WOOD RESEARCH
62 (2): 2017
223-234

THE IMPACTS ANALYSIS OF MOISTURE CONTENT ON MECHANICAL PROPERTIES OF WORMWOOD STEM

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(Received August 2016)

ABSTRACT

The disposable chopsticks caused a large amount resources waste of bamboo and wood. Thus, it has a significant resources and environmental benefits using wormwood stem as raw materials to make disposable chopsticks. In this paper, the radial compression and bending performances of wormwood stem were tested with different moisture content, which provide a reference for reasonably design the grinding device of wormwood stem and the feasibility of wormwood stem instead of bamboo chopsticks. The test results show that: the mechanical properties decrease with the increase of moisture content. In the actual grinding process, the moisture content of wormwood stem is controlled about 20%, it can withstand the radial force of 600*N* and the bending force of 41*N*, which meet the load requirements of the grinding processing and use. This study provides a theoretical basis for reasonably design grinding device of wormwood stem, producing and storing high quality herbal chopsticks.

KEYWORDS: Wormwood stem, moisture content, stem microstructure, grinding process, mechanical properties.

INTRODUCTION

Nowadays, a large number of wood products and disposable bamboo utensils are used more and more widely, thus, the consumption of forest resources is inevitable increasing, the forest resources have been seriously damaged. China's current forest area is 134 million hectares, total volume is 10.1 billion cubic meters, ranking fifth in the world. However, the per capita forest area and the per capita forest stock were 11.7 % and 12.6 % of the world average respectively, so China is one of the forest resources-poor countries in the world (Ke et al. 2016, Dai et al. 2013). The decrease of forest resources has caused global ecological imbalance and the environment is deteriorating. Therefore, protecting forest resources and ecological environment has become an important topic in current research.

Due to the disposable bamboo chopsticks are inexpensive and easy to use, they are extensively consumed in China, which also brings great negative effects. According to the statistics, Chinese people consumes 45 billion pairs annually (about 1.66 million cubic meters timber). In addition, China exports 25 billion pairs of wooden chopsticks to South Korea, Japan and other countries every year (Tian and Yin 2006, Gao et al. 2012). The contradiction between the effective supply of forest and the increase of social demand is still significant, the sustainable development of our country seriously restricted (Shi et al. 2013). Wormwood (*Artemisia integrifolia* Linn.) is an annual herb, it common distributed in road, river, thickets and semi humid region, and its fruit period is from August to November. The fast breeding, strong regeneration ability and short growth period are its main advantages, which mainly grows in Heilongjiang, Jilin, Liaoning, Inner Mongolia and Hebei (Zhou et al. 2008). The wormwood stem height can reach more than 1.5 m and the average diameter is about 5 ~ 9 mm, which can meet the requirements of the disposable chopsticks. Due to the wormwood is easy to collect and widely distributed, so it has obvious material and price advantage (Sun et al. 2015). It is significant to use wormwood stem rather than bamboo resources as raw material to produce the disposable chopsticks.

There are many effects for moisture content on the mechanical properties of plant stem, such as the effect of different moisture content on the mechanical strength and internal fibrous tissue is different (Ishimaru et al. 2001, Sudijono et al. 2004, Güntekin et al. 2016, Percin et al. 2016). In recent decades, the experts have conducted many studies between moisture content and wood properties, the results show that the mechanical properties will increase with the decrease of moisture content (Kojima and Yamamoto 2003, Green et al. 2007, Gorisek and Straze 2013). In 1976, the effect of moisture content on the mechanical property of wood was called mechanical adsorption deformation by Grossman (1976), it directly affects the wood strength when the load is relatively low. Yilmaz and Gokduman (2014) pointed out that the moisture content had a significant effect on the physical and mechanical properties of *Origanum onites*. Esehaghbeygi et al. (2009) believed that the bending stress and Young's modulus of canola stems decreased as the moisture content increased. Galedar et al. (2008) obtained the conclude that an increase in moisture content of stem leads to a decrease in the tensile strength, bending stress and torsional stress. Many scholars will the cause of moisture content change on wood destruction ascribe the physical mechanism, but this argument has not been endorsed by other scholars (Hanhijarvi and Hunt 1998). At present, some scholars have combined the macroscopic mechanical properties of herb and microstructures to analyze the effect of different moisture content, but there is no related content for use wormwood stem as raw materials to process disposable chopsticks, and study the relationship between wormwood stem mechanical properties and moisture content.

