well fits into the six UN Sustainable Development Goals (SDGs), ie., reduction of poverty, ecological functions, protection of terrestrial ecosystems, providing affordable housing, sustainable and reliable modern energy services as well as to address the climate change related issues.

As bamboo is widely used for furniture, handicrafts as well as construction, the proper treatment of extracted culms are essential to prevent insect-pest infestation. It is well known that untreated bamboo culms have a service life of only three to five years and as a biological material, it is susceptible to degradation by different organisms such as insects and fungi (Schmidt *et al*., 2011). The carbohydrate content, especially starch plays an important role in the durability and service life

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of bamboo which is a major attraction for various bio -degradants (Chavan and Attar, 2013) and the durability of bamboo against mould, fungal and borer attack is strongly associated with the chemical composition. Most of the studies show that these variations in bamboo durability strongly depend on the species (Suprapti, 2010; Schmidt *et al*., 2011; Wei *et al*., 2013), the length of the culm and thickness of the wall and also the time of harvesting. As bamboo has low durability in an exposed environment, bamboo protection has long been employed to try and enhance its natural durability by means of chemical treatment.

According to Liese and Kumar (2003), the harvesting time affects the durability of bamboo species and generally, the dry season is more susceptible to attack by bio-degradation agents because of the increased starch content. Traditionally, the water leaching method is used for various local constructions in which the bamboo culms are submerged in running or stagnant water leading to an increase in their durability by removal of starch. Another method is smoke treatment where the culms are stored in the kitchen over the fireplace to prevent insect attack. Common chemicals used for bamboo treatment include Copper Chrome Arsenic (CCA), sodium pentachlorophenol, boric acid-borax, Cu/Zn naphenates/abietates, tebuconazole, IPBC (3-iodo 2-propynyl butyl carbamate), chlorothalonil, isothiazolones, and synthetic pyrethroids etc., It has shown that the bamboo culms treated with CCA, CCB and BBA etc., even creosote preservatives have been able to extend the service life of bamboo to around 36 years. However, their mammalian toxicity cannot be ignored, and the odour of creosote makes it a preservative for outdoor application only. Chemicals like CCA, AAC, and CCB contain arsenic, and chromium and the carcinogenicity of chromium and arsenic is a well-known fact. However, the proper treatment of bamboo culms should be ensured before the construction of houses, furniture and handicrafts etc., The strength of bamboo after the treatment process, especially its mechanical physical and chemical properties is also a major concern. Only a very few studies are available on the physical and chemical and mechanical properties of treated and untreated bamboos.

Paes (2009) analysed the physical-mechanical properties of glue-laminated bamboo (GLB) of *Dendrocalamus giganteus* in which the bamboo culms were separately dipped in a solution containing CCB and water and found that the one which is dipped in CCA is found to be more stable as compared to the water-treated culms (Paes *et al*., 2009). In another study on *Pseudoxytenanthera ritcheyi*, the steeping method was used for treating bamboo by using Boric acid Borax, Copper Chrome Boron and Cashew Nut Shell Liquid and found that tensile strength for bamboo treated with Boric Acid Borax, Copper Chrome Boron and Cashew Nut Shell Liquid was 38.20 N/mm², 30.69 N/mm² and 8.03 N/mm² for under soil and 48.09 N/mm², 39.09 N/mm² and 9.35 for over soil sample and compressive strength was 5.04 N/mm², 4.02 N/mm² and 0.39 N/mm² for under soil sample and 5.17 N/mm², 4.87 N/mm² and 0.58 N/mm² for over soil sample (Kurhekar 2014). Daud *et al*., (2018) studied the physical and chemical properties of *Gigantochloa scortechni* in which BBA-treated and untreated samples were used to evaluate the parameters like moisture content, compressive strength, Modulus of Rupture (MOR), compression shear and bending. With regard to the compressive strength for untreated bamboo varied between 19.96 to 23.80 MPa and BBA-treated bamboo recorded between 31.74 to 36.60 MPa and MOR between 53.64 to 73.66 MPa for untreated samples and 58.23 to 62.86 MPa for treated samples. In the case of species like *Dendrocalamus strictus*, samples were taken from three different geographical regions of Kerala and parameters such as fibre stress at the elastic limit, Modulus of Elasticity (MOE), Modulus of Rupture (MOR), Maximum crushing stress (MCS) were evaluated (Gnanaharan, 1991) and found that no significant difference in the value of MOR on the strength properties. Narasimhamurthy *et al*., (2013) studied the physical and mechanical properties of *Thyrsostachys siamensis* and *Dendrocalamus membranaceous* and found that the compressive strength of the former species was found to be 15% more than later species and the MOE value was also high for *T. siamensis*.

