Root Tensile Strength of Bermuda Grass (*Cynodon dactylon*)

Joenel Galupino[1,*], Ram Voltaire Gonzaga[2], Geofferson Montemayor[2], and Erica Elice Uy[1]
[1] *Faculty, Department of Civil Engineering, De La Salle University, Manila*
[2] *Student, Department of Civil Engineering, De La Salle University, Manila*
**Corresponding Author: joenel.galupino@dlsu.edu.ph*

Abstract: This study investigates the root tensile strength of Bermuda grass (Cynodon dactylon) to evaluate its potential for geotechnical applications, particularly in slope stabilization and erosion control. Root samples were collected and tested using an improvised tensile testing setup. Each root was segmented into top, middle, and bottom portions to analyze the variation of tensile strength along its length. Results revealed a wide range of tensile strengths, from 0.13 MPa to 79.1 MPa, with an average of 7.82 MPa. Notably, thinner root segments demonstrated higher tensile strength, exhibiting a clear inverse relationship between diameter and tensile stress capacity. The bottom sections consistently showed the highest strength, with a peak average of 12.65 MPa. These findings align with existing literature on root mechanics and highlight Bermuda grass capability to contribute to shallow slope reinforcement through its dense, fibrous root network. Despite lower tensile values compared to vetiver grass, Bermuda grass remains a viable, cost-effective, and ecologically beneficial alternative for bioengineering. The study provides new local data on Bermuda grass root strength under Philippine conditions and reinforces its application in sustainable soil stabilization strategies.

Key Words: Bermuda grass; root tensile strength; soil stabilization; bioengineering; erosion control;

1. INTRODUCTION

Soil erosion has long been a critical geotechnical and environmental issue, both globally and in the Philippines. In tropical countries such as the Philippines, the extensive deforestation and agricultural use have left many slopes vulnerable, with nearly half of arable lands experiencing moderate to severe erosion. Concrete retaining structures, for example are conventional engineering solutions to slope instability that can be environmentally disruptive and costly. In response, bioengineering techniques that employ vegetation for slope stabilization have become increasingly popular as sustainable and cost-effective solutions (Teerawattanasuk et al., 2014). Vegetation contributes to slope stability by anchoring the soil: plant roots bind soil particles, improve soil structure, and significantly increase the soil's resistance to shear failure. The use of plants to mitigate shallow landslides and soil loss has been the subject of numerous studies that have been inspired by this natural reinforcement mechanism.

In shallow slope stabilization, perennial grasses have demonstrated exceptional performance among a variety of plant options. Vetiver grass (*Chrysopogon zizanioides*) is a species that has been extensively studied in this context. It is known for its remarkable root strength and deep, fibrous root system. The tensile strength of vetiver roots is inversely proportional to their diameter, with fine roots (~0.2 mm diameter) capable of reaching as high as 180 MPa and thicker roots (~2 mm diameter) reaching approximately 40 MPa. A tensile strength of approximately 75 MPa is demonstrated by the roots of vetiver at a diameter of 0.7–0.8 mm, which is approximately one-sixth that of mild steel (Noorasyikin & Zainab, 2016). on average. Vetiver's exceptional root strength, which surpasses that of numerous hardwood tree roots, allows it to effectively reinforce soil by augmenting its shear strength. The stability of slopes is significantly enhanced by the roots of vetiver, as evidenced by large-scale shear tests, which primarily involve the enhancement of soil cohesion in the rooted zone. As a result, vetiver has been effectively implemented in erosion control projects across the globe, frequently being attributed with a significant role in the stabilization of embankments and the protection of slopes.