Due to the mechanical properties of materials largely depend on the microstructure (Hofstetter and Gamstedt 2009, Tomasz et al. 2015) so it is more intuitive to study the influence of moisture content combines the mechanical properties of wormwood stem and internal characteristics. This paper focuses on the research of wormwood stem in Northeast China, starting from testing the mechanical performance and microstructure, then obtaining their strength characteristic parameters of compression and bending according to the use of chopsticks and grinding process (it is mainly subjected to bending and compression loads). Finally, this paper summarized the effects of moisture content on internal microstructure and mechanical properties of the wormwood stem, which provides theoretical support for reasonable design multi-functional grinding machine and improve the quality of chopsticks.

MATERIALS AND METHODS

Materials and equipment

Wormwood is an annual plant. From outside to inside, the cross-section of stem include epidermis, bast fiber layer, xylem and bone marrow etc.. Here, it is mainly use the xylem to process the disposable chopsticks. In this paper, the 30 test samples of wormwood stem from Dalian in November 2014, which require straight without pest. The plant height is 1.3 ~ 1.5 m, the average branches of these plant are up to 76~90 and the leaves and branches are removed by hand. In the middle of stem (height 0.4 to 1.1 m), we will intercept the length is 210 mm to make test sample, which store in a cool ventilated place with a temperature of 15°C. The specification of sample is shown in table 1. In the test process, the moisture content is controlled in the saturated state, 40% ~ 30%, 20% ~ 30% and 20% below. Meanwhile, as can be seen from the Tab. 1, the diameter of whole batch wormwood stem became smaller from bottom to top. Therefore, it can be seen that the middle position of wormwood stem is the best processing position compared to the diameter about 5 ~ 6mm chopsticks in our daily life.

In this paper, the moisture content was tested by the SMART AR971 (moisture measuring instrument), whose measurement error is ± 2% and the reaction time is 1s. In order to obtain the changes of internal fibrous tissue with moisture content for wormwood stem, the internal structure was observed by the Ruihoge XSP-06-1600x electron microscope.

Tab. 1: Properties and specifications of sample.

Sample position	Diameter range (mm)
Bottom part	6.93~8.52
Middle part	5.32~6.90
Tip part	4.21~5.23

Test content and methods

In order to reveal the relationship between moisture content and wormwood stem mechanics characteristics, looking for the suitable grinding device for wormwood stem and judging the feasibility of wormwood stem as the disposable chopsticks, this paper analyzes the impact of moisture content on the mechanical properties of wormwood stem from the following aspects:

1) Using the MTS test suite MP2.3 universal testing machine to test the radial compression characteristics of wormwood stem under different moisture content.
2) In order to obtain the bending strength of wormwood stem, the test select 30 middle stems as samples, whose diameter and length about 6 mm and 210 mm after removing the epidermis.

Then, they were flooded up to the water saturation state and used natural drying to 30% ~ 40 %, 20 % ~ 30 % and less than 20 % moisture content. In order to determine the feasibility of herbal chopsticks, where used the MTS universal testing machine to test the bending performance. Natural drying is carried out in the outdoor wind conditions and a non-direct sunlight, whose temperature range (12 ± 3)°C, the average temperature is 14.3°C and the relative humidity range of 25 % ~ 45 %.