The present study is to undertake a comparative analysis of the mechanical properties of two different species of bamboo viz., *Thyrostachys siamensis* and *Dendrocalamus strictus* both treated and untreated samples. Samples were treated with CCA and borax boric acid 6% combination using bucherie process as well as untreated samples were studied for the parameters like MOR, MOI, static bending test, compression parallel to grain, and compression perpendicular to grain. The variations in anatomical structure if any were also analyzed from bottom to top of both these species.

Materials and Methods

Three bamboo culms (samples) of *Thyrostachys siamensis* numbered S1, S2, and S3 were taken, out of which S1 and S2 were treated with Boron and boric acid (BBA) and Copper chrome boron (CCB) respectively, and S3 was kept untreated. Likewise, three culms of *Dendrocalamus strictus* were taken and marked as D1, D2, and D3; out of which D1 and D2 were treated with BBA and CCB respectively, and D3 was kept untreated. The length of the samples used for the study was 5 m, and BBA and CCB treatment was done through the Boucherie process. All the treated and untreated samples were kept for shade drying for about 4 days in a closed space to prevent the development of cracks and splits and the mechanical testing was done at the Central Wood testing lab at Kottayam, Kerala where the mechanical properties (maximum compressive strength, Modulus of elasticity, Moment of Inertia, ultimate strength were analysed in accordance with the IS 6874: 2008. The formula used for the study is as follows:

The moment of inertia in mm^4, shall be calculated as follows:

$$1 = \pi/64[D4 - (D\text{-}2t)^4]$$

Where, D = outer diameter, in mm; t =wall thickness, in mm.

The ultimate strength, in static bending, in N/mm shall be determined as follows:

$$\sigma_{ult} = [1/6I \{FL*D/2\}]$$

Where I = moment of inertia, in mm^4; F = maximum load, in N; L = effective span in mm; D = outer diameter, in mm.

Ultimate strength shall be reported to an accuracy of 1 N/ mm'.

The modulus of elasticity (Young's modulus), E, in N/mm2, shall be determined as follows:

$$E = 23s\ L^3/1296*I$$

The maximum compressive strength σ in N/mm^2, shall be determined as:

$$\sigma_{ult} = F_{ult}\ /A$$

$$A = \pi/4\ [D2\text{-}(D\text{-}2t)2] \text{ in } mm^2$$

A = Area of cross section of test specimen; D= outer diameter, in mm; t= wall thickness, in mm; σ =F/A shall be rounded to the nearest 0.5 N/mm^2.

Anatomical sections from the bottom and top portions of these two species were carried out in order to understand the time taken for differences in the penetration of chemicals by analysing the vascular bundle pattern.

Results and Discussion

In the boucherie process, the chemicals were filled in the tank of the boucherie apparatus, and an initial pressure of 10 psi was given to develop the inbuilt pressure inside the apparatus for penetration of the chemicals slowly and then the pressure was increased to a maximum of 20 psi. It was found that the rate of penetration of chemicals in *T. siamensis* is very quicker as compared to *D. strictus* due to their peculiar anatomical characteristics. In *T. siamensis* the chemicals get penetrated in around 20 minutes at a maximal rate, whereas in *D. strictus*, two hours were taken for the complete treatment of each sample. It was found that *T. siamensis* samples were treated with BBA and CCB applied with a pressure of 18 psi in which the BBA treated samples took 45 minutes for complete treatment whereas CCB-treated samples took only 20 minutes. Similarly, in *D. strictus*, the sample when treated with BBA at a pressure of about 25 psi took one and a half hours for complete treatment and the sample treated with CCB solution at a pressure of 15 psi took two hours thirty-five minutes for the complete treatment. In boucherie process, the preservative treatment time required was 30 minutes to hours with a loading of about 2 kg/cm^3 (Kumar *et al.*, 1994). Satish Kumar *et al.*, (1994) pointed out that penetration and absorption of the preservative depend upon several factors like concentration of the solution, treatment time, nature of chemicals used, dimensions of bamboo, its age, and moisture content and 30-60 minutes will take to treat short bamboo lengths using pressures up to 2 kg/cm.

