Mechanical and Physico-Chemical Properties of Bamboos carried out by Aerospace Engineering Department, Indian Institute of Technology – Bombay with Prof. NK Naik as Principal Investigator

1.0 Introduction

Bamboo is a rapid growing fibrous plant available in abundance on the earth. It has tremendous economic potential. Bamboo is one of the strongest building materials. The specific objectives of the study are: mechanical and physico-chemical characterization of the following seven species of bamboos.

1. Bambusa Balcooa
2. Bambusa Bambos
3. Bambusa Nutans
4. Bambusa Tulda
5. Dendrocalamus Giganteus
6. Dendrocalamus Strictus
7. Melocanna Bambusoides

Studies have also been carried out on the following bamboo species as supplied by M/s Emmbee Forest Products Pvt. Ltd.

8. Dendrocalamus Hamiltoni
9. Gigantichola Macrostachya
10. Phyllastachys Bambusoides

Bamboo samples have not been received for Dendrocalamus strictus.

Bamboos mainly consist of the roots, culm and leaves. The culms are the most distinguishable part in a bamboo plant species. They are usually hollow and vary in sizes, diameters, colours and textures. Countless tiny black spots can be seen at the cross-section of the culm (hollow stem). These are the cellulose fibers which run the length of the culm carrying nutrients between roots and leaves. The rest of stem is lighter coloured lignin. Individually, cellulose is stronger of the two components [1]. The cellulose fibers can be compared with the reinforcing fibers in an advanced carbon/epoxy composite whereas the surrounding lignin can be compared with the epoxy matrix.

Even though there are some representative studies [1-15], detailed information regarding mechanical and physico-chemical properties of bamboos are not available. The objective of the present work is to look into these aspects in detail and generate comprehensive data bank for nine species of bamboos.

The present studies have been taken up at three levels :

1. Green bamboo culms,
2. Bamboo slivers / strips treated and dried,
3. Bamboo composites.

Green bamboo culms, bamboo slivers/strips treated and dried and bamboo composites have been supplied by M/s Emmbee Forest Products Pvt. Ltd. Bamboos were obtained from State Forest Research Institute (SFRI), Itanagar.

2.0 Photo-micrographic Studies

Generally, bamboo is an orthotropic material, i.e., it has particular mechanical properties in the three directions: longitudinal, radial and tangential. However, bamboo is a biological material. It is subjected to greater variability and complexity due to various conditions such as years of growth, soil and environmental conditions and the location of bamboo culm within the bamboo. Additionally, distribution of cellulose fibers within the bamboo culm is not uniform. To look into these aspects typical photo-micrographic studies have been undertaken.

The culm mainly consists of the strands of microscopic cellulose fibers and the lignin matrix. The cellulose fibers run the length of the culm. The spaces between adjacent strands of fibers are filled with lignin, a thermoplastic resin. Toward the outer surface of the culm, the number of fibrous strands increases rapidly. When considered from the outermost surface inwardly number of cellulose strands decreases.

Generally, cellulose fiber is stronger than the lignin matrix. Also the cross-sectional area of the culm changes from location to location. Hence, the cellulose strand distribution would be different at different sections of the culm. Hence, it is generally observed that the mechanical properties of bamboos vary enormously. Optical photo-micrographic studies have been carried out for all the bamboo species studied. It is generally observed that the cellulose strand distribution is denser near the outer part of culm than the inner part of culm.

3.0 Green Bamboo Culms

The bamboo culms are the main components that can be used as building materials. The culms consist of cellulose fibers which run the length of the culm carrying nutrients between roots and leaves and the light coloured lignin. Also, the culm contains the moisture. The moisture content is influenced by the years of growth, the season of felling and the species. In the green stage, greater difference in moisture content exists. The mechanical and physico-chemical properties of green bamboo culm are influenced by moisture content as well as cellulose-lignin content.

3.1 Mechanical properties

Analysis of mechanical properties is the investigation of behavior of the materials under different loading conditions. Information about the deformation behavior, stress state and the failure behavior of different bamboo species in different forms is an important requirement for the effective use of these bamboo species for different engineering applications. Generally, bamboo is an orthotropic material. Different test techniques, specimen preparation and test data have been presented for typical bamboo species.

3.1.1 Tensile strength parallel to grains

Standard test method to cover the determination of tensile properties of wood based structural panels is as per ASTM D 3500 - 90 [16]. This test method employs the specimens that should have reduced cross-section at the center of their length to avoid failure in the grip area. The specimens were made parallel to the grains. Such specimens are similar to glass-epoxy unidirectional composites. The first mode of failure was the failure along the grains at the location of reduced cross-section starting at the end of the reduced cross-section and continuing up to the grips. This is the usual mode of failure observed in the case of unidirectional glass-epoxy composites. Hence, such specimens with reduced cross-section at the center of their length are not suitable. Considering this aspect, flat specimens with rectangular cross-section have been used for the evaluation of tensile properties.
Tensile behavior studies have been carried out on nine bamboo species. Specimens parallel to grains have been prepared using the bamboo culms supplied by M/s Emmbee Forest Products Pvt. Ltd.

Since the diameter and the thickness of bamboo culms were different for different bamboo species, the cross-sectional dimensions and the length of the specimens were different. Dimensions of a typical specimen for SFRI/1 are: length 200 mm, width 10 mm and thickness 6 mm.

The specimens were tested on Hounsfield Universal Testing Machine of capacity 50 kN. The loading rate was 1 mm / min. It can be seen that the cellulose fibers

are pulled out of lignin matrix, i.e., interfacial debonding has taken place which is a typical mode of failure for unidirectional glass-epoxy composites. The results are for specimens without nodes, i.e., specimens were made from culms between two nodes.
Specimens were also made from culms with a node within the specimen length. Generally, it was observed that the tensile strength is lower for the cases with nodes within the specimen length compared to the cases where there were no nodes within the specimen length.

3.1.2. Compressive strength parallel to grains

Compressive strength properties have been evaluated using the specimens made parallel to the grains. Since, the specimen width available was only up to a few millimeters, ASTM D 695 – 96 [17] test technique has been used for the evaluation of compressive strength properties. The specimens were tested on Hounsfield Universal Testing Machine of capacity 50 kN. The loading rate was 0.9 mm / min.

