THE EFFECT OF PH AND SOIL MOISTURE ON THE GROWTH AND STRENGTH OF BAMBOO

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ABSTRACT

Bamboo is a fast-growing, hardy alternative to traditional sources of lumber, making its cultivation especially important for nations with rapidly developing infrastructure. The best soil water concentration and pH for growing D. sanderiana, a woody plant similar to bamboo, was determined by growing three groups of 6 stalks, each at specified soil moisture levels with water of known pH. The stalks were given several days to grow, after which change in height and mass and effective Young's modulus under compression and three-point bending were measured. ANOVA tests yielded statistically significant better growth for neutral pH and 50% water concentration and no differences in strength between any groups with 95% confidence. There was a statistically significant positive linear correlation between change in mass and water concentration, with slope of approximately 19mg.

INTRODUCTION

Construction is one of the oldest and most important industries in human history, as people have always needed to build structures for shelter and industry. In the modern day, construction has a global economic engagement of almost $7.5 trillion, which is an estimated ten to thirteen percent of global GDP [1]. The importance of construction is directly connected to the significance of silviculture—agriculture specifically concerned with the production of lumber. Construction activity is rapidly growing across the world; this is most evident in developing nations [1]. As developing nations rapidly build up infrastructure, they consume large amounts of lumber—unfortunately, this demand is typically addressed by cutting down ecologically important old growth forests. To alleviate this environmental catastrophe, hardy, fast-growing woody plants must be explored that can supply this lumber such that these societies can quickly cultivate and harvest a sustainable source of lumber. One incredibly promising candidate is bamboo, a resilient woody plant that can grow up to multiple feet per day [2].

Using bamboo as an alternative lumber supply requires maximize the speed of growth and the mechanical strength of bamboo. Having identified the ideal growth conditions for each species of bamboo enables the best species to be selected for each geographic region, and what cultivation practices to use. Given this, the water concentration and pH that yields the strongest and fastest growing Dracaena sanderiana plants was investigated. D. sanderiana has a very similar internal structure to bamboo, making it a good stand-in. The methods of the experiment can be repeated on a larger scale for various species of bamboo.

In order to determine the effects of pH and water concentration on the growth and strength of dracaena sanderiana, stalks of D. sanderiana were grown using water of various pHs and at a variety of soil water concentration; the stalks were watered by an electronic control system that ensures the target water concentration is maintained. After being allowed to grow in these conditions, the change in mass and height and effective Young's moduli in bending and compression were calculated and compared across the different pH—water concentration groups to determine if there were differences and relationships between the conditions and the growth and strength. The results will be compared to the informal wisdom that D. sanderiana prefers an abundance of water at near-neutral pH.

BACKGROUND

PRIOR RESEARCH INTO BAMBOO STRENGTH

Almost all prior research on the strength of bamboo centers on glued laminated bamboo lumber (GLBL), in which long, rectangular strips of bamboo are layered and glued together specifically to be used as structural members [3]. The creation of these building materials is still an area of active research, with new formulations consisting of multiple species and different resins [3] and advanced treatments [4] all enabling higher strength. There have been demonstrated advantages of GLBLs, such has higher stiffness in tension and bending than Douglas fir, a common construction wood [5], and generally higher strength-to-mass ratio than steel, aluminum alloy, cast iron, concrete, and traditional timber [6].

Minimal research has been done into the strength of raw bamboo stalks because the cylindrical geometry and proneness to splintering makes a challenging building material in its natural form. Furthermore, there is a wide variation in material properties of bamboo are heavily dependent on the radial position of the material [7]. That being said, existing work in the mechanical testing of raw bamboo have yielded stress-strain curves in 3-point bending that suggest bamboo does behave elastically for small deformations [8].

PRIOR RESEARCH INTO SOIL CONDITIONS FOR BAMBOO

Past research on the effect on soil conditions of bamboo have centered around the effects of the addition of synthetic chemicals and heavy metals to the soil [9] [10] [11]. Research on the effects of soil moisture or pH, however, is very rare. Examples include investigating how soil moisture affects respiration at the bamboo's roots [12]; however, this study was observational in nature, with respiration and soil moisture simply being being measured across various outdoor plots of land. A review of the literature suggests that no past research has been done in which the soil moisture level or pH are actively controlled—this makes sense; bamboo grows very quickly in the regions and climates that it is native to, so the motivation to manipulate growth conditions has probably been historically minimal.

