Experimental Analysis of the Relationship Between Stem Diameter with Physical and Chemical Characteristics and Mechanical Characteristics of Plant Stem for Slope Protection

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Abstract: *In order to explore the relationship between the stem of slope protection plant and its mechanical, physical-chemical characteristics, the Bidens pilosa L. and Ophiopogon bodinieri Levl. were selected for sampling in Baoxiang river basin. The failure load and bending strength of the plant stem were obtained by applying vertical load in the middle of the plant stem, the mechanical indexes were analyzed by mathematical statistics, and the change interval of these indexes were obtained. The relationship between the plant stem diameter and the content of cellulose in the plant stem was analyzed. The results showed that the failure load and bending strength were increased with the increase of stem diameter, and the failure load and bending strength of Bidens pilosa L. were higher than those of Ophiopogon bodinieri Levl. The cellulose content of the plant stem was positively correlated with plant stem diameter.*

Keywords: *Plant stem, Failure load, Bending strength, Cellulose*

1. Introduction

Engineering, construction, gully erosion, and shallow landslides have led to a large amount of soil erosion. To reduce soil erosion, measures such as building intercepting ditches and mortar rubble masonry pavement are often used to protect the slope, yet these methods destroy the good conditions needed for vegetation growth and have an adverse effect on the original plants growing on the slope [1]. Under the abrasiveness of running water, the above-ground stems and leaves of plants can intercept rainwater and reduce water's flow rate, thereby lowering the water's kinetic energy and can reduce runoff soil erosion[2], therefore plants can hinder soil erosion [3]. The combination of traditional civil engineering measures and vegetation protection plays an important role in preventing and controlling slope soil erosion and ensuring slope stability.

Regarding the influence of plants on slope soil fixation and erosion resistance, some researchers believe that, by covering the ground surface, the above-ground part of plants increase the surface roughness, block, decompose, and decrease near-surface wind speed, thereby effectively reducing wind speed, and weakening the separation and handling of grains incurred by wind, and controlling wind erosion [4,5]. In addition to being cover vegetation, there are several influencing factors for the soil-fixing performance of plants that are closely related to biomechanical properties such as the plant base stem matter density, base unit volume biomass [6], and the plant branches' resistance to bending, as well as the distribution pattern of plants, etc.[7]. This research systematically studied the mechanical characteristics and cellulose content of two common typical slope protection plants on the Baoxiang River slope in Kunming and explored the mechanical characteristics of the plant stem for slope protection, and the relationship between the stem diameter and cellulose content, to make effective plant species selection and allocation for the biological measures needed for river channel environmental protection works and for providing a theoretical basis for plant selection to secure soil from a river channel and slope protection.

2. Research Methods

2.1. Overview of the Research

The research area was Baoxiang River Basin in Kunming City (geographic coordinates: 102°41'—102°56' east longitude and 24°58'—25°03' north latitude), featuring a typical subtropical humid monsoon climate with uneven rainfall distribution. The rainy season is primarily from June ~ October, accounting for 80% of the annual rainfall, the annual mean temperature is 14.7℃, and the soil type is primarily red soil. The dominant plants in the research area were Bidens pilosa L. and Ophiopogon bodinieri Levl. on different slopes, the time in the light, light intensity, and angle of the light on the plants varied, which affects photosynthesis and thus the plant's growth[8]. The shady slopes had relatively higher soil moisture, and sufficient nutrients required by the plants, thus the plants on the shady slope were growing better. Therefore, for this experiment, Bidens pilosa L. and Ophiopogon bodinieri Levl. from shady slopes were selected for research.

2.2. Test Data

2.2.1. Stem Strength Bending Index

At test site 1a, dominant plants for slope protection that were growing well without diseases, insects, or pests were selected. Some studies have shown that the length of the first elongated node of the plant has a non-negligible effect on lodging resistance[9]. Therefore, during testing, the plant stems 0~20cm from the root of the plant were cut by scissors, put into sealed bags, and numbered accordingly. Then they were brought back to the laboratory and stored in a refrigerator at 4℃, and the root bending strength test was completed within 24 hours. For the diameter of the plant stem, the two points before and after the break of the plant stem were measured by a caliper and the mean of the two measurements was taken as the diameter of the break. The length L of the stem during the bending strength test was adjusted according to the diameter D of the stem[10]. Under the water scouring, the above-ground part of the plant could be regarded as a cantilever structure with the fixed end on the ground[11], but for the bending mechanical characteristics bending test of the plant stem a three-point bending method with a concentrated load at a central position on the stem was applied[12]. In this experiment, it was assumed that the end support of the plant stem is hinged. With different loads acting on the stem, the bending moment generated on the stem varied. According to material science, when the load is applied to a central position on the stem, the bending moment value generated is at a maximum. Therefore, a vertical load was applied to a central position on the stem during the test. The load was applied in the middle of the stem (figure 1).

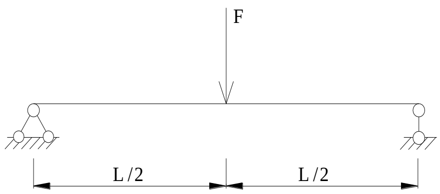

Figure 1: Schematic diagram of the plant stem when under a load.