Generally, the failure modes under longitudinal compression are: micro buckling of fibers leading to kink band formation and shear failure mode. For most of the specimens, shear failure mode was observed under longitudinal compression.

Compressive strength properties were determined using specimens of cuboid shape also. The loading was along the grain direction. Overall, both the test techniques gave nearly identical results.

3.1.3. Shear strength parallel to grains

In-plane shear strength has been evaluated as per ASTM D 3846 - 94 [18]. The specimens were made parallel to grains. This test method covers the determination of in-plane shear strength in flat sheets in thicknesses ranging from 2.5 mm to 6.0 mm.

The specimens were tested on Hounsfield Universal Testing Machine of capacity 50 kN. The loading rate was 1 mm / min.

3.1.4. Flexural strength and bending elasticity modulus

Standard test method to cover the determination of flexural properties of wood based structural panels is as per ASTM D 3043 - 95 [19]. The test specimens are rectangular in cross-section and the length of the specimens is parallel to grains. Load applied at mid-span of the specimen and resulting deflection are measured. The test proceeds at a constant rate of head motion until either sufficient deflection data in the elastic range have been gathered or until specimen failure occurs. For the case when the grains are parallel to the span, the length of the specimen is 48 times the depth of the specimen.

The above mentioned specifications are as per Method A, i.e., center point flexural test have been used. This method is applicable for the materials that are relatively uniform with respect to elastic and strength properties along the span.

Specimens with rectangular cross-section made from the culms between two nodes were used for the study. Since, the span length available between two nodes was not sufficient to have the required thickness-to-span ratio, thickness-to-span ratio of 1:16 was used for the present study (ASTM D 790 - 99) [20]. Since, the thickness of culms was different for different bamboo species, the actual cross-section dimensions were different for different cases. For the case of SFRI/2, thickness was 6 mm and width was 18 mm. The cross head motion was calculated as per ASTM D 3043 - 95 [19]. For the case of SFRI/2 the cross head motion was 3.88 mm/min.
The testing was carried out with the specimens arrangement as follows :

1) Outer side of bamboo culm on the loading side
2) Inner side of bamboo culm on the loading side

Load – center point displacement plots were obtained for different cases. Based on this bending elasticity modulus and flexural strength have been calculated. The slope of the initial straight line portion of the curve gives the bending elasticity modulus.

Typical studies were carried out on specimens with knots within the span length. It was observed that the bending elasticity modulus as well as flexural strength values are considerably lower for such specimens compared to those specimens without knots within the span length.

3.2 Hardness test

The hardness modulus method of determining equivalent Janka ball hardness has been used for determining hardness modulus and hardness of the bamboo species. The tests have been carried out as per ASTM D 1037 - 99 [21].

The test was carried out by applying the force on to the specimen. The rate of penetration of the Janka ball of 11.3 mm diameter was used for determining hardness modulus. The minimum thickness of specimen used was 10 mm. For the cases when the culm thickness was less than 10 mm, several bamboo culms were stacked together to provide required thickness for the specimen. The specimen width was 25 mm and the length was 150 mm. During loading, cross head speed was 1.3 mm/min. Each test was continued until the penetration was about 2.5 mm.

Load – penetration plots were obtained during testing. The slope of the initial straight line portion of this curve gives the hardness modulus. The hardness modulus (in pounds per inch of penetration) divided by 5.4 gives the equivalent Janka ball hardness. It may be noted that Janka ball hardness is a number [1].

3.3 Density

ASTM D 2395 - 93 [22] test technique was used for the determination of density of different bamboo species. The specimens were regular in shape with rectangular cross-section and right angle corners. The surfaces of the specimen were smooth for accurate measurement of dimensions. The specimen length, width and thickness were measured at sufficient number of places to ensure an accurate indication of volume of the specimen. The dimensions of a typical specimen were 100 mm x 10 mm x 3 mm. The dimensions were measured up to second decimal accuracy.

The specimens were oven dried. The weight of the specimen was measured up to milligram accuracy. Based on the volume and the weight of the specimen measured, density of each specimen was calculated.

3.4 Chemical properties

The main constituents of the bamboo culm are: cellulose, hemicellulose and lignin. Other constituents consist of resins, tannins, waxes and inorganic salts. The composition varies based on years of growth, season, species and the part of the culm. Studies on moisture, ligno-cellulosic, starch and silica content are presented in this section.

Ligno-cellulose is a loose compound of lignin and cellulose. Lignin is not a single chemical compound. The name represents a class of closely resembling chemical compound. Lignin is the binding material for the fibrous cellulose material in plants.

The ideal method of estimating ligno-cellulose is to determine lignin and cellulose contents individually and add the values. But procedures for estimating both lignin and cellulose separately are lengthy and involve handling chemicals like chlorine. Hence, for routine analysis, ligno-cellulose is found by method of elimination by determining moisture, hot water solubles, one per cent caustic soda solubles, alcohol - benzene solubles and ash.

Moisture content was evaluated based on TAPI Standard T 3 m – 44 [23]. The specific procedure is as follows.