Fig 1. Experimental setup of bamboo sample for bending test

Fig 2. Test to determine the Modulus of Elasticity (MOE)

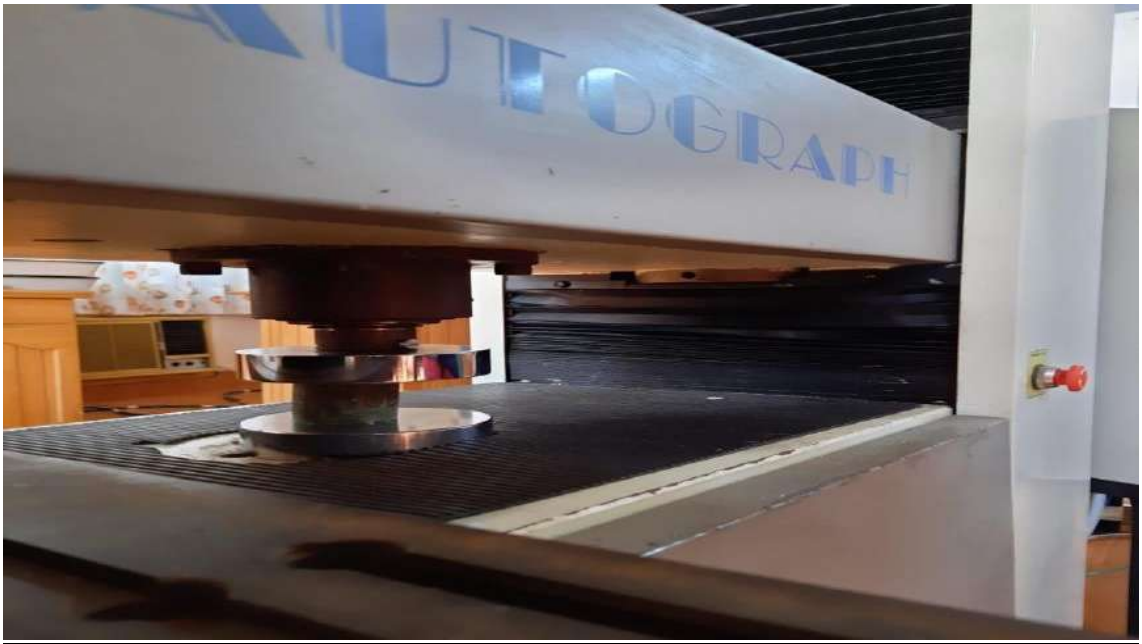

Fig 3. Shows the test for ultimate strength determination.

For mechanical testing using UTM, the 5m samples were cut into two parts of one meter each (top and bottom) the variation in mechanical properties in treated bamboo with respect to untreated ones was done.

Maximum Compressive strength

The maximum compressive strength of the top portion of both treated and untreated samples of *T. siamensis* and *D. strictus* are higher as compared to the bottom portions. It was also examined that the maximum compressive strength does not affect the strength properties, in fact, in the untreated samples, the maximum compressive strength values of (*T. siamensis* top = 58.5N/mm^2, bottom=54.5 N/mm^2, *D. strictus* top = 47 N/mm^2, bottom = 38N/mm^2) samples have higher value of compressive strength as compared to the treated bamboos (*T. siamensis* BBA treated top=51.5N/mm^2, bottom=40N/mm^2 CCB treated top=49.5N/mm^2, bottom=40.5 N/mm^2) and (*D. strictus* BBA treated top=45.5N/mm^2, bottom = 30.5N/mm^2, CCB treated top=38N/mm^2 bottom = 36.5N/mm^2). In some cases, it was shown that CCB-treated samples show superior performance in maximum compressive strength