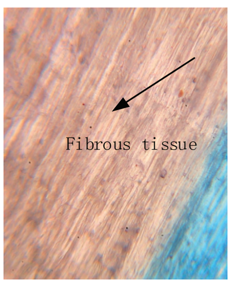
RESULTS AND DISCUSSION

Effect of moisture content on the internal fiber of wormwood stem

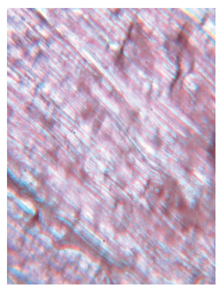
All kinds of mechanical properties of wood and stem plants are closely related to their internal microstructure characteristics (Kim et al. 2014, Zhang et al. 2015, Shang et al. 2015). The internal structure of wormwood stem is composed of cells arranged in a crisscross pattern. When the moisture content is below fibre saturation point, the change of moisture content will affect the mechanical properties of wormwood stem. Their explanation in the microscopic significance is that: the water continues to penetrate into the fibrous tissue with the increase of moisture content, which makes the distance between microcrystal, microfibril and fibre slowly increases, and the internal fibers tissue from density to thinning, meanwhile, the strength of wormwood stem will decrease with the increase of absorbed water. There are two main purposes to explore the effect of moisture content on the inner structure of wormwood stem:

(1) Looking for the suitable moisture content range of the wormwood stem as disposable chopsticks to ensure the quality.
(2) Obtaining the best grinding conditions of wormwood stem to ensure the machining efficiency and quality.

It can not only improve the quality of disposable chopsticks, but also provides the application basis for processing and storage of wormwood stem raw material by reasonably control the moisture content of wormwood stem. In order to reveal the effect of different moisture content on the microstructure of wormwood stem, we used electron microscopy to test the fibrous tissue changes of wormwood stem when the moisture content in the saturated state and the absolute dry state. Fig. 1a for the fibrous tissue of absolute dry, Fig. 1b for the fibrous tissue of saturated state. (Images are magnified 200 times)



(a) Absolute dry



(b) Saturated state

Fig.1: The microscopic detection images of wormwood stem with different moisture content

From Figs. 1a and 1b can see the changes of internal microstructure with the increase of moisture content. As Fig. 1a shown, the internal fiber structure is arranged closely and there is no fiber gap in the absolute dry condition. It has a high resistance when subjected to an external forces, so that can better improve the mechanical strength of wormwood stem. Fig. 1b clearly demonstrate the impact of moisture content on the internal fiber structure. The moisture continues to penetrate into the fibrous tissue with the increase of moisture content, which makes the changes for links and arrangement of stem internal structure and increases the distance between fibers, thereby reducing the bond strength of fiber and fiber, fiber and parenchyma cells or even cell wall between the layers.

Force analysis of wormwood stem in the grinding process

The mechanical strength of stem is closely related to cellulose mass fraction, arrangement tight loose degree and tissue structure etc.. Lignin is filled in the cellulose frame to make the cells connected to each other, it determines the strength and stiffness of stem and improves their durability (Wang et al. 2015). However, due to the bone marrow of wormwood stem has a larger proportion, the wormwood stem will lead to collapse when subjected to excessive radial load during the grinding process.

Because of the characteristics of high productivity and easy to realize automation of centerless cylindrical grinding, so this paper mainly uses the centerless cylindrical grinding as shown in Fig. 2. It carries out the outer circle processing of wormwood stem under the suitable radial pressure by adjusting the parameters of grinding wheel, guide wheel center distance, the height of bracket and other technical parameters. Here, 1 ~ 4 correspond to grinding wheel, guide wheel, wormwood stem and support plate (it mainly play a guiding role) respectively, D_k, D_t, d for the grinding wheel, guide wheel and wormwood stem diameter, H is the distance from wormwood stem center to the grinding wheel and guide wheel center, δ represents the tangent angle (grinding wheel and wormwood stem, wormwood stem and guide wheel). In the cylindrical grinding process, the wormwood stem is mainly affected by F_{t1}, F_{n1}, F_{t2}, F_{n2} and other forces, F_{t1} and F_{t2} are the tangential force of grinding wheel and guide wheel on wormwood stem, and are the radial force of grinding wheel and guide wheel on wormwood stem, all these forces meet the following relationship:

$$\begin{cases} F_{t1}\cdot\sin\theta_1 + F_{n1}\cdot\cos\theta_1 + F_{t2}\cdot\sin\theta_2 = F_{n2}\cdot\cos\theta_2 \\ F_{t1}\cdot\cos\theta_1 = F_{n1}\cdot\sin\theta_1 + F_{t2}\cdot\cos\theta_2 + F_{n2}\cdot\sin\theta_2 \\ F_{t2} = \mu\cdot F_{n2} \end{cases} \tag{1}$$