Other grass species, such as Ruzi grass (Brachiaria ruziziensis), have also been explored for bioengineering. While the roots of ruzi grass are shorter and individually weaker than those of vetiver, they are more effective at keeping the topsoil from erosion. Consequently, a dense mat of fine, surface roots is formed. Ruzi's fibrous shallow roots offer superior protection against surface soil loss, while vetiver roots provide greater deep-soil reinforcement (higher contribution to shear strength) according to previous comparative studies. The combination of Ruzi and vetiver results in superior overall slope stability compared to vetiver alone, as the two root systems are mutually beneficial (Teerawattanasuk et al., 2014). Ruzi's networked roots knit together the soil near the surface, while Vetiver's deep roots anchor the soil and increase shear resistance at depth. These results emphasize the critical role that root architecture (deep versus spreading) plays in the performance of bioengineering. They also suggest that the strengths of each species can be leveraged to achieve more effective erosion control by employing multiple species in tandem.

Bermuda grass (Cynodon dactylon), a fast-growing prostrate perennial, is another promising candidate for slope stabilization. Common Bermuda grass is a drought-tolerant and hardy grass that is frequently employed as a turf and pasture grass. It is distinguished by its extensive fibrous roots and creeping rhizomes. Under favorable conditions, these roots typically extend approximately 0.5–1 m deep, resulting in a thick sod that is resistant to surface erosion. Bermuda grass has been acknowledged by agricultural agencies for its exceptional erosion control capabilities, which are attributed to its rapid establishment and the formation of a weed-resistant ground cover. Bermuda grass is frequently cultivated in disturbed lands and highway embankments to mitigate runoff and establish rapid vegetation cover. From an ecological perspective, it provides the benefits of rapid propagation and resilience, establishing a vegetative cover that not only stabilizes soil but also restores green cover to barren slopes. Nevertheless, the mechanical reinforcement capacity of Bermuda grass's root system is less well-documented in scientific literature than that of vetiver and similar grasses, despite its widespread use. In reality, Bermuda grass root–soil interactions and properties have been the subject of only a limited amount of research, in contrast to species such as vetiver, which have been the subject of dozens of published studies. This knowledge gap is particularly apparent in local contexts, as numerous engineering practitioners depend on general observations of Bermuda's efficacy rather than quantitative data on its soil strengthening or root strength. The mechanical properties of Bermuda grass roots in a Philippine setting were investigated in order to address the knowledge gap regarding Bermuda grass.

2. METHODOLOGY

In this study, a root tensile strength test was conducted to evaluate the resistance of Bermuda grass (Cynodon dactylon) roots to tensile forces. The behavior of a material under a pulling load until failure is determined by tensile tests. An improvised setup was developed in response to the absence of a standard tensile testing machine. This setup involved the use of clamps as gripping jaws on the root ends and the application of a downward pulling force by adding weight to a bucket, shown in Figure 1. Preliminary tests were conducted to validate the setup, utilizing nylon fishing line as a calibration benchmark due to its well-documented tensile strength.

A total of 27 root specimens were tested (one trial per root), providing a sufficient sample for analysis of variability (Holanda et al., 2022). The surrounding soil and intact roots of each grass clump were meticulously excavated, shown in Figure 2. The natural moisture content of the roots was preserved by gently extracting them from the soil and immediately sealing them in plastic bags and containers prior to testing. This pre-test procedure ensured that the roots were kept moist and undamaged in near-field conditions until they were tested, thereby preventing any dehydration or decay that could have impacted their strength. The test results would accurately represent the mechanical behavior of the live roots by maintaining the roots in a state that is similar to their in-situ condition.

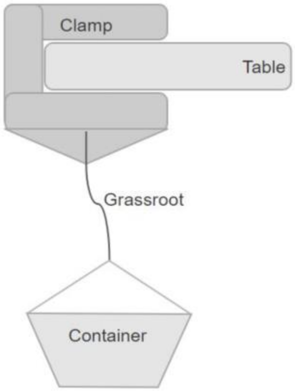

Fig. 1. Improvised set-up for Tensile Testing

Each root specimen was examined and measured prior to the tensile test. The diameter of the root was measured at three predetermined locations along its length, and the root's length was recorded in its natural, unstretched state using a Vernier caliper. These locations were designated as the Top, Middle, and Bottom segments, respectively, and they correspond to 25%, 50%, and 75% of the total root length from the top (soil surface) end. The typical taper of the root was captured by measuring its diameter at multiple points: roots are typically thickest in the middle and thinnest at the tip. In order to prevent any pre-test elongation, all measurements were meticulously taken without the application of tension. This guaranteed a precise baseline for stress calculation.