As compared to the BBA-treated samples (Table 1). Uno (1932) studied the compressive strengths in the upper, middle, and lower portions of the culm of *Phyllostachys bambusoides* and found as 81.89MPa, 33.54MPa, and 43.35MPa, whereas in *Phyllostachys lithophila* the strengths were found to be as 125.92MPa, 65.41MPa and 63.15MPa. He pointed out that the upper portion of a bamboo culm is stronger than its middle and lower portions in compression. The study on *Pseudoxytenanthera ritcheyi* shows that bamboo treated with copper chrome boron treatment had less compressive strength than that treated with boric acid borax treatment (Kurhekar, 2012). In the case of species like *Gudua augustifolia*, the culm sample from the node part (1M) reported the highest compressive strength of 80.5379 N/mm2 while the culm sample from the internode part (1B) had the lowest compressive strength of 60.8930 N/ mm^2 (Kenneth and Uzodimma, 2021). According to Naik (2000), the tensile and compressive strength of raw bamboo is around 111- 219 MPa and 53-100 MPa, respectively as per ASTM (1990) standards. Daud *et al*., (2018) studied (ISO 22157) the physical and mechanical properties of treated and untreated bamboo samples of *Gigantochloa scortechinii* and found that the top section for both untreated and treated bamboo had the highest compressive strength and pointed out that it might be due to the large thickness of the bamboo wall and high cross-sectional area compared to the middle and bottom section. Huang *et al*., (2018), pointed out that the bamboo stem's top has the highest density, impacting the stem's highest point of compressive strength. The age of the culm is also an important factor in which Hidalgo (1978) tested 76 samples of *Guadua angustifolia* and reported that the compressive strength of bamboo increases with age and the maximum values for compressive strengths occur in specimens that are 3-5 years old.

Modulus of Elasticity

The Modulus of Elasticity (MOE) of treated and untreated samples of *Thyrostachys siamensis* and *Dendrocalamus strictus* varied from sample to sample. In *T. siamensis*, BBA treated top portion was 2300N/mm^2, whereas in the bottom recorded 2200N/mm^2. In the case samples treated with CCB, the top portion recorded 2200N/$mm^{2,}$ and in the bottom it was found as 2000N/mm^2. In *D. strictus*, BBA treated top was 3900 N/mm^2, and the bottom

Table 1. Results of bending and compression tests

Sample	MOE (N/mm^2)	MOI (mm^4)	Ultimate strength (N/mm^2)	Maximum compressive strength (N/mm^2)
Sample 1 (S1)	T=2300 B=2200	T=151703.31 B=217321.24	T=89 B=88	T=51.5 B=40
Sample 2 (S2)	T=2200 B=2000	T=148824.75 B=215177.94	T=95 B=88	T=49.5 B=40.5
Sample 3 (S3)	T=2500 B=2400	T=87185.50 B=137595.46	T=92 B=121	T=58.5 B=54.5
Sample 4 (D1)	T=3900 B=2000	T=39686.56 B=88735.66	T=105 B=73	T=45.5 B=30.5
Sample 5 (D2)	T=2100 B=2100	T=155601.90 B=163015.63	T=79 B=98	T=38 B=36.5
Sample 6 (D3)	T=1400 B=1800	T=137595.46 B=127353.26	T=79 B=104	T=47 B=38

Sample 1=*Thyrostachys siamensis* (Borax boric acid treated); Sample 2= *Thyrostachys siamensis* (CCB treated); Sample 3= *Thyrostachys siamensis*(untreated); Sample 4= *Dendrocalamus strictus* (borax boric acid treated); Sample 5= *Dendrocalamus strictus* (CCB treated); Sample 6= *Dendrocalamus strictus*(untreated); T and B are the top and bottom respectively of the samples; MOE (Modulus of Elasticity) and MOI (Moment of Inertia).