Where, μ is a dynamic friction coefficient between guide wheel and wormwood stem. The diameter d of the wormwood stem raw material is 6mm, D_k and D_t are determined by referring to the relevant specifications, here take D_k = 200 mm, D_t = 125 mm, δ is a value that changes within a certain range in the centerless cylindrical grinding process of wormwood stem. In order to ensure the quality of cylindrical grinding, it needs to keep the δ in the range of 6~7°. At this time, the change range of H is 4.2 ~ 4.9 mm, the supporting plate angle θ_1 is the angle between o_1o_3 and o_1o_2, and θ_1 is the angle between o_2o_3 and o_1o_2, the specific calculations are as follows: from Fig. 2,

$$\sin\theta_1 = \frac{2H}{D_k + d} \tag{2}$$

$$\sin\theta_2 = \frac{2H}{D_t + d} \tag{3}$$

By the Eqs. 2 and 3,

$$\frac{\theta_1}{\theta_2} \approx \frac{D_t + d}{D_k + d} \tag{4}$$

$$\delta = \theta_1 + \theta_2 = 6.5^\circ \tag{5}$$

By the Eqs. 4 and 5 can be obtained,

$$\theta_1 \approx 2.5^\circ, \theta_2 \approx 4^\circ$$

In the centerless cylindrical grinding process, the is the largest radial force of wormwood stem, it can be obtained by the Eq. (1),

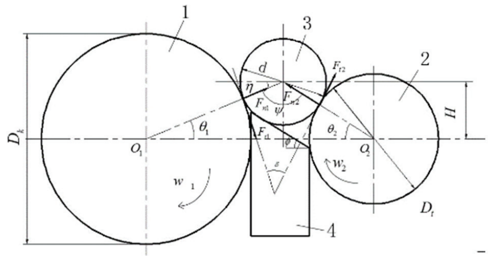
$$F_{n2} = \frac{F_{t1}}{(\mu\cos\theta_2 + \sin\theta_2)\cdot\cos\theta_1 - (\mu\sin\theta_2 - \cos\theta_2)\cdot\sin\theta_1} \tag{6}$$

According to the Eq. 6, in the centerless cylindrical grinding process, the largest radial force of wormwood stem is as follows:

$$F_{n2} \approx \frac{F_{t1}}{\mu + 0.1} \tag{7}$$

In the grinding process of wood materials, the cutting force of unit area for 90N ~ 190N, the friction coefficient between material and guide wheel is 0.2 ~ 0.5, take 0.3, according to Eq. 7:

$F_{n2} \approx 250N$



Note: ϕ is the supporting plate angle (°) η is the angle between center line of wormwood stem and o_1o_3 (°): ϕ is the angle between o_1o_3 and o_2o_3(°).

Fig. 2: The force of wormwood stem centerless grinding process.

Effects of moisture content on the mechanical properties of wormwood stem

From the previous section analysis, we can see that the proportion of wormwood stem bone marrow is larger, which will cause the stem is easy to absorb moisture and affect the strength. Therefore, it can not only increases the strength, but also provides reference basis for the design abrasive tools, prevent corrosion and improve the quality of finished products reasonably by controlling the moisture content.

The disposable chopsticks are mainly affected by the radial force of the grinding machine on the wormwood stem and the bending force during the machining process and application. In order to test the feasibility of wormwood stem as disposable chopsticks, avoid the surface collapse of stem due to improper grinding force and the breaking phenomenon in the practical application, so this paper mainly analyzes the mechanical properties of the different moisture content levels on radial compression and bending for wormwood stem.