Bend strength can characterize the performance of plant stems to resist lodging. Assuming that the stem section of the plant is round, according to the theory of material science, the formula for the bend strength of a plant stem is as follows:

$$\sigma = \frac{M}{W} = \frac{FL/4}{\pi D^3/32} = \frac{8FL}{\pi D^3} \tag{1}$$

Where: σ: Bend strength of plant stem (MPa); M: Maximum bend moment of a plant stem ($N \cdot mm$); W: Bend resistance cross-section coefficient of a plant stem (mm^3); F: Maximum load on plant stem (N); L: Length of plant stem at test time (mm); D: Diameter of the plant stem (mm). The stem diameter was measured with a gauge caliper.

2.2.2. Determining the Stem Cellulose

The plant stem was cut with scissors at 20cm above the plant root, the lower part of the plant stem

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was taken as the sample and then put into the 65℃ oven. The sample was dried to a constant weight, and then the dried sample was pulverized with a grinder. Refer to the literature for the determination method of cellulose content in plant stems.

2.3. Test Data Analysis Method

The maximum failure load F, bend strength σ, cellulose, and lignin content of the stem were recorded in the test. The test data was fitted by CurveExpert to get the fitting equation. Origin software was used for data analysis and graphics rendering.

3. Test Results

3.1. Bend Strength of Plant Stems

The test results of the stem bend strength for the two slope protection plants, i.e. Bidens pilosa L. and Ophiopogon bodinieri Levl, are shown in Table 1. According to Table 1, the mean stem diameter of the two plants was 1.88~5.14mm, and the maximum failure load was 4.61~147.98N. The bend strength of Bidens pilosa L. was greater than that of Ophiopogon bodinieri Levl, which indicates that Bidens pilosa L. is less prone to fracture and damage when subjected to external loads.

Table 1: Mechanical characteristic of the stem.

Plant	Mean diameter/ mm	Maximum failure load/ N	Bend strength/ MPa
Bidens pilosa L.	4.05 ± 0.82	68.07 ± 42.73	188.70
Ophiopogon bodinieri Levl.	2.82 ± 0.58	29.38 ± 26.79	156.01

Note: The relevant data in this table are mean values ±standard deviation.

The probability distributions of stem diameter, failure load and bending strength were recorded, according to the recorded data, the stem diameters of the two plants are relatively dispersed. The failure load of Bidens pilosa L. was primarily 20~100 N, and that of Ophiopogon bodinieri Levl. was 0~20 N. The bend strength of Bidens pilosa L. was primarily 100-200 MPa, and that of Ophiopogon bodinieri Levl. was 0-100 MPa.

The stem diameters of the two plants were fitted with the test data of load failure and bend strength, and the equation is shown in Table 2. The relationship between the load failure, bend strength, and stem diameter of Bidens pilosa L. can be espressed with a power function, and the relationship between the load failure, bend strength, and the stem diameter of Ophiopogon bodinieri Levl. can be expressed with an exponential function. The test data and the fitting data are plotted in figure 2 and figure. 3. According to figure 2 and figure 3, the load failure and bend strength of the two plant stems are positively correlated with the stem diameter. As the stem diameter increases, the load failure and bend strength also increase, which is similar to the conclusion of the relationship between the stem diameter and bend strength of plants in the loess hilly and gully areas as studied by Xu Haiyan[13].

Table 2: Equations for stem diameter with load failure and bending strength.

Plant	Stem diameter and failure load	Stem diameter and bending strength
Bidens pilosa L.	$F = 0.86D^{3.05}$	$\sigma = 41.55D^{1.08}$
Ophiopogon bodinieri Levl.	$F = 0.28e^{1.53D}$	$\sigma = 13.67e^{0.83D}$

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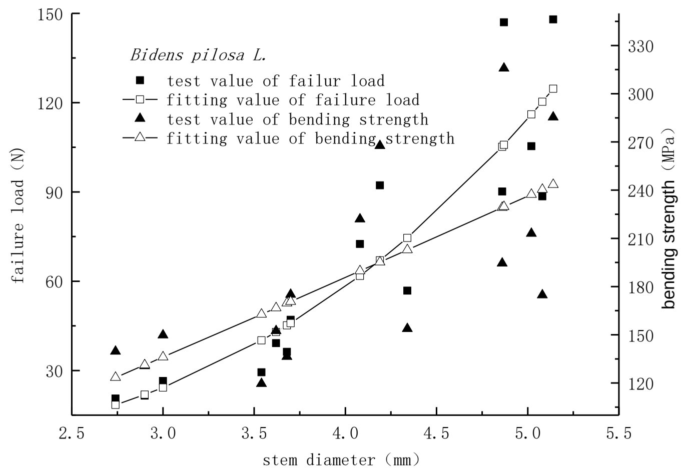

Figure 2: Relationship between the stem diameter of Bidens pilosa L. with failureload and bend strength.