2000N/mm^2, and CCB treated top was found as 2100N/mm^2 and in the bottom, it was recorded as 2100N/mm^2. In the case of untreated samples of *T. siamensis* the value of MOE in the top portion was 2500N/mm^2 and in the bottom portions, it was 2400N/mm^2. In untreated samples of *D. strictus* MOE the top was 1400N/mm2 and at the bottom, it was 1800N/mm^2. MOE for untreated samples of *T. siamensis* is higher as compared to its treated samples. The modulus of Elasticity of treated samples of *Dendrocalamus strictus* was found higher as compared to its untreated sample and it was also observed that the species treated with BBA shows a high value of MOE in comparison with CCB. Gnanaharan (1991) studied the modulus of elasticity obtained from the static bending test as per IS: 8242 (BIS, 1976) and reported that climate plays a major role in determining the strength properties. Similarly, the study by Narasimhamurthy (2013) shows that the MoE in the bending of *Thyrsostachys siamensis* was observed 5% higher than *Dendrocalmus membranaceous*. The study on *Gigantochloa scortechinii* (Daud *et al*., 2018) shows that the MOE of untreated bamboo was between 26.70 GPa to 36.31 GPa while treated bamboo was between 28.83 to 33.41 GPa as per ISO 22157 standards.

Moment of Inertia

The moment of inertia of the bottom part of all the treated and untreated samples was found as high as compared to the top part of all treated and untreated samples, except in the bottom part of the untreated sample of *D. strictus*. It has also been found that the species treated with CCB shows better results in Moment of Inertia than of BBA treated.

Ultimate Strength

The ultimate strength samples of *T. siamensis* treated with the top portion of BBA value found as 89N/mm^2, and the bottom as 88 N/mm^2, and in CCB treated, it was 95N/mm^2, and 93N/mm^2 respectively. Samples of *D. strictus* treated with BBA were found as 105 N/mm^2 in the top portion and 73N/mm^2 in the bottom. The samples treated with CCB, it was 79N/mm^2 and 98N/mm^2 respectively. In the case of untreated samples of *T. siamensis* the ultimate strength at the top was found to be 92N/mm^2 and the bottom was found to be 121 N/mm^2 and in the untreated sample of *D. strictus* top portion, it was 79 N/mm^2, and bottom = 98 N/mm^2. The effective strength of *Thyrostachys siamensis* is high as compared to *Dendrocalamus strictus* and samples treated in BBA show superior properties in strength as compared to species treated in CCB. The studies on the tensile strength test of different bamboo species (Handana, 2023) showed the bottom of the bamboo has greater tensile strength both in dogbone and strip-shaped bamboo and also pointed out that the internode had a greater tensile strength value than bamboo with the node in either dogbone or strip-shaped bamboo.

Anatomical observations

The microscopic examination of the selected species in this study revealed the presence of type 3 ("broken waist type") and type 4 vascular bundles ("double broken waist" type). Most fibres have a thick poly lamellate secondary wall (Parameswaran and Liese, 1976) and fibres are grouped in bundles and sheaths around the vessels. In bamboo, the epidermal walls consist of an outer and inner layer; the latter is highly lignified. The outer layer contains cellulose and pectin with a wax coating. Silica particles also exist in the peripheral parts of the culm. From the microscopic analysis, it was found that the arrangement of vascular bundles in *D. strictus* (Fig. 4 and Fig. 5) was highly denser compared to *T. siamensis* which leads to the loss of ease of penetration of chemicals along the pole which may result in a tedious situation for penetration of chemicals. Also, the density of vascular bundles is more in the top part as compared to the bottom which can lead to more time in penetration. In the case of *T. siamensis* (Fig. 6 and Fig. 7), the lower density of vascular bundles is found especially in the top section as compared to the bottom.

The xylem vessels play a key role in preservative treatment in bamboo (Razak *et al*., 2013) and penetration of liquids into the bamboo culms takes place through the vessels in the axial direction, from end to end (Razak *et al*., 2005) and from the vessels, the liquids are distributed to the surrounding fibres and parenchyma cells (Razak *et al*., 2005). According to Satish Kumar *et al*., (1994), axial flow is quite rapid in green bamboo as the end-to-end alignment of vessels and the degree of penetration decreases as the distance from the conducting vessel increases. Generally, larger vessels tend to get a larger amount of preservative than smaller vessels.

Fibres in bamboos are grouped in bundles and sheaths around the vessels. The epiderma1 walls consist of an outer and inner layer; the latter is highly lignified. The outer layer contains cellulose and pectin with a wax coating. Silica particles also exist in the peripheral parts of the culm. These anatomical features are responsible for the poor penetration of preservatives into round culms during treatment. Although vessel elements in bamboo are easily permeable, lateral flow is restricted because of the absence of ray cells. (Satish kumar *et al.,* 1994).

