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The effect of strain rate and specimen length on the stress-strain relationship of vegetation roots used in slope stabilization

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ABSTRACT

The ability of vegetation roots to remain intact during impact problems and earthmoving forces is critical to slope stability. Vegetation resistance to failure depends on the mechanical properties of its roots. An investigation of strain rate and gauge length effects of the English broom shrubs (*Cytisus scoparius*) has been undertaken. Four root specimens have been tested at strain rates of 2mm/min, 4mm/min, 8mm/min and 16mm/min. Also gauge lengths of 70mm, 100mm, 120mm and 150mm have been tested at test speed of 2mm/min. Stress-strain diagrams demonstrate that with increasing strain rates, the stresses tend in general to increase. As speed was increased from 2 to 16mm/min, elongation was reduced by almost half. The Ultimate Tensile Stress increased by 17%. The increase in strain rate did not significantly affect the Young's Modulus of Elasticity. A 13% decrease in strength is observed for increase in gauge length from 70 to 150mm and a corresponding increase in elongation of 32%. Young's Modulus of Elasticity remained fairly constant regardless of the gauge used. Strain rate and specimen length variation significantly alter the stress-strain behavior of the specimens causing substantial changes in the yield stress and specimen failure mechanism.

KEYWORDS: *Strain rate, shrubs, stress, specimen failure mechanism,*

INTRODUCTION

As part on research at the University if Nairobi on the effect of vegetation roots on slope stability, the tensile strength properties of vegetation roots were investigated. Testing was conducted in the University of Portsmouth, UK, as part of the research collaboration between the two institutions.

Vegetation roots affect the properties of soils, such as infiltration rate, aggregate stability, moisture content, shear strength and organic matter content, all of which control soil erosion rates to various degrees. One of the important mechanical characteristics of roots is that they are strong in tension. Soils, on the other hand, are strong in compression and weak in tension. As such, the combined effect of soil and roots results in a reinforced soil (Easson, *et al*., 2002, Norris, *et al.,* 2004). When shearing the soil roots mobilize their tensile strength whereby shear stresses that develop in the soil matrix are transferred to the soil fibers via

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interface friction along the root length or via the tensile resistance of the roots. Thus the magnitude of root reinforcement depends on;

1. morphological characteristics of the root system (e.g. root distribution with depth; root distribution over different root diameter classes);
2. root tensile strengths;
3. root tensile modulus values;
4. the interface friction between roots; and
5. the soil and the orientation of roots to the principal direction of strain (Greenway,1987).

The use of vegetation to stabilize soil slopes is becoming an increasingly used environmentally friendly alternative to traditional soil improvement methods. However, at present, widespread use of vegetation to stabilize soil has been inhibited by a lack of verified methods to predict the reinforcing effect of various plant types (Bromhead, 1992).

In the past many parts of Kenya have experienced many cases of slope instability leading to very destructive landslides that have destroyed properties and loss of life. Slope instability is very common in Central Kenya and parts of the Rift Valley. A major impediment to the effective disaster prevention from mass movement is the lack of sufficient knowledge on the part of local communities of the main factors responsible for the failure and the best methods to minimize the instability. In many cases a slope failure disaster is simply taken as an act of God. Thus few bother to seek the expert opinion on the possible causes and mechanisms to put in place to avoid a repeat of the same. Research on stability of slope using vegetation roots is scarce.

This paper seeks to investigate the effect of varying the strain rate and specimen length on the stress-strain curves of vegetation roots commonly used in soil reinforcement as a preliminary step in highlighting key areas which will eventually lead to more refined methods of root-reinforced slopes. A root-reinforced slope will be a cost-effective option as compared to more expensive ordinary earth-reinforced methods.

As landslide problems induce sudden and high strain rates on the ground, vegetation roots acting as reinforcement require a correct knowledge of the deformation and failure processes for proper design of root-reinforced slopes. Investigation with small root specimens should make sure that the results are transferable to the real problem and that the essential effects are adequately simulated. These effects are strain-rate and gauge length (Hegde *et al.*, 2009, Lindholm, *et al*., 1968).

1. The "Engineering" Stress-Strain Curves

The engineering tension test is widely used to provide basic design information on the strength of materials and as an acceptance test for the specification of materials. In the tension test, a specimen is subjected to a continually increasing uniaxial tensile force while simultaneous observations are made of the elongation of the specimen. A transducer connected in series with the specimen provides an electronic reading of the load $P(\delta)$ corresponding to the displacement. An engineering stress-strain curve is constructed from the load elongation measurements (Goh *et al*., 1982, Wang, *et al*., 2003).

The strain used for the engineering stress-strain curve is the average linear strain, which is obtained by dividing the elongation of the gauge length of the specimen, δ, by its original length, L_0.