Effect of moisture content on the radial compression performance of wormwood stem

Wormwood stem processed into the finished disposable chopsticks need to be completed by the cylindrical centerless grinding, the radial compressive force of wormwood stem is very important to the grinding quality. However, the different moisture content of stem will show different radial compression performance. In order to obtain the optimum grinding conditions, the wormwood stems of Northeast China were selected, whose diameter is about 6 mm and length for 210 cm, the radial compression characteristics of different water content were analyzed by the MTS universal testing machine. The test results are shown in Fig. 3.

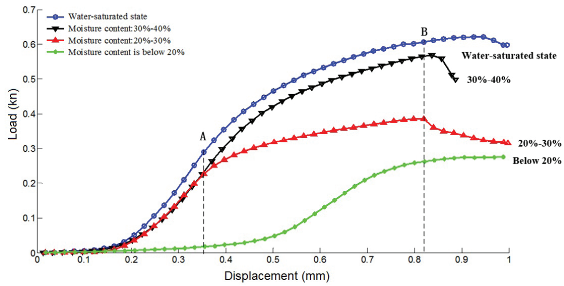


Fig. 3: The radial compression load – displacement curve of different moisture content.

From the Fig. 3, the wormwood stem of different moisture content levels show the elastoplastic characteristics under radial load. However, the curves are approximate to nonlinear characteristics from the AB to the fracture stage. The load which produces the same displacement is gradually larger with the increase of moisture content. In the radial compression test of wormwood stem xylem, the four curves have a significant change in the yield point, which show that the stem has obvious brittle fracture. The relationship between load and displacement can be approximately expressed as follows:

$$F_n = K_{n1} \cdot x_n \tag{8}$$

Where, K_{n1} is the stiffness of elastic deformation range, take $K_{n1} = 1000\ N{\cdot}mm^{-1}$.

With the increase of compression displacement, the microwave treatment material is approximately enter the reinforced plastic state after the A point, the relationship between load and displacement can be approximately expressed as:

$$F_n = K_{nl} \,.\, x_{ns} + K_{n2} \,.\, (x_n - x_{ns}) \tag{9}$$

Where, x_{ns} is the radial compression displacement corresponding to the A point, K_{n2} is the stiffness of reinforced plastic deformation range, $K_{n2} = 300\ N{\cdot}mm^{-1}$.

According to the analysis of section 3: In the cylindrical grinding process, the wormwood stem (the length of 210 mm) can bear maximum radial pressure is about 250N; According to the testing results from the Fig. 4, the minimum radial pressure of wormwood stem is 600N when the moisture content is below 20 %, which is much larger than the force of cylindrical grinding process, so it is feasible to process the wormwood stem through the cylindrical centerless grinding when the moisture content is below 20 %.

Fig. 4 is the change of maximum compressive load of wormwood stem with different moisture content.

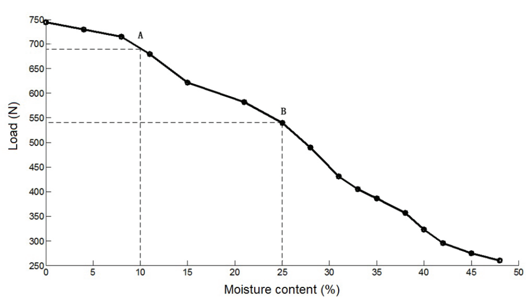


Fig.4: The curve of peak load and moisture for radial compression.

From the Fig. 4, we can clearly see the relationship between the moisture content variation and the compressive load. From the origin to the B point, the moisture content is gradually increasing and the maximum compressive load of wormwood stem is constantly decreasing, which demonstrates that the moisture has a softening effect on wood.

Effect of moisture content on the bending properties of wormwood stem

Due to the disposable chopsticks are mainly influenced by the bending force during the actual usage. Although the chopsticks will not be broken when applying a certain bending force, because of the insufficient rigidity and large deformation will also affect the normal actual usage. Therefore, in order to ensure the normal usage of chopsticks, the deformation must be limited within a certain range, which should satisfy the stiffness requirements.