MECHANICAL PROPERTY TESTING

For the mechanical property testing, the bamboo stalks will be subjected to axial compression and 3-point bending. The Instron Universal Testing Machine generates a force-displacement curve, in which the small-displacement regime will exhibit a linear relationship, reflecting the material's elastic behavior. In compression, the effective Young's modulus can be determined in accordance to Equation 1, knowing the slope m of the force-displacement curve, the diameter d of the stalk, and the length L_0 of the compression sample.

$$E_{comp} = m \cdot \frac{4L_0}{\pi d^2}. \tag{1}$$

In three-point bending, calculating effective Young's modulus is a similar process. Equation 2 describes how to calculate the effective Young's modulus in three-point bending given the slope m of the force-displacement curve, the diameter d of the stalk, and the distance L between the two support points.

$$E_{bend} = m \cdot \frac{4L^3}{3\pi d^4}. \tag{2}$$

EXPERIMENTAL DESIGN

In order to determine the effects of pH and water concentration on the growth and strength of dracaena sanderiana, stalks of D. sanderiana were grown using water of various pHs and at a variety of soil volumetric water concentrations (VWC). The experimental setup was constructed to grow a trial set of bamboo stalks using water of a specified pH, with each trial set split into groups that were all grown at different, specified VWCs. The VWC was maintained at the desired target using an electronic control system with moisture sensors and water pumps. Both prior to and following the growth period, the mass and height of each stalk were measured, allowing the growth to be quantified. Additionally, each stalk was loaded under compression and 3-point bending using an Instron Universal Testing Machine (UTM), generating force-displacement curves that enable the calculation of the effective Young's Modulus.

GROWTH AT SPECIFIED WATER CONCENTRATION AND PH

The pH of the water was measured using the HM Digital Water Quality Tester (COM-300), and the VWC was measured using the Vernier Soil Moisture Sensor (SMS). However, given an estimated growth rate of 1 inch per week, the stalks were be grown for a period of 8 days—without additional watering during that time frame, the soil moisture would have decreased over time due to uptake and evaporation. Thus, the soil's moisture was monitored, water was periodically added to maintain a consistent VWC. To do this, the experimental setup depicted in Figure 1 has been designed.

In a given trial, all of the water being used was stored in the tank—thus, all plants being grown simultaneously were grown with water at the same pH. However, six individual pots containing 3 stalks of D. sanderiana each were be coupled with a completely buried, horizontally-oriented soil moisture sensor and water pump, such that the control system was able to monitor each pot independently and pump water to maintain the VWC at a specified set-point. The soil moisture sensors interface with the Vernier Arduino shield (ARD), which allowed the Arduinos to read the VWC. Each pair of pots is is assigned to a single Arduino can interface with the pump and soil moisture sensor corresponding to each pot. Each Arduino runs a script that reads and logs to an SD card the VWC of each pot every five minutes; if it is more than 2% below the target, water was pumped until the soil reached the desired VWC. To activate/deactivate each water pump, each Arduino interfaced with a MOSFET for each pump, which routed power to the water pump when the Arduino supplied a digital high to it.

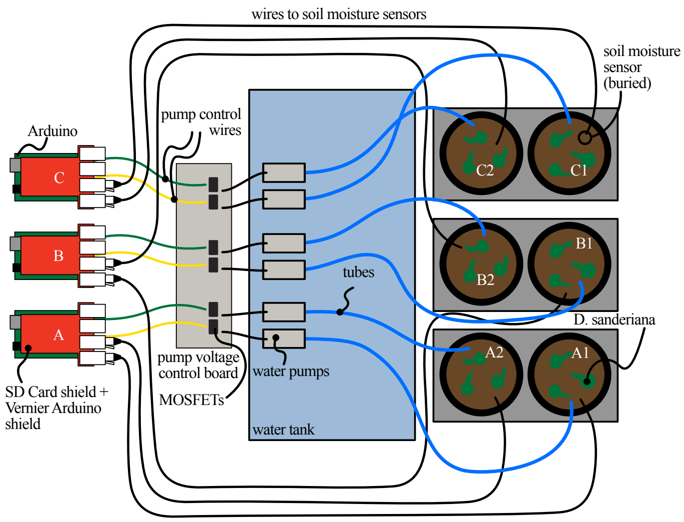

Figure 1: Diagram of experimental setup that maintains soil moisture concentration. Each of the six plant pots on the left contains three bamboo stalks planted in soil. Each pot is coupled with a fully buried Vernier Soil Moisture Sensor and a water pump. Each pair of pots is logically grouped into trays A, B, and C, with one Arduino independently controlling both water pumps and reading from each soil moisture sensor. Soil moisture sensors are read via the Vernier Arduino Shield, and the pumps are controlled by writing digital output voltages to the MOSFET that directs power to each pump.

Two trial were conducted: one with distilled water and one with tap water and, measured to have pH 7.2±0.1 and 9.3±0.1, respectively. In each trial, trays A, B, and C had target volumetric water concentrations of 20%, 25%, and 50%, respectively. The VWC over the course of the growth period for the pH 9.3 trial is shown in Figure 2, demonstrating that the control system did maintain the actual water concentration to within ±2% of the desired VWC. The factory calibration for the pH sensor and soil moisture sensors were used.