3.4.1 Moisture content

The steps involved are :

1. Bamboo is powdered.
2. Powder is conditioned at relative humidity of 65 % and temperature of 27 ± 3^0 C for 48 hrs.
   Conditioning is achieved by keeping the sample in a closed desiccator containing saturated sodium chloride solution in numbered bottles with perforated cap. Equilibrium is reached at about 48 hours.
   (At 27^0 C temperature, relative humidity is 65 %)

3. Determination of moisture content
   - About 2 gm of sample is taken in a weighing bottle (A).
   - Dried in an oven for 2 hrs at 100 -105^0 C.
   - Stopper is put on the bottle.
   - Cooled in a desiccator containing silica gel to room temperature.
   - Weighed again (B).
   - Moisture content is calculated as,

$$\%\ Moisture\ \ content = \frac{Initial\ \ weight\ \ (A) - Final\ \ weight\ \ (B)}{Initial\ \ weight\ \ (A)} \times 100$$

3.4.2 Ligno-cellulosic content

Ash content was determined as per TAPI Standard T 15 m - 58 [24]. Water solubility was determined as per TAPI Standard T 1 m – 59 [25]. One percent caustic soda solubility was determined as per TAPI Standard T 4 m – 59 [26]. Further, alcohol–benzene solubility was determined as per TAPI Standard T 6 m – 59 [27].

$$Ligno-cellulosic\ \ content\ \ (\%) = \left[\frac{\begin{array}{l} weight\ \ of\ \ sample\ \ (A) - (moisture + \\ water\ \ solubles + ash + one\ \ percent\ \ caustic \\ soda\ \ solubles\ +\ alcohol - benzene\ \ solubles) \end{array}}{weight\ \ of\ \ oven\ \ dry\ \ sample\ \ (C)} \right] \times\ 100$$

where,

Weight of oven dry sample (C) = weight of conditioned sample (A) - moisture

3.4.3 Silica content

- Silica crucible is dried over a burner for 10 min, cooled in a desiccator containing silica gel up to room temperature.
- About 2 gm of sample is taken (A').
- Crucible with sample is kept in a muffled furnace at 600 ± 50^0 C for 2 hrs.
- Ascertain all the carbon particles are removed.
  This can be ascertained if there are no black particles in the sample. If black particles are present, heat it again.
- Cool the crucible in a desiccator with silica gel up to room temperature.
- Weighed (B').

$$Ash\ \ content\ \ (\%) = \frac{weight\ \ of\ \ Ash\ \ (B')}{weight\ \ of\ \ oven\ \ dry\ \ sample\ \ (C)} \times 100$$

Ash in the crucible is treated (add concentrated hydrochloric acid to ash, heat it in a water bath) with 10 ml of concentrated hydrochloric acid at 100^0 C for 30 min.

- 100 ml of distilled water is added to the mixture.
- Heat it for 10 min over a burner.
- Solution is filtered through a dried and weighed sintered glass crucible applying low vacuum.
- Residue in the crucible is washed four times with 50 ml of hot distilled water.
- The crucible with the contents is dried in an oven at 100 - 105^0 C for 2 hrs.
- Cooled to room temperature and weighed.
- To ascertain complete drying of silica, crucible is kept in an oven for 30 min.
- Cooled to room temperature and weighed again (D).

$$Silica\ \ (\%)\ = \frac{weight\ \ of\ \ silica\ \ (D)}{weight\ \ of\ \ oven\ \ dry\ \ sample\ \ (C)} \times 100$$

3.4.4 Starch content

- 2 gm of conditioned sample is taken in a 250 ml conical flask.
- 100 ml of distilled water is added with the sample.
- An air condenser is fixed to the flask.
- The flask is kept in a heating mantle.
- Heating is started and when water starts boiling, temperature is adjusted in such a way that water continues to boil with minimum evaporation.
- After 3 hrs of boiling, the flask is cooled to room temperature.

- The clear liquid in the flask is poured into a funnel provided with weighed filter paper.
- Solid in the flask is washed 4 - 5 times with 50 ml of hot distilled water and after every washing the liquid is poured into the funnel.
- Solid residue in the flask is also transferred to the filter paper.
- Any fibers adhering to the flask are washed into the funnel.
- When filtration is over, the funnel with filter paper is kept in the oven at 100 - 105^0 C for 2 hrs.
- Cooled to room temperature and weighed.
- Drying and weighing are repeated till weight is constant.
- Water extract (filtrate) is poured into a beaker.
- The flask is washed, added to solution obtained from filtration.
- 10 ml of saliva is added and beaker is kept in an oven for 4 hrs at 50 - 55^0 C.
- Few drops of solution of iodine in potassium iodide is added to it.
- Appearance of blue colour indicates that conversion of starch into sugar is not complete.
- If reaction is not complete, keep beaker into the oven for sometime.
- At this stage starch is converted into sugar.
- 10 ml of concentrated HCL is added to solution in a beaker and beaker is kept into the oven for 2 hrs at 50 - 55^0 C.
- The solution in the beaker is diluted to 250 ml using a volumetric flask.
- Take 25 ml of diluted solution into a conical flask.
- 25 ml of copper reagent is added to this sample.
- Solid sodium carbonate is added little by little until evolution of CO_2 stops. At this point the solution is alkaline.
- This mixture is boiled for 8 min over a burner, taking care that all solution is not evaporated, i.e., add distilled water as and when required.
- The flask is cooled to room temperature using cold water (cooling should be rapid).
- Add 25 ml of 4 N H_2SO_4 and 10 ml of 15 % of potassium iodite. Brown colour appears due to liberation of iodine.
- The solution is then titrated against 0.1 N sodiumthiosulphate.
- When the brown colour becomes faint, add 1 ml of starch solution as an indicator.
- Blue colour appears. Continue titration till blue colour disappears.
- Note the volume of thiosulphate used.
- Repeat a blank experiment using 25 ml of copper reagent and 25 ml of distilled water.
- Note volume of thiosulphate used.

- Difference between these two volumes gives quantity of thiosulphate solution used by invert sugar.
- 1 ml of 0.1 N thiosulphate solution is equivalent to 3 mg of invert sugar or 2.7 mg of starch.
- Amount of starch present in 250 ml of sample gives sugar content in the weight of bamboo sample taken.

$$starch\ (\%) = \frac{weight\ of\ starch}{weight\ of\ oven\ dry\ sample} \times 100$$

4.0 Bamboo Slivers / Strips Treated and Dried

Bamboos, like most ligno-cellulosic materials, have very low resistance to biological degrading agents. Hence, to enhance durability of bamboos, different preservation techniques need to be applied. All the nine bamboo species (Set II) have been treated and dried. This process was carried out by M/s Emmbee Forest Products Pvt. Ltd. All the mechanical and physico-chemical properties have been evaluated on the bamboo species after treatment and drying. The test techniques are as explained in section 3.0.

