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Bending properties of loblolly pine

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ABSTRACT

A three-point bending test was used to assess the effects of moisture content, radial location, and tree height on the specific toughness and bending stress of loblolly pine. Test samples were collected at 20%, 40%, 60%, and 80% of the radial distance between the tree pith and bark, across four heights (0 mm/tree base, 116.84 mm/breast height, 304.80 mm, and 457.20 mm) of five randomly selected loblolly pine tree trunks. The wood samples were cut into cuboid shapes (40 mm by 10 mm by 5 mm). The samples from the various tree radius and tree height combinations were then adjusted to 10%, 20%, or 30% moisture content (wet basis). The average specific toughness of loblolly pine varied between 14.41 kJ/m^2 and 100.75 kJ/m^2 whereas the average bending stress of loblolly pine varied between 35.14 MPa and 117.65 MPa. Increase in the moisture content of loblolly pine caused increase in its specific toughness and decrease in its bending stress. The bending stress and specific toughness of loblolly pine decreased with decreasing tree radius and increasing tree height. This result show that wood materials get tougher and stronger as they mature. Regression analysis revealed that moisture content was the most important factor influencing the specific toughness and bending stress of loblolly pine. The r^2 for the polynomial regression model developed to predict specific toughness and bending stress from moisture content, tree height, and tree radius were 0.614 and 0.662, respectively.

1. Introduction

Loblolly pine wood is the predominant wood species grown (about 45% of the forestland is covered with loblolly pine) in the southeast portion of United States (Schultz, 1999; Samuelson et al., 2013). Therefore, feedstocks from loblolly pine will play a major role in the emerging biomass industries in this region of the country (DOE, 2016). Similar to other woody biomass feedstocks, loblolly pine trees that are harvested as logs have to be ground into particulate materials before they can be efficiently converted into fuels, chemicals or materials. Information on grinding behavior are needed to size and design grinding equipment but the grinding behavior of biological materials are influenced by the mechanical behavior of the material (Phanphanich and Mani, 2011).

Strength and toughness are typically used to characterize the grinding related mechanical behavior of biological materials (Kretschmann, 2010). Strength and toughness are obtained from force-displacement curves when materials are subjected to tensile, compression, bending, shear or hardness test. The choice of the type of test however depends on the predominant force in the process of interest. For example, shear test is more appropriate for cutting plant stems during harvest operation (Tavakoli et al., 2009) whereas compressive test is used to simulate food sensory/chewing because of the dominance of compressive force (Peleg, 2003).

Hammer mill is the most common equipment used for grinding biomass feedstocks because of the relatively cost, ease of operation and maintenance, versatility, and high throughput of this grinding equipment (Ghorbani et al., 2010). The design of the hammer mills is such that the hammers apply impact force on the material being ground (Fellows, 2009). Bending tests are used by material scientists to simulate and study impact forces on solid materials (Brostow et al., 2015; Kubojima et al., 2000). Static bending test are more commonly used in biological testing because of the ease of conducting this test on a universal testing machine, and because the results from static bending test are comparable to those of impact bending tests (Dongdong and Jun, 2016; Srinivasa et al., 2011; Yu et al., 2008).

Dahlen et al. (2012) reported that the mean bending stresses of Southern pine and Douglas-fir at 15% moisture content were 48.3 MPa and 42.1 MPa respectively. Esehaghbeygi et al. (2009) demonstrated that moisture content and stem height have significant effects on bending stress of wheat straw. The authors reported that the bending stress of wheat straw decreased from 26.8 MPa to 17.7 MPa as the moisture content of wheat straw increased from 15% to 45%. The authors also showed that the bending stress of wheat straw decreased

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from 21.4 MPa to 17.9 MPa as wheat straw stem height increased from 100 mm to 300 mm. Similar effect of moisture content on bending stress was reported for safflower stalk by Özbek et al. (2009). A second order polynomial model ($r^2 = 0.99$) between bending stress and moisture content was developed by the authors. Galedar et al. (2008a) divided alfalfa stem into three equal sections (upper, middle, and lower). The authors showed that the upper part of the stem has the highest bending stress whereas the lower part has the least bending stress. Kumar and Reddy (2015) reported that bending stress of maize stalk residue increased linearly with increasing stalk girth.

Previous work on mechanical properties of biomass have focused on herbaceous biomass. Since limited information exist in literature on the mechanical properties of loblolly pine trees, the objective of this study was to investigate the effects of moisture, tree radius and tree height on the bending properties (bending stress and specific toughness) of loblolly pine. The measured bending properties were compared to experimental grinding energy data from Oyedeji et al. (2016) to provide a comprehensive picture of the relationship between loblolly pine trees bending properties and energy consumed during hammer milling. Regression models were developed to predict the specific toughness and bending stress of loblolly pine as a function of moisture content, tree height and tree radius.