EVALUATION OF GROWTH AND MECHANICAL PROPERTIES

Once the D. sanderiana completed their 8-day growth period, they were removed from the soil to have their growth and strength evaluated. Prior to planting, each stalk was numbered, and the pot to which it is planted is recorded; the mass of each stalk was measured using the Jewelry Scale (SCALE-100G) with ±1mg uncertainty, and 9 height measurements are taken using the Mituyo Electronic Calipers with ±0.01mm uncertainty. After growth, these sets of measurements are made again.

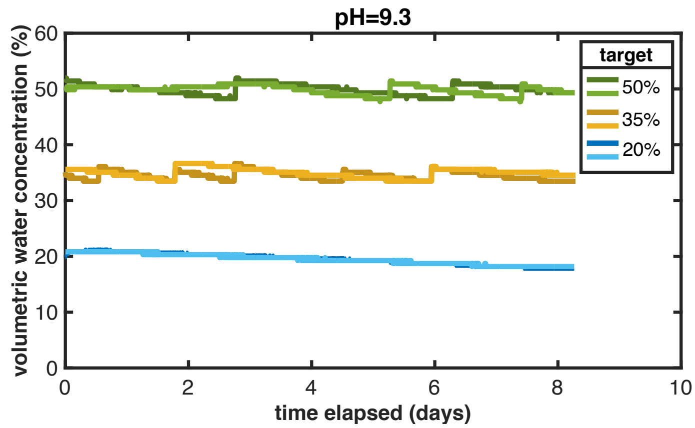

Figure 2: Volumetric water concentration in each pot at pH=9.3 as a function of time. Each trace represents one of the pots, in accordance with the legend. For instance, dark blue corresponds to one of the two pots with 20% volumetric water concentration. These data show that the pots were kept within 2% of the desired VWC.

For the mechanical property testing, each stalk was subjected to two tests on the Instron Universal Testing Machine (UTM): 3-point bending and compression. The samples were prepared and tested according to Figure 3, with a short segment being isolated for compression testing and the remainder of the stalk being subjected to three-point bending.

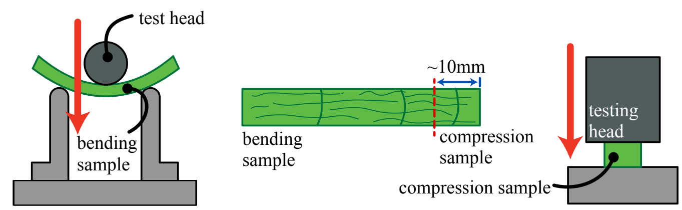

Figure 3: Diagram of the testing procedure for each stalk. A small segment is isolated for compression testing, and the remainder of the stalk is subjected to three-point bending.

As dictated by Equations 1 and 2, calculation of the effective Young's moduli require two sets of procedural measurements to be made of the stalks prior to mechanical testing. Both effective moduli require diameter; thus, for each stalk, calipers were used to take 12 diameter measurements along the length of the stalks —these data are shown in Figure 4. Furthermore, the compressive modulus requires the sample height. For the ~10mm compression sample sawed off of the bottom of each stalk, 12 measurements of the sample height were taken using calipers; these data are shown in Figure 5.

These samples were placed in the UTM and compressed at a rate of 0.75mm/min for a distance of 2mm. The longer sample was placed in the UTM and bent at a rate of 3.0 mm/min for a distance of 15mm. using the three-point bending stand with the two prongs spaced 12 ± 0.02 mm apart. In both three-point bending and compression, the UTM moved the testing head down at a constant linear speed, recording the force measured by a load cell and the vertical displacement at a rate of 2 samples per second.

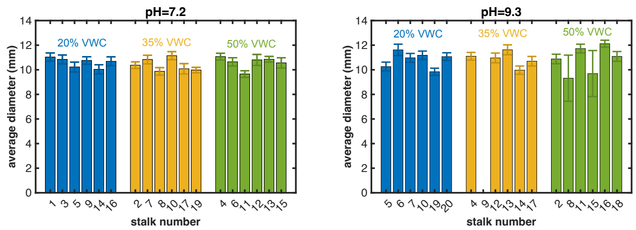

Figure 4: Average of the 12 diameter measurements taken along the length of each stalk, used to calculate the effective Young's modulus in both compression and bending, as prescribed by Equations 1 and 2, respectively.