5.0 Bamboo Composites

The bamboo composites can be made in the form of final products or versatile products such as boards, strips, tiles etc. For the effective use of such versatile bamboo products for structural applications, mechanical and physico-chemical properties have been evaluated.

5.1 Compressive strength

Compressive strength properties have been evaluated for the bamboo composite tiles / strips. Studies have been carried out as per ASTM D 695 - 96 [17]. Also studies have been carried out using specimens of cuboid shape. The loading was parallel to grains, perpendicular to grains as well as along through-the-thickness direction. The specimens were tested on Hounsfield Universal Testing Machine of capacity 50 kN. The loading rate was 0.9 mm / min.

5.2 Hardness test

Hardness modulus and hardness values have been determined for bamboo composites. The tests have been carried out as per ASTM D 1037 - 99 [21]. The test details are given in section 3.3.

5.3 Abrasion resistance

Abrasion resistance characteristics of different bamboo composites have been evaluated as per ASTM C 501 - 84 [28]. Studies have been carried out on Taber abrading machine equipped with replaceable hard abrasive H-22 Calibrade wheels.

As per ASTM D 4060 - 95 [29], abrasion wear index is defined as follows:

Abrasion wear index, $I = (m_1 - m_2) \times 1000$ / (number of cycles)

where,

m_1 = initial mass of the specimen in gm

m_2 = final mass of the specimen in gm

And, abrasion wear cycles per mm, $II = D / T$

where,

D = number of abrasion cycles required to wear through the substrate

T = thickness of the substrate abraded in mm

Mass of the material removed by abrasion, $m = (m_1 - m_2) = \rho \times A \times T$

where,

ρ = density of the material in gm/mm^3

A = surface area of the material removed in mm^2

Now,

$$II = D / T = (\rho \times A \times D) / m \qquad \text{cycles per mm}$$

5.4 Slip resistance

Slip resistance characteristics of different bamboo specimens have been evaluated. The test is based on ASTM D 2047 - 99 [30]. The objective of the study was to measure the static coefficient of friction of flooring surfaces with respect to human locomotion safety. Friction is the resistance developed between the physical contacting surfaces of two bodies when there is movement or tendency for movement of one body relative to other parallel to the plane of contact. Coefficient of friction is the ratio of horizontal component of force required to overcome or have a tendency to overcome friction, to the vertical component of the object weight or normal force applied through the object, which tends to cause the friction.

Static coefficient of friction is the ratio of the horizontal component of force applied to a body that just overcomes the friction or resistance to slipping to the vertical component of the weight of the object or force applied to it. The vertical component shall result in a contact pressure of not less that 6.9×10^{-3} MPa (1 psi) and not more than 89.7×10^{-3} MPa (13 psi) applied uniformly over the area in mutual contact.

Slip resistance is the property of floor surface which is designed to prevent slipping.

Test specimens were prepared using bamboo composite tiles / strips. The test specimen dimensions were 229 mm x 229 mm x 9.5 mm (ASTM D 4103 - 90) [31]. The test specimen surface condition was as supplied by M/s Emmbee Forest Products Pvt. Ltd. Test shoe material was leather. The dimensions were 75 mm x 75 mm x 6 mm. Surface sanding of the test shoe material was carried out using 400 A carborandum paper.

5.5 Nail withdrawal test

Nail withdrawal test on different bamboo composites has been carried out as per ASTM D 1037 - 99 [32]. Nail holding tests are made on nail driven through the specimen from face to face to measure the resistance to withdrawal in a plane normal to the face.

The test specimens were of 75 mm in width and 150 mm in length. The thickness was in the range of 5-20 mm. Nails 2.8 mm in diameter were driven through the specimen at right angles to the face. At least 12 mm of shank portion of nail was projecting above the surface of specimen.

Nail withdrawal test was carried out on Hounsfield Universal Testing Machine of capacity 50 kN. The pulling rate was 1.5 mm / min. The maximum load required to withdraw the nail was noted. Nail holding strength is maximum load divided by the specimen thickness.

5.6 Flammability

Flammability test on different bamboo composites has been carried out. The tests are based on ASTM E 648 - 99 [33]. This fire test response standard measures the critical radiant flux at flame-out. It provides a basis for estimating one aspect of fire exposure behavior for floor covering systems. The imposed radiant flux simulates the thermal radiation levels likely to impinge on the floors of building whose upper surfaces are heated by the flames or hot gases or both, from a fully developed fire in an adjacent room or compartment.

Another important consideration is estimating flame spread behavior of floor covering in building areas. In this report flame spread behavior is presented for different bamboo composites.

Flammability tests have been carried out on different bamboo composites of rectangular cross-section. The specimens were oven dried at about 170^0C. The specimens of length of about one meter were clamped on one side. A pilot burner was ignited and the tip of the bamboo specimen was preheated for five minutes keeping the pilot burner at 50 mm away from the specimen. Then the pilot burner flame was brought into contact with specimen tip. The pilot burner flame was left in contact with the specimen tip for five minutes, then the pilot burner was removed and the pilot burner flame was extinguished.

It was observed that all the specimens caught fire within five minutes and the flame was propagating. For all the specimens, flame-out length and flame-out time were noted. At flame-out, the last vestige of flame or glow disappears from the surface of the test specimens. Flame-out time is the time beginning with the time when the pilot burner is removed from the tip of the specimen to the final flame-out. Flame-out length is the length of the flame propagating during flame-out time.