Conclusion

Bamboo are generally treated for enhancing their durability. In the present study, two bamboo species, *D. strictus* and *T.siamensis*, were treated using chemicals CCB and BBA through the Boucherie process. Both treated and untreated culms were evaluated for various parameters. Samples of *D. strictus* and *T.siamensis* treated with CCB solution show good results in their maximum compressive strength as compared to BBA treated samples. As per the study it was found that the BBA treated samples of *D. strictus* and *T.siamensis* showed superior performance in MOE. Treated samples of *D. strictus* and *T.siamensis* with CCB solution show higher value of MOI than BBA treated samples. The maximum compressive strength in the top and bottom part of *D. strictus* and *T.siamensis* which are untreated is found to be higher than their treated

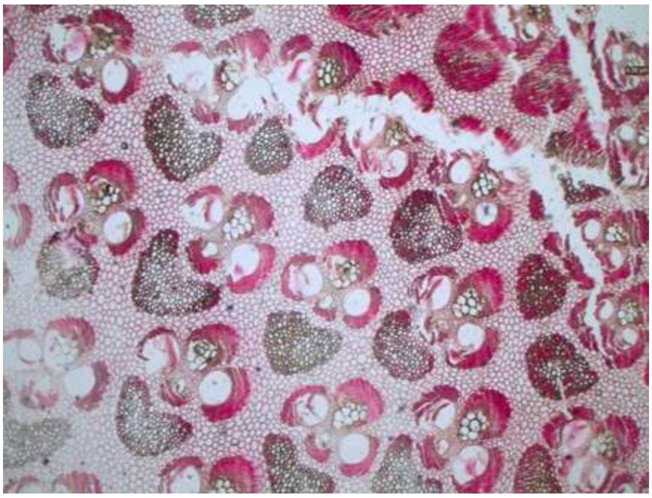

Fig 4. *D. strictus* top section (4X)

Fig 5. *D. strictus* bottom section (4X)

Fig 6. *T. siamensis* top section (4X)

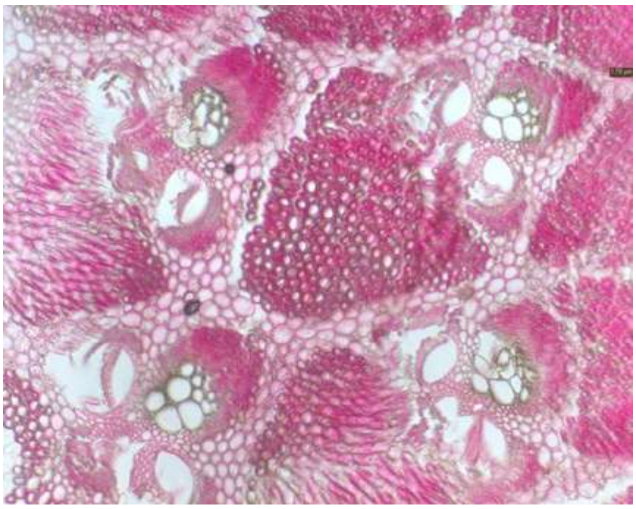

Fig 7. *T. siamensis* bottom section (4X)

is found to be higher than their treated samples. According to the evaluation of MOE, top and bottom of untreated sample of *T. siamensis* was found to be higher as compared to its corresponding treated samples, whereas the top and bottom of BBA treated sample of *D. strictus* shows higher value of MOE as compared to CCB treated and untreated samples of *D. strictus* . The top and bottom of treated samples of *T. siamensis* shows good value in Moment of Inertia as compared to the top and bottom of untreated samples of *T. siamensis*. whereas in *D. strictus* CCB sample shows high value of Moment of Inertia. It was examined that the average value of ultimate strength of both the species which are untreated are higher as compared to its treated sample. Anatomical observation revealed that due to the irregularities in arrangement of vascular bundles in bamboo the rate of penetration of chemicals may vary. It was revealed that the vascular bundles arranged so tightly in *Dendrocalamus strictus* make it difficult and time consuming for performing the Bucherie process.

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