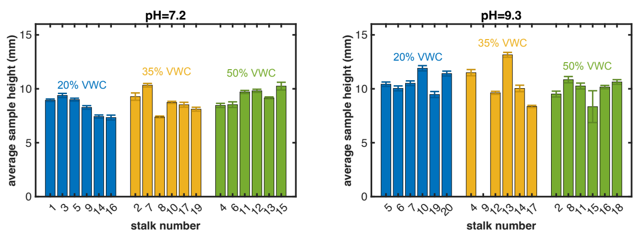

Figure 5: Average of the 12 height measurements taken of the short samples sawed off of the bottom of each stalk, used to calculate the effective Young's modulus in both compression as dictated by Equation 1.

RESULTS AND DISCUSSION

CHANGE IN MASS

The first analysis is the change in mass. As described earlier, the mass was measured for each stalk both prior to and after the growth period. The calculated differences in mass for each stalk are shown in the Figure 6. Overall, almost all plants seemed to lose mass. This is likely because the other growing conditions were not ideal. The experiment was conducted in an air-conditioned room with always-on artificial lighting with the intent of keeping the other variables that influence growth (namely temperature and light) consistent. However, the temperature of the room was not controllable, and it is likely that it was too cold and there was not sufficient light. However, since the conditions were identical for all of the samples, comparisons between the different groups can still be made. For both pH trials, there appears to be better growth in the higher VWC groups.

The changes in mass over all of the stalks for each of the VWC groups within both trials were then averaged, yielding the plot in Figure 7. In line with the observations of the individual stalk data, the mean change in mass decreased with increasing water concentrations, with the uncertainty bounds for both pH's 50% groups extending into the positive change in mass region. The high variation in mass changes for the pH 9.3 data, however, contributed to large uncertainty bounds. Variation in individual stalk growth is to be expected, though, and with the relatively small number of stalks per group, this evidently expanded the uncertainty bounds by a significant amount. The ANOVA analysis yielded that, at a 95% confidence level, there was a statistically significant difference between the mean change in mass of the 20% group and 50% group.

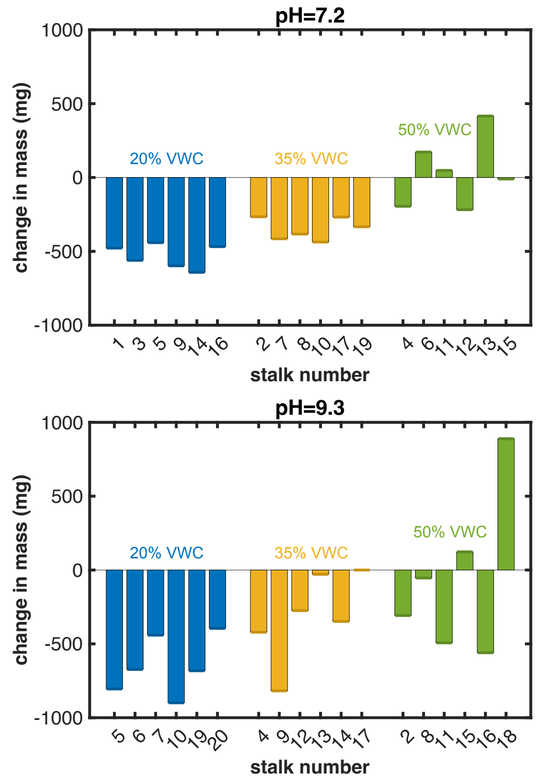

Figure 6: Change in mass for each stalk over the course of the growth period, grouped by VWC. Data for the 7.2 pH trial shown on the left, and 9.3 pH trial on the right. Error bars are not shown due to the high precision of the mass measurements. In both trials, positive growth was only witnessed in the 50% VWC group, with the 35% group seemingly performing slightly better than the 20% group.

Finally, different types of fit were attempted on the data (polynomial, power, etc), and a linear fit was selected. For both trials, the data were plotted and fit with VWC as the independent variable and average change in mass as the dependent variable as shown in Figure 8. The linear fit was statistically significant, with a visual inspection of the residual plot yielding no noticeable trend. The pH 7.2 data yielded a slope of 18.8 ± 6.3 mg and an intercept of -930 ± 240 mg. The pH 9.3 data yielded a slope of 19 ± 15 mg and an intercept of -1000 ± 500 mg. While the uncertainties were large, the results were statistically significant, confirming that there indeed is a positive correlation between VWC and change in mass.