In this paper, the curve of maximum bending stress of wormwood stem under different moisture content as shown in Fig. 5.

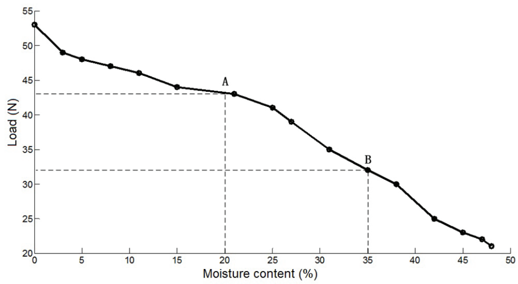
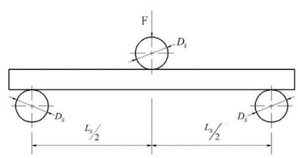


Fig.5: The curve of peak load and moisture for bending.

From the Fig. 5, we can see that the bending strength of wormwood stem is gradually decreased with the increase of moisture content from the origin to the B point. The bending strength of wormwood stem is the maximum and the numerical value is basically maintained when the moisture content is below 20%. However, the peak load is sharply decrease when the moisture content is more than 35%.

Through the typical situation for clip vegetables, remove the meat from the bones and split glutinous rice products to analyze the bending load of chopsticks: splitting glutinous rice products have the maximum bending load, its value is 6 ~ 10N. In practical application, in order to ensure the rigid requirements of chopsticks, using the three points bending loading method of simple supported beam structure to test the bending and stiffness characteristics of wormwood stem under different moisture content, the specific test method is shown in Fig. 6. The wormwood stem sample take the diameter of 6mm, the length of 210mm and the support span is 120mm.



Note: F is the applied load, (N): D_k is the platen diameter, (mm); D_s is the supporting point diameter, (mm).
Fig.6: The bending property loading ways of wormwood stem.

The elastic modulus can be regarded as an index to measure the difficult degree of material elastic deformation, the larger value indicates that the stress of material elastic deformation is greater, that is the elastic deformation is smaller. During the test, the stem bending loads under different moisture content were measured by universal testing machine. According to the load - displacement curve data in Fig. 7, the elastic modulus of stem were obtained by the Eq.10:

$$E = \frac{Fl^3}{48WJ} \tag{10}$$

where: F - the concentrated load in the middle of the beam (N),
l - the effective length of beam (mm),
W - the deflection of beam central,
J - the inertia moment of central axis (mm^4).

For the wormwood stem, it can be seen as solid circular tube, so,

$$J = \frac{\pi D^4}{64} \tag{11}$$

Where, D is the diameter of stem (mm).
Thus,

$$E = \frac{Fl^3}{48WJ} = \frac{64Fl^3}{48W\pi D^4} = \frac{4Fl^3}{3W\pi D^4} \tag{12}$$

According to the relation curve between moisture content and the maximum peak load in Fig. 5, the specific dates of the moisture content above 35% and the moisture content below 20% were calculated by the Eq. 12:

When the moisture content is below 20%:

$$E = \frac{Fl^3}{48WJ} = \frac{64Fl^3}{48W\pi D^4} = \frac{4Fl^3}{3W\pi D^4} = 1785.6MPa$$

However, when the moisture content is more than 35%:

$$E = \frac{Fl^3}{48WJ} = \frac{64Fl^3}{48W\pi D^4} = \frac{4Fl^3}{3W\pi D^4} = 1006.5MPa$$

It can be seen from the above data, the elastic modulus of moisture content below 20% is higher than the moisture content more than 35%, which shows that the bending resistance of wormwood stem is better when the moisture content was below 20%.