Fig. 2. Bermuda Grass Sample

The root was clamped at both ends of the tensile test setup, with one clamp secured to a fixed support frame and the other to a hanging bucket, shown in Figure 3. The bucket was subsequently incrementally loaded with weight (water or sand) to apply a tensile force that gradually increased along the root until the root failed (broke). The principles of conventional tensile testing are mirrored by this improvised method, which involves a gradual increase in load until rupture occurs. The method was derived from similar root testing methods that have been reported in the literature. For example, Teerawattanasuk et al. (2014) employed custom grips and loading devices to assess the tensile resistance of vetiver and ruzi grass roots. It assured the consistency of the root loading rate and boundary conditions, as well as the clear observation and recording of the failure load, by adhering to a comparable procedure.

The failure load was determined by the maximum weight that the root could support before breaking during each trial. The total mass of the bucket was weighed immediately following the snapping of a root. By multiplying with gravitational acceleration, this mass was transformed into a force

(Newtons). The diameter measurements were used to infer the cross-sectional area of the root at the failure point. Following the assumption of a circular cross-section, the tensile stress (strength) was calculated as σ = F / A, where F represents the failure force and A represents the root's cross-sectional area. The tensile strength of each specimen was denoted in MPa (megapascals), which is equivalent to N/mm². For analysis, all data (root dimensions, failure loads, and computed tensile strengths) were tabulated. The thesis provides a comprehensive description of the modified tensile strength test procedure, which was conducted in accordance with the pertinent ASTM testing principles, despite the use of improvised equipment. The methodology guaranteed that established practices were adhered to in the acquisition of reliable tensile strength data for the roots, despite the limitations of the equipment.

Fig. 3. Actual Tensile Test Set-up

3. RESULTS AND DISCUSSION

The Bermuda grass roots that were tested demonstrated a variety of sizes. The average length of the roots was 14.68 cm, with a range of approximately 9.6 cm to 22.1 cm. The average diameter of the roots was approximately 0.95 mm, with a range of approximately 0.56 mm for fine roots and 2.08 mm for thicker roots. However, these metrics suggest that root dimensions can be quite heterogeneous, even within a single grass plot. It is important to note that the roots that were the longest (approximately 22 cm) were still shorter. or Bermuda grass in more open environments. The limited growth space of the collected grass patch, which restricted root development in comparison to natural field conditions, is likely the reason for the relatively modest root lengths observed in this study. In other words, the turf sampled was unable to develop the extensive stolons and deep roots that Bermuda grass can achieve in soil volumes that are less restricted.

Each root was subjected to tension until it ruptured, and the force required to break the root was recorded. The 27 roots that were tested exhibited a significant amount of variation in their failure loads. The hanging mass of certain roots was so low that they snapped under a load of approximately 0.65 kg, while others were able to withstand a load of approximately 1.5–1.6 kg before succumbing. These forces are equivalent to tensile forces of approximately 0.6–0.7 N at the low end and approximately 8–9 N at the high end. For instance, in a single trial, a root with a diameter of approximately 1.0 mm broke under a weight of 0.96 kg, resulting in a force of 3.24 N. Conversely, the root that was the most robust in the test series (a thinner specimen) was able to withstand a load of 1.52 kg, which is equivalent to 8.73 N, without experiencing any damage. These values illustrate a broad spectrum of the force-bearing capacity of individual roots, which may be indicative of variations in root thickness and condition (e.g., defects, age). The maximum load was observed at the point at which all roots failed in a clear tensile mode, typically breaking near their midspan or where a weak point existed.