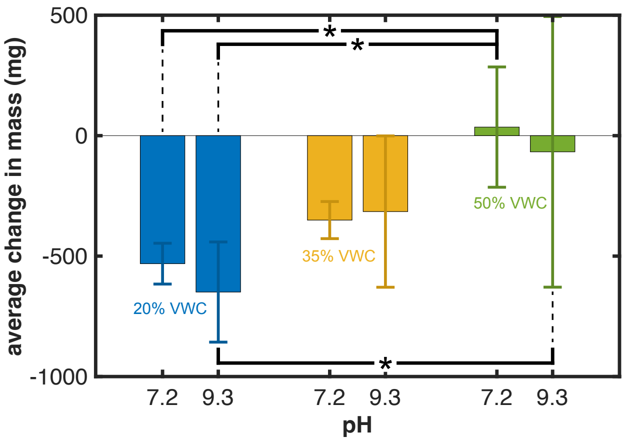

Figure 7: Average change in mass for all stalks in each VWC group over the course of the growth period. For both trials, there is an increasing trend in the mean change in mass, with the 50% group having positive growth within its uncertainty bounds. An ANOVA analysis performed with 95% confidence yielded that the pH 7.1—50% VWC was greater than both 20% VWC groups, and pH 9.3—50% VWC was greater than pH 9.3—20% VWC. Statistically significant differences denoted with —*—.

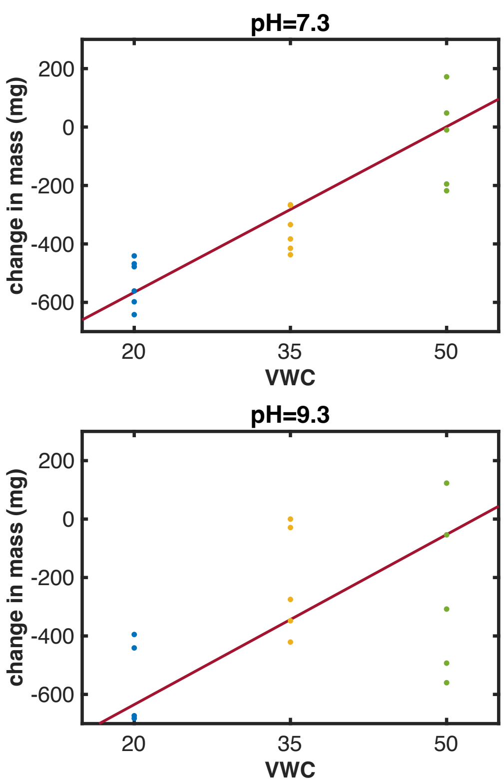

Figure 8: Change in mass for each stalk trials plotted against VWC for both pH trials. Linear fits in the form of y=Ax+b yielded pH 7.2 data yielded A=18.8 ± 6.3 mg and B=-930 ± 240 mg for the pH 7.2 data, and A=19 ± 15 mg and B=-1000 ± 500 mg for the pH=9.3 data.

CHANGE IN HEIGHT

Next, change in height is analyzed. Before and after growth, each stalk of bamboo had its height measured 9 times and averaged. Then, the differences between the averaged height before and after growth for each bamboo were calculated, yielding the data in Figure 9. Similarly to mass, almost all the bamboo lost height with the exception of two stalks in the 50% group. However, with the exception of larger changes in height for the pH 9.3—35% VWC group, the stalks generally seem to have decreased in height by roughly the same amount.

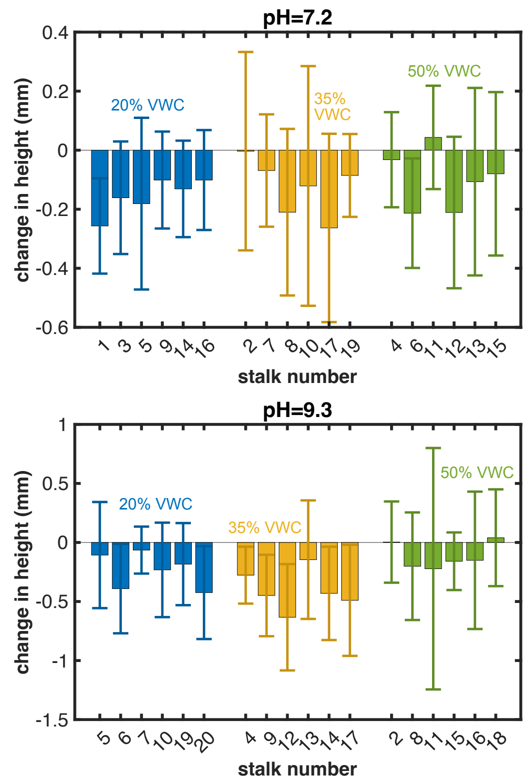

Figure 9: Change in averaged height for each stalk over the course of the growth period, grouped by VWC. Positive growth was only witnessed in the 50% VWC group, with almost all stalks losing height. For pH 7.2, there appears to be an upwards trend in change in height. However, for pH 9.3. the worst performing group appears to the the 35% VWC.