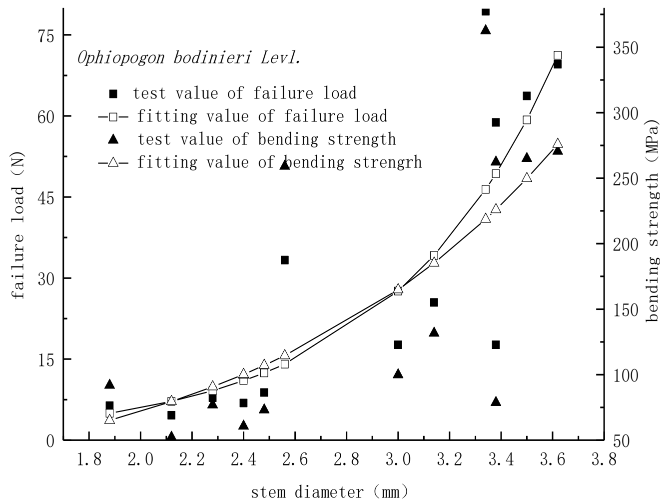

Figure 3: Relationship between the stem diameter of Ophiopogon bodinieri Levl. with failureload and bend strength.

3.2. Relationship Between Stem Cellulose Content and Stem Diameter

The cellulose content of the two plants was compared (see Table 3). The results showed that the cellulose contents of the two plants were 28.79%~37.91. The cellulose content of Bidens pilosa L. was higher than that of Ophiopogon bodinieri Levl..

Table 3: Cellulose content from the stem.

Plant	Cellulose/%
Bidens pilosa L.	33.93 ± 2.79
Ophiopogon bodinieri Levl.	33.41 ± 2.40

The stem diameters and cellulose contents of the two plants were expressed and solved using the equations shown in Table 4.

Table 4: Equation for stem diameter with cellulose content.

Plant	Stem diameter and cellulose
Bidens pilosa L.	$y = 6.13D^{0.978}$
Ophiopogon bodinieri Levl.	$y = 17D^{0.569}$

The experimental data and fitting data of the stem diameter and cellulose content were plotted in figure 4, which shows that as the diameter of the plant stem increases, the cellulose content increases accordingly.

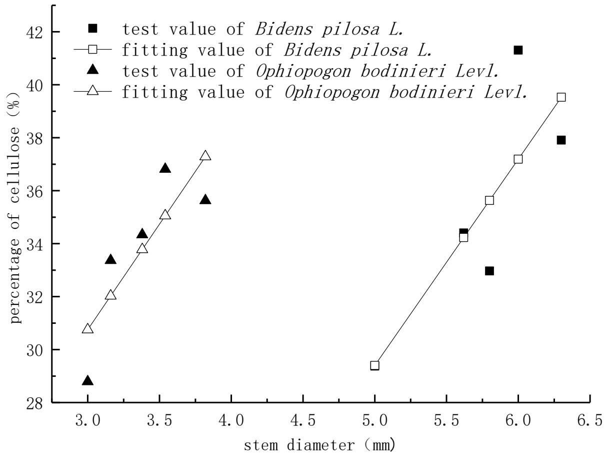

Figure 4: Relationship curve between the stem diameter of Bidens pilosa L、Ophiopogon bodinieri Levl. and cellulose percentage.

4. Conclusions

The stem strength of a plant is a key factor affecting the lodging and stem bending[14]. As shown in Fig. 2 - Fig. 3, different stem diameters lead to different mechanical properties. For example, as for Bidens pilosa L., when the diameter of the stems increases from 2.74mm to 5.14mm, the failure load of stems increases from 20.58N to 147.98N, and the corresponding bending strength increases from 139.68MPa to 285.41MPa. The greater the load failure of the stem, the greater the corresponding bend strength. This is similar to the research conclusions found in the consulted literature[15]. As shown in Fig. 4, as the diameter of the stem increases, the cellulose content in the stem gradually increases. Based on the equation of stem diameter, bend strength, and cellulose in Table 2 and Table 4, the relationship between the bend strength σ and cellulose content y was established as $\sigma = 5.48y^{1.09}$, which indicates that the more cellulose content in the plant stem, the greater the load failure of the stem is in terms of mechanical properties. This is because cellulose is the main component of the plant cell wall, which is a skeleton composed of microfibrils polymerized by long-chain macromolecular cellulose, a structure similar to "reinforced concrete"[16]. The skeleton strengthens the mechanical strength of the plant stems and provides mechanical support to the plant stem, which indicates that the cellulose content has a significant impact on the stem's mechanical properties[17].

A plant stem's mechanical and biological properties for slope protection in Baoxiang River in Kunming were studied. The force analysis of the stems showed that plants would be prone to bending under the influence of natural conditions such as wind and rain. The diameter of the plant stem correlates positively with the load failure and bend strength of the stem, which indicates that the stem diameter is closely related to the mechanical strength of the stem. The paper conducted an experimental analysis on the plant stem diameter and load failure, bend strength, and cellulose content. The relationship between plant stem mechanical properties and biochemical properties should be established in a follow-up study to better guide the selection of plants for river slope protection.

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