Energy released per unit cross-sectional area and flux are calculated as follows :

Mass of the bamboo composite, $m = \rho \times A \times L$

where,

ρ = density in kg/m^3

A = cross-sectional area of the bamboo composite specimen in m^2

L = flame-out length in m

Energy released, $E = C \times m$

where,

C = calorific value of bamboo composite in J/kg

Calorific value for a typical bamboo is C = 14.2 MJ/kg

Power, $P = E / t$

where,

t = flame-out time in seconds

Flux = power per unit area = P / A

$$\text{Flux} = E / (t \times A) = (m \times C) / (t \times A) = (\rho \times C \times L) / t$$

6.0 Results and Discussion

6.1 Photo-micrographic studies

The suitability of bamboos for structural composite products is demonstrated by its mechanical and physical properties. These properties depend upon years of growth of bamboo, season, location of bamboo culm and the species. The bamboo mainly consists of the roots, culm and leaves. The culm is divided into segments by nodes. The nodes separate culms into several sections termed internodes. Generally, bamboo is an orthotropic material, i.e., it has particular mechanical properties in the three directions : longitudinal, radial and tangential. However, bamboo is a biological material. A greater variability is observed in mechanical and physical properties. To look into the possible reasons for the variability in the properties, optical photo-micrographic studies have been carried out. Also, the culm composition has been studied along the length of the culm. The culm consists of strands of cellulose microscopic fibers parallel to each other. The spaces between adjacent strands of fibers are filled with lignin, a thermoplastic resin. It can be seen that, toward the outer surface of the hollow culm, the number of fibrous strands increases. When considered from the outermost surface inwardly the number of fibrous strands decreases. Individually, cellulose fiber is stronger than the lignin matrix. Hence, there would be variability of property along the radial direction.

Even though the fibers are considered to be parallel to each other generally, it is observed that the fibrous strands are not exactly straight and not parallel to each other. Hence, it is observed that there is a variability of properties along the longitudinal direction also, even within bottom, middle and top regions. This is a general observation for all the bamboo species studied.

6.2 Mechanical and physical properties

The specimens were made from the internode bamboo culms. For green bamboo culms, the minimum tensile strength is for Dendrocalamus Hamiltoni whereas the maximum strength is for Bambusa Tulda, Bambusa Nutans and Melocanna Bambusoides. For treated and dried bamboos, the minimum strength is for

Bambusa Bambos and Dendrocalamus Hamiltoni whereas the maximum strength is for Bambusa Tulda, Bambusa Nutans and Gigantichola Macrostachya. For all the bamboo species tested together, the tensile strength varies in the range of 111 - 219 MPa. Within each species of bamboos also, the variation was considerable. This can be attributed to possible different years of growth for different samples tested, location of the culm within the bamboo and other environmental conditions.

Details of the different bamboo culms are given in the technical report provided by State Forest Research Institute (SFRI) [34]. The bamboo culms were collected in the month of August / September 2002. Age of the culm varies from 2 to 7 years. Also the number of culms in the clump varies from 8 to 205 numbers. These are some of the growth conditions that can affect the mechanical and physical properties significantly in addition to microstructural variation. Bamboo culms have been collected from different geographical locations. This can also affect mechanical properties.

Tensile strength of a typical bamboo flooring parallel to grain is 105 MPa (15,290 psi) as reported in reference [1]. As reported in reference [5], tensile strength parallel to grains is 200 MPa for a typical bamboo. Further, tensile strength values reported is in the range of 130 -138 MPa [7]. The lower values are for green bamboos whereas the higher values are for air dry bamboos.

Density varies from 0.56 gm/cc to 0.96 gm/cc. Minimum density is for Dendrocalamus Hamiltoni. It can be seen that tensile strength is also less for Dendrocalamus Hamiltoni. Possibly this lower tensile strength can be correlated to lower density. Bambusa Tulda, Bambusa Balcooa, Bambusa Nutans and Gigantichloa Macrostachya have higher densities. Generally, it is observed that these species have higher tensile strength. As seen from reference [5], density varies from 0.5 gm/cc to 0.9 gm/cc for different bamboo species.

Dendrocalamus Hamiltoni has lower tensile strength. The age of growth for this species was only two years as compared to more number of years of growth for the other species [34]. This can be one of the reasons for lower tensile strength for Dendrocalamus Hamiltoni. As indicated in reference [5], it is general assumption that bamboo reaches maturity in about three years and has then reached their maximum strength.

Compressive strength varies from 53 MPa to 100 MPa. Again, Dendrocalamus Hamiltoni has the minimum compressive strength value. Significant variation of compressive strength values is also observed.

Compressive strength values for different bamboo species are also presented in reference [3]. It is reported that the variation is in the range of 40 – 50 MPa in green condition and 60 – 70 MPa in dry condition. The compressive strength values are also presented for different species of bamboos in reference [4]. The reported values are in the range of 40 – 70 MPa. Here, the lower values are for green bamboos whereas the higher values are for dry bamboos.

Variation is from 5.9 MPa to 13.4 MPa. Bending strength is in the range of 86 – 229 Mpa. Bending elasticity modulus is in the range of 6,882 – 20,890 MPa. As per reference [7], bending elasticity modulus for a typical bamboo species varies in the range of 8,945 – 11,691 MPa. The lower values are for green bamboos and higher values are for air-dry bamboos. As per reference [1], bending strength value for typical flooring is 94 MPa.

Hardness modulus is in the range of 902 – 1,833 N/mm. Janka ball hardness varies in the range of 953 – 1937. Only Dendrocalamus Hamiltoni has much lower values. Janka ball hardness value reported for a typical bamboo species is 1640 [1].

All the test results presented for the mechanical properties are from the specimens made from internode regions. Representative studies have also been carried out using specimens with nodes present within the span length. For these cases, it is observed that mechanical properties are lower.

6.3 Chemical properties

Ligno-cellulosic, starch, silica and moisture content of different bamboo species have been evaluated as explained in section 3.4.

The bamboo culms were collected from the forest in the month of August / September 2002. The mechanical and physical tests were carried out during November 2002 – January 2003. The chemical tests were carried out during December 2002 – February 2003. There was a time gap of about 2 – 3 months between the felling of bamboos and actual testing.

During this period, the stored food materials are utilized and, thus, sugar / starch content in the bamboos is lowered [I3]. Also, because of the time gap between felling of bamboos and testing of samples, moisture content would be significantly reduced. The green bamboos tested would not be exactly the green bamboos as they were immediately after felling. Hence, the moisture content is less as compared to moisture content reported for green bamboos in the literature.The lingo-cellulosic content varies in the range of 69.25 % - 85.21 %. The silica content varies in the range of 0.5 % - 1.75 %.

6.4 Bamboo slivers / strips treated and dried

As explained earlier, because of the time gap between felling of bamboos and testing of specimens, significant difference is not seen between the properties of green bamboo culms and bamboo slivers / strips treated and dried.