The average changes in height over all of the stalks in each VWC group were calculated and graphed in Figure 10. There appears to be a slight positive correlation between height change and VWC for the 7.2 pH group. The pH 9.3 group, however, with its large uncertainties, suggests no obvious trend. An ANOVA analysis performed with confidence level 95% yielded that there was a there was a statistically significant difference between the mean change in averaged height of the 35% group and 50% group. Likely due to the high variance relative to change in height, no function was found that yielded statistically significant fit parameters.

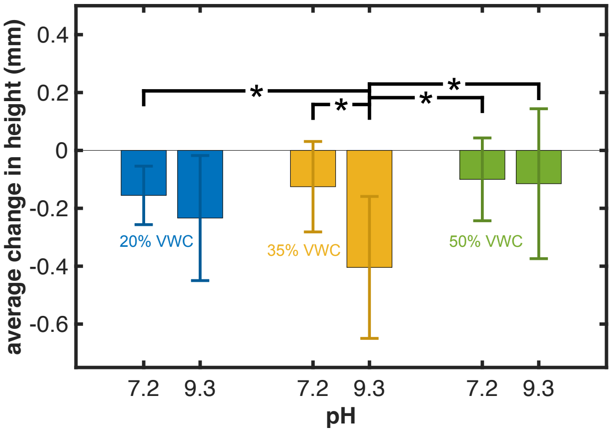

Figure 10: Average change in height for all stalks in each VWC group. The 50% VWC groups again appear to have performed best; for the 7.2 pH, the increasing mean change in height with increasing VWC is observed; however, for pH 9.3, the 35% experienced the largest drop in height. An ANOVA analysis performed with 95% confidence level yielded that the pH 9.3—35% VWC was less than all groups except for pH 9.3—20% VWC. Statistically significant differences denoted with —*—.

EFFECTIVE YOUNG'S MODULUS IN COMPRESSION

Moving to mechanical properties, the first test that was conducted is the compression test. In this test, short samples were separated from each stalk—their heights, as well as the diameters of the stalks, were measured multiple times each, giving average dimensions that can be used in Equation 1 to calculate the effective Young's modulus. The other data that are needed are the force-displacement data collected by the Instron UTM. For the resultant curve, the materials will behave elastically in a certain regime of low displacement, evidenced by a linear relation in the force-displacement curves. Each curve was visually inspected to determine the bounds of the linear fit, with the fit then performed. One example is visible in Figure 11.

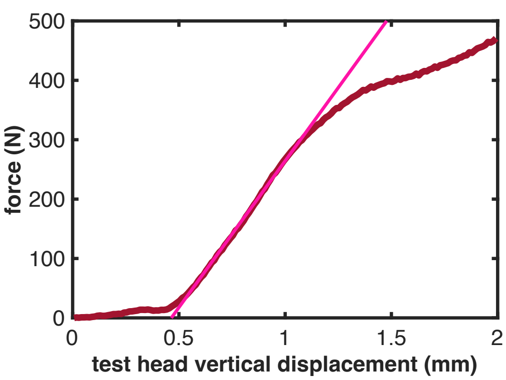

Figure 11: Example of Instron data, showing force as measured by the load cell versus vertical head displacement in the compression test for sample 16. The linear region spans from approximately 0.6mm to 1.0mm, and the linear function was fitted, yielding a slope of 493.5 ± 6.1 N/mm.

The effective moduli, calculated using Equation 1, are shown in Figure 12. For all stalks across all pHs and VWCs largely lie within the 20 to 80 MPa range, with certain stronger stalks scattered seemingly randomly throughout the data.

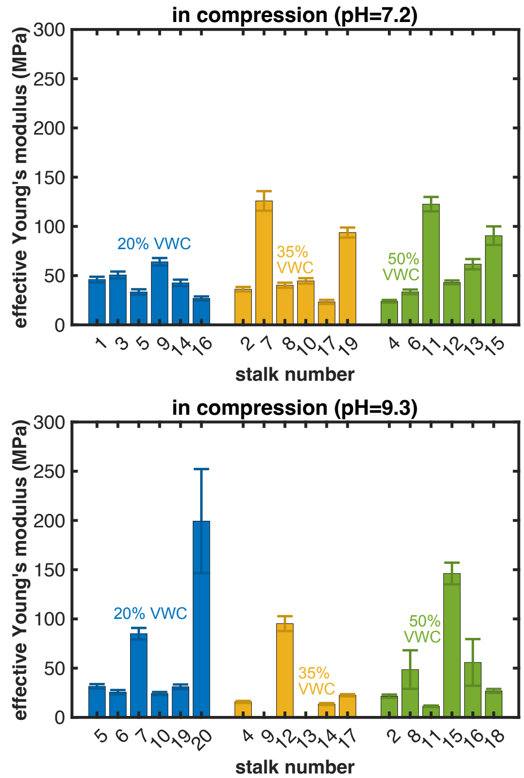

Figure 12: Effective Young's modulus in compression for each stalk, grouped by VWC. As with for bending, no obvious trend in the elastic modulus as a function of VWC is visible. The data from pH 9.3 stalks 9 and 13 were corrupted, and the permanent plastic deformation of the samples prevented new data from being gathered.