When the stress σ is plotted against the strain ϵ, an engineering stress-strain curve is obtained. These are determined from the measured tension and elongation using original specimen cross-sectional area A_0 and length L_0. [1]. The strength parameters, which are used to describe the stress-strain curve for most materials are the Ultimate Tensile Strength (UTS), Yield strength (YS) and Young's Modulus of Elasticity (E).

$$\sigma = \frac{P}{A_0}, \quad \varepsilon = \frac{\delta}{L_0} \tag{1}$$

Young's Modulus of Elasticity (E) is a measure of material stiffness and is the slope of the stress-strain curve [2].

$$E = \frac{\Delta\sigma}{\Delta\varepsilon}, \tag{2}$$

2. Sampling:

Vegetation roots of English broom shrubs (*Cytisus scoparius*) comprising in total of 4 samples were collected from Luton, England, and transported to the University of Portsmouth laboratory where the 50kN Universal Testing Machine is installed. The samples were stored in a cold room to maintain their moisture content although sample testing was conducted on the same day as collected. Figure 1a, 1b and 1c shows the typical shrubs.

Figure 1a:English broom shrub in Luton, England on a hillside.

Figure 1b: Close view of English broom shrub

Figure 1c: Typical English broom shrub showing growth size and root propagation

3. Experimental procedure and equipment:

A 50kN Universal Testing Machine was used to investigate the effect of strain rate and specimen length on stress-strain relationships of roots. The equipment assembly is shown in Fig. 2 and the corresponding set of wedge grips in Fig. 3. This equipment is suitable for tensile, compression, bending, shearing, peeling and tearing test of metal and nonmetal materials to ISO 75001, and other relevant international testing standards.

Figure. 2: The 50kN Universal Testing Equipment assembly

Individual roots from each sample were cut and their skin peeled off. This was found to be necessary to provide the best grip to the root sample. Straight and uniform diameter specimens were selected and cut to gauge lengths of 70mm, 100mm and 120 and 150mm.

Figure. 3: Wedge grips

Each sample to be tested was clamped between two grips. Clamping was the most critical issue when measuring root strength, with the roots clamped using wedge grips as shown in Fig. 3. They are self gripping, quick release, and do not have to be removed from the machine for each test. To improve the clamping and avoid slippage, fine sand paper was attached to the grips. After placing the 70mm samples in the jaws, the upper wedge grip was connected to a crosshead which was moved upwards at a pre-programmed rate to apply tension to the sample. During the tensile test the cross-head movement and resulting force were logged. The data was then used to calculate material properties. Test speeds were varied, i.e., 2mm/min, 4mm/min, 8mm/min, and 16mm/min for each 70mm fresh sample and the resulting graphs recorded for analysis. Tests which failed prematurely as a result of slippage at the grips were discarded.

Lastly, gauge lengths were varied i.e., 100mm and 120 and 150mm, using a 2mm/min. test speed, repeating the testing procedure for each.

4. Results and Analysis:

4.1 Strain rate variations:

Figure. 4 shows the stress-strain plots of identical specimens with varying test speeds. The stress-strain curves indicate that Young's Modulus for these specimens is consistent at 2.2 – 2.8 kPa and that most of the specimens behave in the same manner in the elastic region. As strain rates approached 16mm/min, elastic deformation was the dominant phase. Failure is seen to occur at different levels of stress. As test speed was increased from 2mm/min to 16mm/min, the samples' Ultimate Tensile Stresses increased from 53kPa to 62kPa while the Yield Stresses improved significantly from 23 – 60kPa. The increase in strain rate did not significantly affect the Young's Modulus of Elasticity.

Given that all specimens behave identically in the elastic region, it is clear that the strain rates have an effect on mainly the plastic deformation behavior. High strain rates tends to cause elastic deformation throughout before failure occurs. As such, it should be noted that vegetation roots can increase their Yield Stress and the Ultimate Tensile Stress during sudden ground movements. This is a characteristic where strain rates are induced such as during earthquakes or a major rainfall event, which can result in plant roots mitigating against landslide occurrence on slopes susceptible to failure.

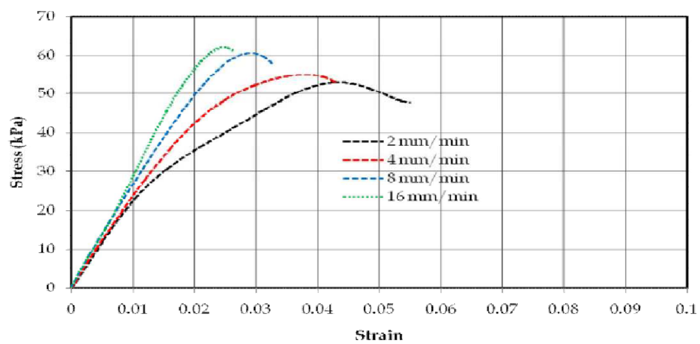

Figure. 4: Stress-strain curves for several strain rates

Table.1 and Figure .5 shows the Ultimate Tensile Strength and Yield Strength for the strain rate domain. With increasing strain rate, the stresses tend in general to increase. As speed was increased from 2 – 16mm/min, elongation was reduced by almost half. The Ultimate Tensile Stress increased by 17%.