6.5 Bamboo composites

Studies have been carried out on six bamboo species. Since, Dendrocalamus Hamiltoni, Melocanna Bambusoides and Phyllastachys Bambusoides have not been supplied, the properties are not available for these species.

Compressive strength parallel to grains varies in the range of 80 – 102 MPa. Other two properties (Y_c and Z_c) are having lower values. As per reference [1], for bamboo flooring, X_c = 52 MPa and Y_c = 18 MPa. Compressive strength values for bamboo composites are generally more than for green bamboo culms and bamboo slivers / strips treated and dried.

Hardness values vary in the range of 1423 – 1760. As per reference [1], hardness value for a typical bamboo flooring is 1640.

Abrasion resistance characteristics have been evaluated on Taber abrading machine equipped with replaceable hard abrasive H – 22 Calibrade wheels. Abrasion resistance is in the range of 0.15 – 0.72 gm / 1000 cycles. As per reference [1], abrasion resistance for a typical bamboo flooring is 0.349 gm / 1000 cycles.

Slip resistance along grains varies in the range of 0.50 – 0.71 whereas it varies in the range of 0.63 – 0.85 across grains. Generally, slip resistance is higher across grains than along grains.

It varies in the range of 23.3 – 56.9 N / mm along through-the-thickness direction whereas it varies in the range of 21.1 – 40.4 N / mm along the width direction.

Results for flame-out length and flame-out time are not available for Bambusa Tulda and Bambusa Nutans as material was not available. Flame-out length was in the range of 77 – 139 mm. Flame-out time was in the range of 7.5 – 13 min.

7.0 Inference Analysis

7.1 Bamboo composites

Bamboo products are finding increasing uses in various applications such as : flooring, veneer, handicrafts, decorative boards, sports equipment and other building materials. Bamboo as raw material is used for pulp, paper and panel board industries. Bamboos are used in many traditional applications such as : for fencing, water pipes, fishing rods, umbrella handles, musical instruments and decorative handicrafts. But, presently the focus is on bamboos as structural materials.

The suitability of bamboos for structural products is demonstrated by its mechanical and physical properties. Bamboo composites are normally used for structural products rather than the raw bamboos. This is because of possible variability of properties along the longitudinal and radial directions as well as physical dimensions of the products required. For load carrying structural composite products, mechanical properties such as tensile strength, compressive strength, shear strength, flexural strength and bending elasticity modulus are important. For flooring tiles and veneers, through-the-thickness compressive strength, hardness, abrasion resistance and slip resistance are important. For structural assemblies, nail withdrawal strength is important.

Bamboo grows in different climates from jungles to high mountain side. Bamboo and bamboo composite mechanical and physico-chemical properties are also influenced by the climatic and ecological factors, cultivation techniques and harvesting details. For the present study of mechanical and physico-chemical properties of bamboo composites, bamboo has been supplied by State Forest Research Institute (SFRI), Itanagar. For the nine species of bamboos under study, details regarding climate and ecological factors, cultivation technique used plantation, harvesting guidelines have been provided by SFRI [34].

Bamboo slivers and composites were made by Emmbee Forest Products Pvt. Ltd., Kolkata using the raw bamboos supplied by SFRI [35]. Processing analysis is given by Emmbee Forest Products Pvt. Ltd. The details are given in Appendix B. Slivers are processed from raw bamboos. A number of slivers are glued and hot pressed together to produce a stick. Bamboo composites are produced by pressing together a number of sticks. Thus, average width and thickness of the finished slivers affect productivity, quality and costs of composites produced. Species with very low circumference and thickness are not quite viable for such processes.

For the effective utilization of bamboo composites for structural applications, bamboos need to be generally straight. Slivers made from bent bamboos would lead to varying thicknesses. In such cases reworking may be necessary to produce slivers of smaller lengths and uniform thickness.
Based on the processing analysis provided by Emmbee Forest Products Pvt Ltd., Dendrocalamus Hamiltoni (SFRI/6), Melocanna Bambusoides (SFRI/8) and

Phyllastachys Bambusoides (SFRI/9) were not used for making the bamboo composites [35]. This is because the slivers were not acceptable.

Considering all the species, sliver width was in the range of 23.25 mm to 26.80 mm. The average thickness before processing was in the range of 6.95 mm to 14.25 mm. The average thickness after processing was in the range of 4.4 mm to 7.3 mm. Sliver thickness was the maximum for Bambusa Balcooa (SFRI/2).

Average circumference of the culms was more for Bambusa Balcooa (SFRI/2), Bambusa Bambos (SFRI/3), Dendrocalamus Giganteus (SFRI/5) and Gigantichloa Macrostachya (SFRI/7). Also, average thickness of the slivers after processing was more for the above four species. Because of higher average circumference of the culms and higher average thickness of the slivers after processing, number of slivers obtained for the above four bamboo species was more. Slivers acceptable for further processing was also more. Based on these considerations, i.e., higher average circumference, higher culm thickness and the quality of slivers obtained, the bamboo species Bambusa Balcooa (SFRI/2), Bambusa Bambos (SFRI/3), Dendrocalamus Giganteus (SFRI/5) and Gigantichloa Macrostachya (SFRI/7) are recommended for uses as bamboo composites.

From the present test results, it is observed that Bambusa Tulda (SFRI/1), Bambusa Nutans (SFRI/4) and Gigantichloa Macrostachya (SFRI/7) have higher strength values. Bending elasticity modulus is higher for Bambusa Tulda (SFRI/1) and Bambusa Nutans (SFRI/4). For the structural components where high strength is the main consideration Bambusa Tulda (SFRI/1), Bambusa Nutans (SFRI/4) and Gigantichloa Macrostachya (SFRI/7) can be preferred.

Hardness modulus and hardness are higher for Dendrocalamus Giganteus (SFRI/5) and Gigantichloa Macrostachya (SFRI/7). Abrasion resistance is higher for Dendrocalamus Giganteus (SFRI/5) whereas slip resistance is higher for Bambusa Nutans (SFRI/4) and Dendrocalamus Giganteus (SFRI/5). Flooring composite tiles require higher hardness properties, abrasion resistance and slip resistance. Considering these requirements Dendrocalamus Giganteus (SFRI/5) is recommended for flooring tiles.