The averages across each VWC group were calculated and displayed in Figure 13. The averages have no clear difference in effective modulus for compression—any differences in the means are well within uncertainty bounds. An ANOVA analysis confirms the lack of differences; at a confidence level of 95%, there are no statistically significant differences in mean between any pair of the six sample groups. Furthermore, no function was found that yielded statistically significant fit parameters. This suggests that the different pH and water concentrations did not make a difference in the compressive strength of the stalks.

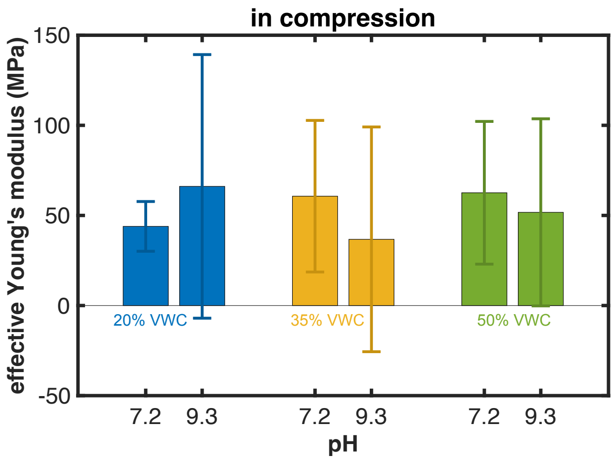

Figure 13: Average effective Young's modulus in compression for each VWC group. No obvious differences in modulus are evident—indeed, the ANOVA analysis performed with a 95% confidence level found no statistically significant difference between the mean modulus between any pair of pH-VWC trial groups.

EFFECTIVE YOUNG'S MODULUS IN BENDING

Finally, the 3-point bending analysis procedure is very similar to that of the compression analysis; a linear function is fitted to the bending Instron data in the same manner as is is for the compression data—an example of this is shown in Figure 14. To calculate the effective Young's modulus in bending, Equation 2 is used, which requires only the slope of the fitted linear function and the stalk diameters.

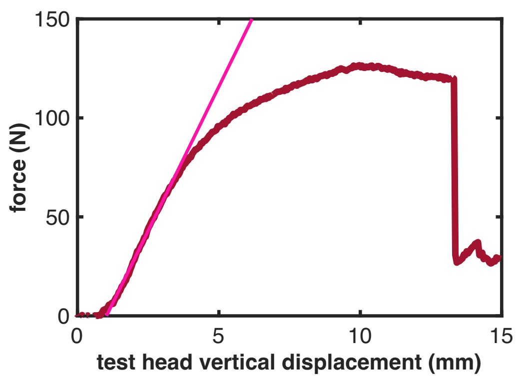

Figure 14: Force as measured by the load cell of the Instron UTM as a function of vertical head displacement in the three-point bending test for sample 2. The linear region spans from approximately 1.0mm to 3.5mm, and the linear function was fitted, yielding a slope of 29.15 ± 0.50 N/mm.

The calculated effective Young's modulus in bending for each stalk as seen in Figure 15. As with compression, the moduli for each stalk have very little variance between them in the sample VWC group and between difference VWC groups. One important detail is the relatively high uncertainties. This can be explained by the fourth-power dependence of Equation 2 on the stalk diameter, which models the stalk as a cylinder. In reality, each stalk is a complex geometry with 2-4 "knuckles" along its length, where the diameter tapers out and then back in. Without being able to develop an accurate, 3D model of the stalk, this approximation yields relatively high uncertainties. Moreover, for the stalks that had higher calculated Young's moduli, such as pH 9.3 stalks 8 and 15, note the very large uncertainty bounds. This is because materials with a high stiffness will respond to small displacements with very large forces, since stress is proportional to the product of Young's modulus and strain, and therefore go from elastic to plastic for relatively short displacement strokes. However, the Instron effectively records data at fixed displacement intervals, meaning that there will be fewer points to fit in the linear elastic region, yielding higher uncertainties.