2. Materials and method

2.1. Sample preparation

Five loblolly pine logs (approximately 12 years old) were obtained from the Auburn University Research Park, Auburn, AL and air dried. Disks were cut at the following distances from the base of the trunk of each log – 0 mm (0 feet), 116.84 mm (4.6 feet), 304.80 mm (12 feet) and 457.20 mm (18 feet) as labelled in Fig. 1a. The disks were labelled and further dried to approximately 10% moisture content (wet basis) using a humidity chamber (model ESL-2CA, Espec North America, Inc., MI). Cuboidal wood samples (40 mm by 10 mm by 5 mm) were thereafter cut from the disks at 20%, 40%, 60%, and 80% of the distance between the pith and bark (as described in Fig. 1b) using a power saw.

The moisture content of wood samples was adjusted to 10%, 20%, and 30% by adding a predetermined quantity of water. The wood samples were there kept in an airtight plastic bag and placed in a refrigerator at 4 ± 1 °C for about 10 days to ensure equilibration of moisture (Al-Mahasneh and Rababah, 2007; Balasubramanian and Viswanathan, 2010). To validate the moisture adjustment process, moisture content of wood samples was determined according to standard E871-82 (ASTM, 2006) by placing samples in an oven at 103 ± 2 °C for 24 h. All deviations from the expected moisture content were within 2% of the targeted moisture content.

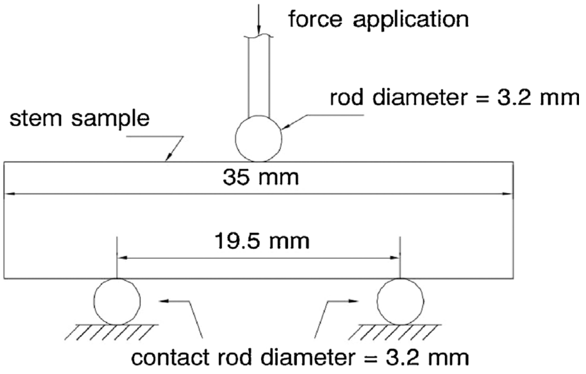

Fig. 2. The bending test experiment setup (Özbek et al., 2009).

$$\tau = \frac{3P_{max}L}{2bh^2} \tag{1}$$

where τ = bending stress (MPa), P_{max} = maximum bending force (N), L = distance between supports or span (m), b = sample width (m), and h = sample thickness (m).

2.2. Bending test

A texture analyzer (model TA-HDi, Stable Micro Systems, Texture Technologies Corp., NY) was used to conduct the three-point bending tests in this study. Each cuboidal sample was placed on two 3.2 mm diameter supports that were placed 19.5 mm apart. A 3.2 mm diameter indenter was applied at the center of the sample (Fig. 2). Loading speed was set at 0.8 mm/s. The force-displacement curve and data were obtained through the software provided by the manufacturer of the texture analyzer. The maximum height and area under the curve were determined and recorded (Fig. 3). The bending stress was computed

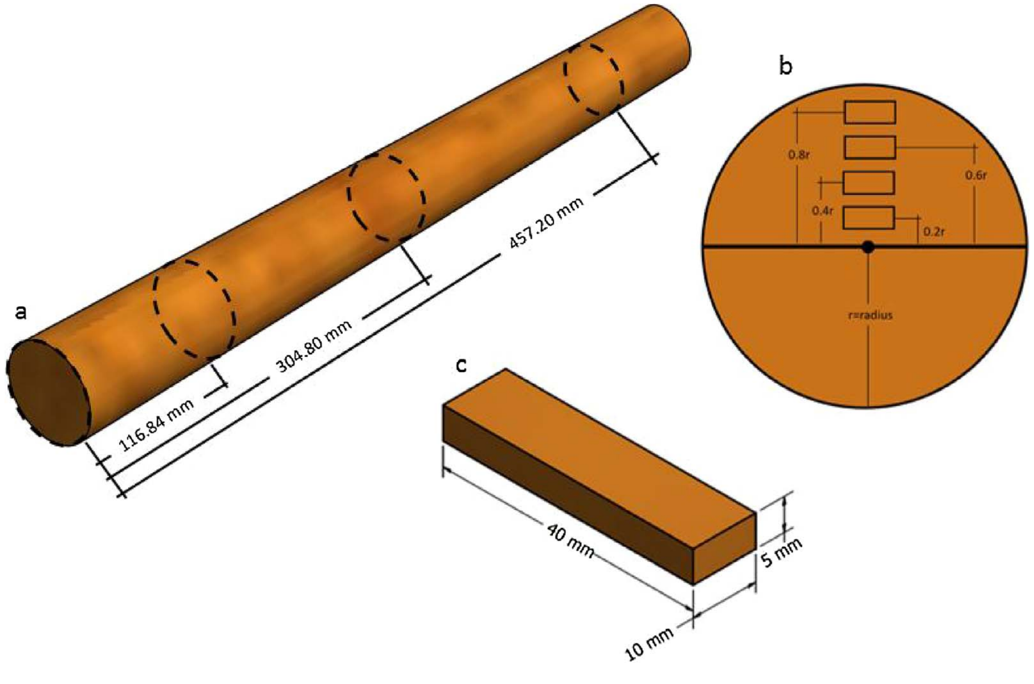

Fig. 1. Sample preparation.