Nail holding strength is higher for Gigantichloa Macrostachya (SFRI/7) along through the thickness direction. Flame out length is higher for Bambusa Balcooa (SFRI/2).

Considering applications of different bamboo composites and their requirements, different bamboo species will be used for different cases.
Recommended bamboo species for different applications are :

1. Bamboo slivers and composites processing conditions point of view : Bambusa Balcooa (SFRI/2), Bambusa Bambos (SFRI/3), Dendrocalamus Giganteus (SFRI/5), Gigantichloa Macrostachya (SFRI/7)
2. For structural applications from higher strength point of view : Bambusa Tulda (SFRI/1), Bambusa Nutans (SFRI/4), Gigantichloa Macrostachya (SFRI/7)
3. Flooring tiles etc. from hardness, abrasion resistance and slip resistance point of view : Dendrocalamus Giganteus (SFRI/5)
4. Nail holding strength point of view : Gigantichloa Macrostachya (SFRI/7)
5. Flame out length point of view : Bambusa Balcooa (SFRI/2)

8.0 Concluding Remarks

Bamboo is one of the strongest building materials. Hence, bamboo products are finding increasing uses in various applications. Generally, bamboo is an orthotropic material, i.e., it has particular mechanical properties in the three directions : longitudinal, radial and tangential. However, bamboo is a biological material. Hence, it is subjected to greater variability due to various conditions, such as years of growth, season, soil and environmental conditions and the location of bamboo culm within the bamboo. Photo-micrographic studies show that the distribution of cellulose fibers is not uniform within the cross–section. Toward the outer surface of the hollow culm, the number of fibrous strands increases. When considered from the outermost surface inwardly the number of fibrous strands decreases. Even though the fibers are considered to be parallel to each other generally, it is observed that the fibrous strands are not exactly straight and not parallel to each other. Hence, it is observed that there is variability in mechanical and physico-chemical properties.

Detailed studies have been carried out on mechanical and physico-chemical properties of nine bamboo species. Bamboo composites can be effectively used as construction materials because of favourable mechanical properties. Specific tensile strength of bamboo composites is about 4 – 5 times more than that of mild steel. Also, specific tensile strength of bamboo composites is comparable to that of a typical glass / epoxy composite.

General comparison of mechanical properties of bamboo composites may not be possible with those of wood or other natural products. This is because there is significant variability in mechanical properties from species to species. Overall, properties of bamboo composites are comparable to those of wood and other natural products. Considering the fact that bamboo is a rapid growing fibrous plant available in abundance, bamboo composites can find various applications.

Test results of physical, chemical and mechanical properties (ASTM) for different bamboo species

Species	Site of collection / locality	Age of the culm (yr)	Average Dia (cm)	Wall thickness		Moisture content,(%)	Silica content, (%)	Starch content, (%)	Ligno-cellulosic content, (%)	Density, ρ (gm/cc)	Tensile strength, X_T (MPa)	Compressive strength, X_C (MPa)	Shear strength, S (MPa)	Bending strength, X_b (MPa)	Bending elasticity modulus, E_b (MPa)
				Bottom (cm)	Top (mm)										
Bambusa tulda	B/setum (Chessa)	4	7.7/ 21	2	7	8.62	1.53	traces	77.14	0.91 (-0.06, +0.06)	207(-26,+15)	79(-12,+11)	9.9 (-1.1,+1.0)	194(-27,+16)	18611 (3105,+5051)
B. Balcooa	B/setum (Chessa)	5	10/ 30.4	4	8	8.46	0.15	traces	78.69	0.82 (-0.10, +0.03)	164(-57.+64)	69(-21,+12)	11.9 (-1.8,+1.2)	151(-35,+22)	13603 (-4040,+3382)
B.bambos (B.arundinaceae)	B/setum (Chessa)	3	21.2/ 37	3.4	4	9.45	0.24	traces	74.96	0.71 (-0.13, +0.17)	121(-28,+38)	61(-10,+8)	9.9 (-0.7,+0.7)	143(-40,+39)	14116 (-743,+3798)
B. nutans	B/setum (Chessa)	3	8/ 30	2	5	8.04	1.17	traces	69.25	0.89 (-0.08, +0.10)	208(-93,+80)	75(-2,+1)	10.5 (-2.2,+3.8)	216(-55,+30)	20890 (-848,+596)
Dendrocalamus giganteus	-do-	2	12/ 39	2	5	8.02	0.83	traces	78.27	0.74 (-0.04, +0.07)	177(-17,+17)	70(-10,+21)	10.6 (-1.9,1.4)	193 (-20, +31)	16373 (2136,+3646)
D. hamiltonii	Zoo Park Forest A.P.	2	7.5/ 24.5	1.2	5	8.46	1.42	3.76	79.04	0.59 (-0.25, +0.17)	177(-20,+13)	70(-10,+21)	6.7 (-2.0,+4.0)	89(-50, +77)	9629 (-3904, +7788)
Gigantichloa macrostachya	B/setum (Chessa)	3	9.5/ 29	3	5	8.08	1.70	0.72	78.07	0.96 (-0.07, +0.09)	168(-16,+28)	71(-13,+16)	9.6 (-2.9,+1.8)	174(-20,+17)	14226 (-1290,+974)
Melocanna Bambosoides	B/setum (Chessa)	3	5.2/ 25	5.7	1	8.28	1.53	0.104	80.80	0.72 (-0.13, +0.11)	210(-14,+22)	81(-14,+24)	7.1 (-1.5,+1.6)	137(-21,+23)	16425 (-3433, +2247)
Phyllostachys Bambusoides	Ziro	3	5/ 16	1	5	7.98	0.79	traces	85.21	0.73 (-0.05, +0.02)	140(-6,+5)	63(-8,+7)	8.7 (2.5,+4.4)	127(-26,+24)	10982 (-3535,+3542