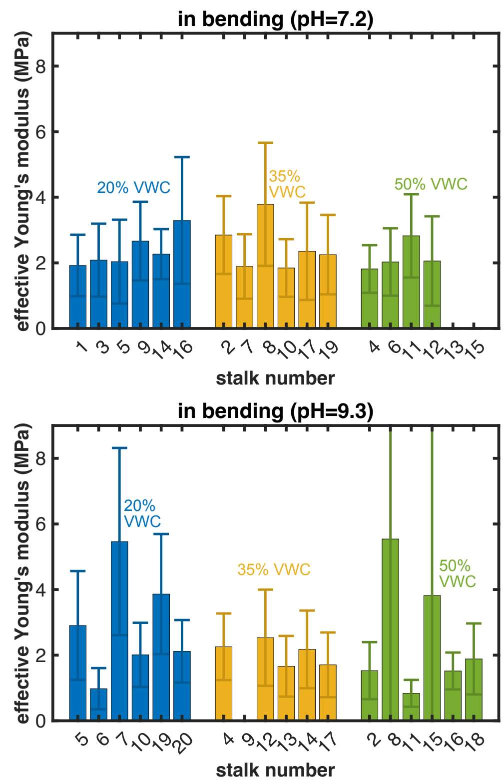

Figure 15: Effective Young's modulus in bending for each stalk, grouped by VWC. No obvious trend in the elastic modulus as a function of VWC is visible. The data from pH 7.2 stalk 13, pH 7.2 stalk 15, and pH 9.3 stalk 9 were corrupted, and the permanent plastic deformation of the stalks prevented new data from being gathered.

Despite the seemingly high uncertainties, Figure 16 demonstrates that the mean effective moduli are actually very similar, with the differences being relatively minuscule and comfortably within uncertainty bounds. Predictably, an ANOVA analysis at confidence level 95% yields no statistically significant difference in mean between any pair of the six sample groups. Furthermore, no function was found that yielded statistically significant fit parameters.

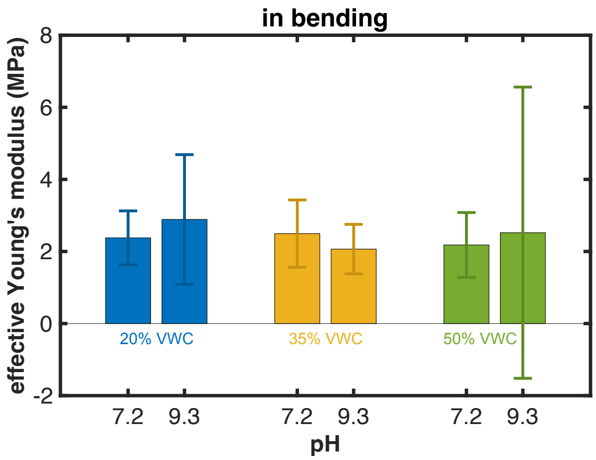

Figure 16: Average effective Young's modulus in bending for each VWC group. No obvious differences in modulus are evident—indeed, the ANOVA analysis performed with a 95% confidence level found no statistically significant difference between the mean modulus between any pair of pH-VWC trial groups.

CONCLUSIONS

For growth, statistically significant differences were determined between the different pH and VWC groups. The change in height data yielded weak correlations, but ANOVA analysis did determine that neutral pH yielded better growth than basic pH. The ANOVA results for the change in mass data, however, were significantly stronger, and further supported the better growth for neutral pH. Additionally, a statistically significant, positively-correlated linear fit was found for both pH trials when expressing change in mass as a function of VWC, with slope parameters of approximately 19 mg for both.

For mechanical strength, ANOVA analyses for all pH and VWCs tested yielded that, with 95% confidence, there was no statistically significant difference in the effective Young's modulus for bending or compression. This means that changing the pH of the water and the amount of watering does not affect the strength of the stalks in compression or in bending. This likely means that, from a materials and structural standpoint, the stalks grow in the same way regardless of conditions—just at different rates.

Thus, D. sanderiana can be grown best with water at a neutral pH and with a 50% soil water concentration. Obviously, the growth results cannot be confidently extended to bamboo, a different species of plant, that would be cultivated for construction, but similar methods to this experiment can be conducted on different species of bamboo to determine the best conditions. However, the strength result is reasonable to extend to bamboo, which has a similar structure and growth pattern to D. sanderiana—this has an important implication for the cultivation of bamboo for lumber. Namely, whatever conditions the plants are grown is does not have a significant effect on the mechanical strength of the resultant lumber, meaning that there does not seem to be a trade-off between faster growth and stronger bamboo. Thus, whatever enables the fastest growth is the cultivation practice that should be used to supply the necessary amounts of lumber needed in rapidly growing parts of the world.

ACKNOWLEDGMENTS

Thank you to Dr. Barbara Hughey and Prof. Sili Deng for help and guidance throughout the project, Steve Banzaert for supplies for and help with the experimental setup, Pierce Hayward for teaching data collection using the Instron Universal Testing machine, and Thalia Rubio for advice on the paper and poster.

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