In order to account for the cross-sectional area of each root, the raw failure forces were converted to tensile strength values. The calculated root tensile strengths also encompassed a wide range. A particularly thick root that failed at a relatively low force was observed to have the lowest recorded tensile strength, which was approximately 0.13 MPa. In contrast, a fine root that, despite its diminutive diameter, sustained a substantial load prior to its failure exhibited the highest tensile strength, approximately 79 MPa. The average tensile strength of all specimens was estimated to be approximately 7.8 MPa, as most roots fell within this range. In general, the Bermuda grass roots can withstand a force of approximately 8 N per mm^2, indicated by this average. The wide statistical distribution of strength is a result of factors such as root diameter, maturity, and potentially microscopic defects, as evidenced by the significant disparity between the minimum and maximum values and the variability in natural root materials. However, even the average strength is substantial for biological fibers with such a small diameter.

In order to comprehend the potential variations in tensile capacity along a root, the results were analyzed in relation to the top, middle, and bottom segments of each root (as defined by the measurement locations), shown in Figure 4. The analysis uncovered systematic differences: the bottom sections, which were located near the root tips, exhibited the highest average tensile strength, whereas the middle sections (central portions) exhibited the lowest. The average tensile strength of the roots was highest in the bottom segment, at approximately 12.65 MPa, and lowest in the middle segment, at approximately 7.82 MPa. The strength values of the top segment, which is located near the crown of the plant, were intermediate and fell between those of the middle and bottom segments. In our samples, the root diameter profile was generally the thickest in the middle (average diameter ~1.05 mm) and the thinnest in the tip (average diameter ~0.93 mm). This trend is consistent with the root diameter profile. Thus, the middle section, which had a larger cross-section, experienced a lower stress at failure, whereas the thinner tip region experienced a higher stress before breaking. It is important to acknowledge that each whole-root test results in a single overall failure. Nevertheless, a pattern indicating that the tip segments were relatively stronger per unit area than the mid-root segments is revealed by comparing numerous roots that broke at different locations.

A detailed examination of individual test data indicates that there is an inverse relationship between tensile strength and root diameter. In numerous instances, the root failure was observed at a thinner section, indicating that the root material could withstand a greater amount of stress as the diameter grew smaller. For instance, one of the thinnest root specimens (bottom segment diameter ≈0.245 mm) was subjected to a tensile stress of approximately 79.1 MPa prior to its failure. In contrast, a root with a mid-root diameter that was significantly larger (~0.99 mm) failed at a stress of only 0.13 MPa. In absolute terms, certain thinner roots exerted a greater force than thicker ones. For example, a 0.26 mm diameter root at the top withstood a 0.69 kg load, while a 0.51 mm root at the bottom failed under 0.64 kg. In fact, the material strength (force per area) was often higher in finer roots, highlighting that a larger root cross-section does not necessarily equate to higher strength. These comparisons. It is well-documented in root mechanics research that younger, smaller-diameter roots can be stronger (stiffer and tougher) than older, lignified, larger roots, a counterintuitive result.

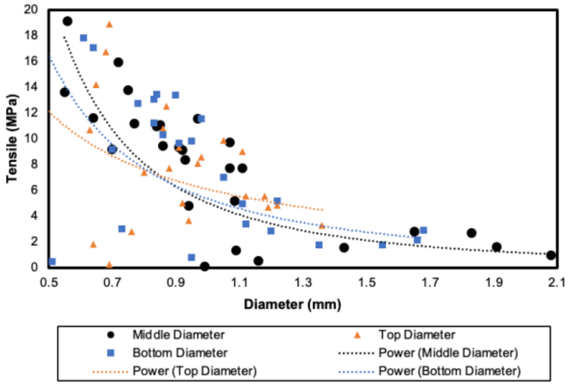

Fig. 4. Tensile strength at Top, Middle and Bottom of the Roots Tested

Trendlines fitted through the data points for each segment confirm an inverse power-law correlation (Badhon et al., 2021). For the bottom segment data, a best-fit curve follows a power law with a high coefficient of determination ($R^2 \approx 0.8815$), indicating a strong inverse relationship (Eq. 1, 2, and 3). The top and middle segment data also follow inverse trends but with weaker correlations—their fitted equations have exponents around -1 to -2 and R^2 values of about 0.65 (top) and 0.43 (middle), respectively. The stronger correlation for bottom segments suggests that the tip diameter is a good predictor of the root's tensile strength in our tests. In practical terms, it demonstrates that as root diameter increases, the tensile strength tends to decrease, which is visually evident from the downward slope of the trendlines. The scatter in the top and middle segment data is larger (hence lower R^2), reflecting more variability, whereas the bottom segment data points align more consistently with the inverse trend.