Test results of physical, chemical and mechanical properties (ASTM) for bamboo composites

Species	Compressive strength parallel to grains MPa	Compressive strength perpendicular to grains MPa	Hardness modulus (N/mm)	Hardness	Abrasion resistance (gm/1000 cycles)	Slip resistance along grains	Slip resistance across grains	Nail holding strength through thickness direction (N/mm)	Nail holding strength along the width direction (N/mm)	Flame-out length (mm)	Flame-out time (min)	Energy released per unit cross sectional area (GJ/m^2)
Bambusa tulda	102	23	1422	1502	0.15	0.54	0.76	23.3	24.0			
B. Balcooa	96	24	1489	1573	0.55	0.58	0.63	31.4	26.6	139	9	1.57
B.bambos (B.arundinaceae)	80	17	1494	1578	0.43	0.53	0.64	35.5	17.4	77	7.5	0.86
B. nutans	87	19	1364	1441	0.32	0.71	0.85	27.5	40.0			
Dendrocalamus giganteus	88	23	1666	1760	0.72	0.66	0.79	33.6	40.4	100	7.5	1.30
Gigantichloa macrostachya	93	30	1347	1423	0.26	0.50	0.65	56.9	21.1	104	13	1.18

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GLOSSARY

1. Abrasion resistance: The ability of materials to withstand the abrading action of the same or another material. The property is usually measured in terms of rate of loss of material by weight when abraded under specified conditions and length of time.

2. ASTM (American Society for Testing Materials) : It is an organization providing a forum for producers, users, ultimate consumers and those having a general interest (representatives of government and academia) to meet on common ground and write standards for materials, products, systems and services. This was established in 1898 and has grown into one of the largest voluntary standards developing systems in the world. It has 129 standards – writing committees and publishes more than 10,500 standards each year.

3. Cellulose: A complex carbohydrate, the chief component of the cell walls of most plants. It consists of long chain-like molecules of glucose which form micro fibrils.

4. Chemical properties: These properties describe, how one kind of matter reacts with another kind of matter to form a new and different substance.

5. Coefficient of friction: It is the ratio of horizontal component of force required to overcome or have tendency to overcome friction, to the vertical component of the object weight or normal force applied through the object, which tend to cause friction.

6. Compressive strength: The maximum compressive stress that can be carried by the specimen during compression test.

7. Composite: A composite material is a heterogeneous combination of two or more materials (reinforcing elements, fillers and binders), differing in form or composition on a macroscale. The combination results in a material that maximizes specific performance properties. The constituents do not dissolve or merge completely and therefore normally exhibit an interface between one another.

8. Culm: The stem of a grass or sedges.

9. Density: It is the ratio of the mass of the material to the volume of the material.

10. Ductility: It is a measure of the deformation at fracture. It is the ability of the material to be drawn into a wire. It indicates the ability of a material to be plastically deformed such as formability during fabrication and relief of locally high stress at crack tips during structural loading. Values for ductility are a function of gage length used.

11. Fibre: It is a long narrow flexible material, may be of animal, plant, mineral or synthetic origin.

12. Flexural modulus: The ratio, within the elastic limit, of the applied stress on a test specimen in flexure, to the corresponding strain in the outermost fibres of the specimen.

13. Flexural strength (Modulus of Rupture): Maximum flexural stress sustained by the test specimen during bending test. Flexural strength can be defined as the maximum stress in bending that can be withstood by the outer fibres of a specimen before rupturing.

14. Friction: It is the resistance developed between the physical contacting surfaces of two bodies when there is movement or tendency for movement of one body relative to other parallel to the plane of contact.

15. Hardness: Hardness is a property of the material which is characterized by the resistance offered by the material for indentation into it. The hardness of a material is determined by either the size of an indentation made by an indenting tool under a fixed load, or the load necessary to produce penetration of the indenter to a predetermined depth.

16. Lignin: A complex organic substance derived from phenylpropane and distinct from carbohydrates. It is a naturally occurring component of plant life that helps to provide strength in plants.

17. Mechanical properties: The mechanical properties of the materials are those which are associated with the ability of the material to resist mechanical forces and loads.

18. Modulus of elasticity: The ratio of stress to the corresponding strain below the proportional limit of the material.

19. Modulus of rigidity: The rigidity modulus refers to the change of shape produced by a tangential stress. The rigidity modulus is also referred to as the shear modulus.

20. Moisture content: The weight of water in the culm expressed as a percentage of the dry weight of the culm.

21. Physical properties: Properties deciding general appearance of the material.

22. Secant modulus: The ratio of stress corresponding to strain at any selected point on the stress-strain curve, that is, the slope of a straight line that joins the origin and the selected point on the actual stress-strain curve.

23. Shear strength: Shear strength means the maximum shear load divided by the shearing area before the initiation of the test.

24. Silica: A substance (silicon dioxide) occurring naturally as quartz, sand or flint in powdered form used as a filler.

25. Slip resistance: It is the property of floor surface which is designed to prevent slipping.

26. Strain: When a system of forces or loads acts on a body, it undergoes some deformation. This deformation per unit length is known as unit strain or simply strain.

27. Standard (As used in ASTM): A document that has been developed and established within the consensus principles of the Society and that meets the approval requirements of ASTM procedures and regulations.

28. Strength: It is the ability of a material to resist externally applied forces at breaking or yielding. The internal resistance offered by a part to an externally applied force is called stress.

29. Stress: When some external system of forces or loads acts on a body, the internal forces (equal and opposite) are set up at various sections of the body, which resist the external forces. This internal force per unit area at any section of the body is known as unit stress or simply stress.

30. Stiffness: It is the ability of a material to resist deformation under stress. The modulus of elasticity is the measure of stiffness.

31. Tensile strength: A measure of the ability of a material to withstand a longitudinal stress, expressed as the greatest stress that the material can stand without breaking.

32. Toughness: It is the property of a material to resist fracture due to high impact loads like hammer blows. The toughness of the material decreases when is heated. It is measured by the amount of energy that a unit volume of material has absorbed after being stressed up to the point of fracture.

33. Yield point: The strain deviates from being proportional to the stress.