With the loading time increasing, the pressure of stem gradually increased until the stem fracture, recorded the maximum pressure $F_{\max}$. At this time, the wormwood stem has fully entered the plastic stage, according to the relationship of plastic limit bending moment is about 1.7 times as much as elastic limit bending moment, the stem stiffness was calculated by Eq. 13 :

$$S = \frac{M_{\max}}{W_Z} = \frac{\frac{F_{\max} l}{4 \cdot 1.7}}{\frac{\pi D^3}{32}} = \frac{8F_{\max} l}{1.7 \cdot \pi D^3} \tag{13}$$

where: M_{max} - the maximum bending moment (N·mm),
W_z - the section coefficient (mm^3),
F_{max} - the maximum force of stem (N).

The specific data into Eq. 13, the stiffness is 35.8 N·mm^{-1} and 20.8 N·mm^{-1} respectively when the water content is about 20 % and 35 %. The results show: the elastic modulus and the stiffness of wormwood stem are increased, the water content had significant influence on the change of wormwood inner fiber structure. In the practical application process, the moisture content can be controlled below 20 % to the maximum extent to meet the requirements of bending and deformation of chopsticks. Meanwhile, the wormwood stem has a small bending force when the moisture content is more than 35 %, which can be harvested at this time to reduce the cutting force and obtain the best wormwood stem resource.

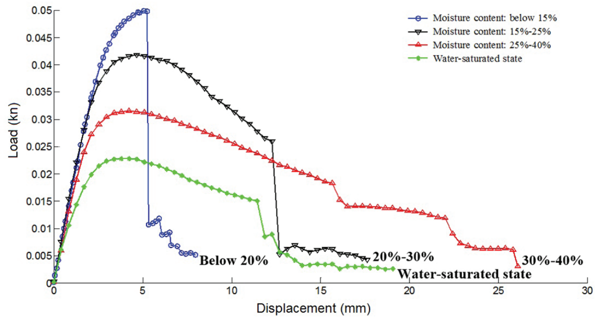


Fig. 7: The bending load - displacement curve of different moisture content.

It can be seen from Fig. 7 the wormwood stem showed an elastic-plastic characteristic under different moisture content. With the load applied, each curve has a linear range change region, and then shows some nonlinear characteristics. The stem is slowly collapse till fracture when the load increases to the maximum load; When the moisture content is smaller, whose characteristics more close to the brittle material, and the flexibility is weakened and easy to fracture; On the contrary, when the moisture content is larger, its characteristic is similar to the plastic material with good flexibility and not easy to break.

CONCLUSIONS

This paper combined the theory and the actual test to reveal the influence of moisture content on fiber structure and mechanical properties of wormwood stem, the research results are as follows:

(1) The moisture content has a significant influence on the fiber structure of wormwood stem. Inner fiber structure of wormwood stem is changed from density to sparse and the distance between the fibers becomes larger with the increase of water content.

(2) The radial compressive strength of wormwood stem will decrease with the increase of moisture content, but it can enough to bear the radial load of wormwood stem in cylindrical centerless grinding. Relative to the absolute dry state, the wormwood stem of saturated state can withstand radial compressive load is reduced by 450N. In the practical application process, the minimum radial force of wormwood stem is 600N, which is enough to satisfy the maximum radial compressive force (about 250N) of the cylindrical centerless grinding process.

(3) The bending strength of wormwood stem is gradually decreased with increase of moisture content. When the moisture is saturated state, the bending strength of wormwood stem is reduced from the absolute dry state (53N) to the saturated state (21N). In order to increase the stiffness and toughness, the moisture content of wormwood stem can be controlled

in about 20 %, where the bending strength is 41N much larger than the normal use of chopsticks about 6-10N.

The research results show that using the wormwood stem as raw material to process the herb chopsticks by the cylindrical centerless grinding has the feasibility of manufacture and application. Reasonably control the moisture content of wormwood stem is crucial for improve the quality of the herbal chopsticks. The moisture content of about 20 % is the reasonable level for processing disposable chopsticks.

ACKNOWLEDGMENT

This work was financially supported by the major projects of science and technology innovation project in Liaoning province (201301002) and the excellent talent cultivation project in Liaoning province (2014028012).

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