$$T_{Bot} = 5.3563D^{-1.626} \qquad R^2=0.88 \qquad \text{(Eq. 1)}$$

$$T_{Mid} = 5.0395D^{-2.117} \qquad R^2=0.65 \qquad \text{(Eq. 2)}$$

$$T_{Top} = 6.0939D^{-0.991} \qquad R^2=0.43 \qquad \text{(Eq. 3)}$$

Where:
T_{Bot} = Tensile Strength at Bottom of Root (MPa)
T_{Mid} = Tensile Strength at Middle of Root (MPa)
T_{Top} = Tensile Strength at Top of Root (MPa)
D = Diameter of Root (mm)

4. CONCLUSIONS

The observed inverse diameter-strength relationship suggests that the strength of root material is size-dependent, a phenomenon that is frequently related to biological and microstructural factors. Thicker roots frequently contain older, potentially hollow or more brittle cores, while those with a smaller diameter may have a higher proportion of strong cellulose fibers in comparison to weak voids or may be younger and more flexible. The tensile stress capacity of the thinner root segments was consistently greater than that of the thicker segments, which serves to substantiate this assertion. The strength of the roots is likely influenced by their inherent properties, including moisture content, age, and tissue composition. Although all of the roots that were tested were relatively young and kept moist (collected from new growth in an eroded area), the strength variability observed could be attributed to even subtle differences in root maturation or health. The data also indicate that, in certain instances, a smaller root can withstand a greater absolute force than a larger root. For example, a fine root can withstand an 8.7 N load, while a thicker root will fail at 3 N. This emphasizes the effectiveness of specific roots in supporting loads, regardless of their size.

The tensile strength values of Bermuda grass roots in this study are consistent with the ranges reported for other fibrous plant roots used in geotechnical engineering. For instance, vetiver grass, which is recognized for its function in slope stabilization, exhibits root tensile strengths that are comparatively high. The tensile resistance of vetiver and ruzi grass roots was measured by Teerawattanasuk et al. (2014), and their findings emphasize the substantial strength that grass roots can mobilize. The tensile strengths of our Bermuda grass roots, which were on the order of 10 MPa (and up to tens of MPa in some cases), are consistent with the robust root systems observed in other studies, despite the fact that species and experimental setups differ. This implies that Bermuda grass, despite its typically finer roots than vetiver, can make a substantial contribution to soil reinforcement due to the high tensile strength of its root network. Furthermore, the trend of decreasing tensile strength with increasing diameter has been observed in a variety of root studies, including those conducted on woody plant roots and other grass species. Consequently, our findings are more broadly applicable. We have demonstrated that the fundamental behavior of root tensile mechanics can be captured even with a simplified apparatus, as our methodology and results are consistent with these prior studies.

The results of the root tensile strength test offer valuable insights for geotechnical applications. The average tensile strength of Bermuda grass roots was approximately 8 MPa, with even greater strengths observed in their finer components. This capacity suggests that a mat of Bermuda grass roots can function as a natural reinforcement mesh within the soil, thereby anchoring soil particles and improving slope stability. This enhancement is facilitated by the high tensile resistance of the roots, which enables the root network to absorb tensile stresses that arise in the soil during loading, such as on a slope or embankment. In conclusion, the root tensile strength tests have verified that Bermuda grass roots have a significant tensile strength, particularly in their thinner root portions. This characteristic is fundamental to their successful application in bioengineering solutions (Wang et al., 2020) for slope stabilization and erosion control. The data collected is used to quantify the contribution of Bermuda grass roots in analytical models and designs, emphasizing that the mechanical properties of even small grassroots can have large-scale benefits for soil stability.

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