Speed (mm/min)	Ultimate Tensile Stress (kPa)	Elongation (mm)
2	53	3.85
4	55	3.0
8	61	2.3
16	62	1.85

Table 1: Corresponding Speed, Ultimate Tensile Stress and Elongation parameters

Figure. 5 shows that as strain rates increase and approach 16mm/min, the difference between Ultimate Tensile Stress and Yield Stress tend to become small. High strain rates either thus significantly influence the failure mode, as the specimens rupture without undergoing plastic process or significant deformation.

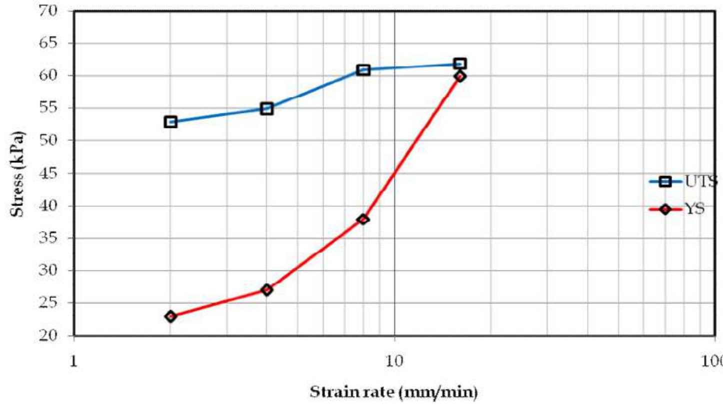

Figure. 5: Behavior of the Ultimate Tensile Strength (LTS) and Yield Strength (YS) against strain rates for four Specimens

Further, Figure. 6 shows that there was little or no variation in the Young's Modulus of Elasticity with strain rate for all of the samples tested.

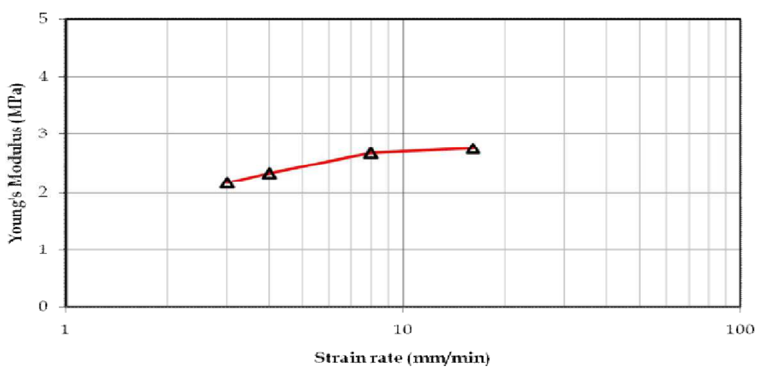

Figure. 6: Young's Modulus of Elasticity (E) against strain rates for four specimens

4.2 Gauge length variations:

Figure. 7 shows the stress-strain curve for varying gauge lengths. Table. 2 summarizes the observations and shows that there is a decrease in strength values with increasing gauge lengths. A 13% decrease in strength is observed for increase in gauge length from 70 – 150mm and a corresponding increase in elongation of 32%. These results show that shorter gauge lengths are stronger for those gauge lengths that approach the 'zero' gauge length plain strain concept between soil particles and vegetation roots. This implies that roots act like other reinforcing materials in slope stabilization works. However, Young's Modulus of Elasticity fairly remained constant regardless of the gauge length used.

GaugeLength (mm)	Ultimate Tensile Stress (kPa)	Elongation (mm)
70	53	3.6
100	48	4.0
120	46	4.5
150	46	4.75

Table 2: Corresponding Gauge Length, UTS and Elongation parameters

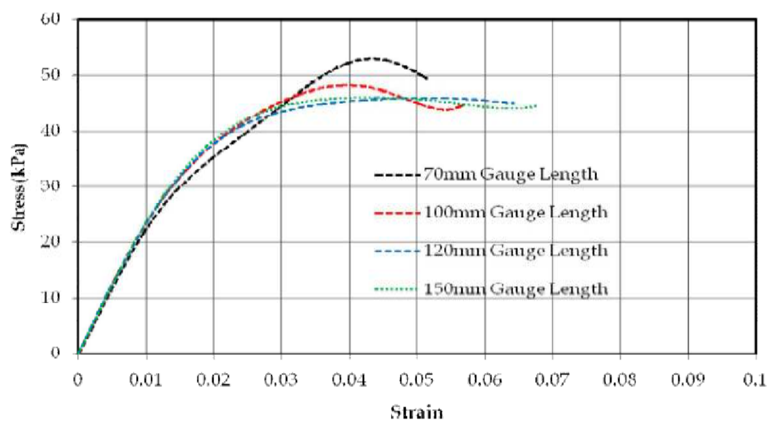

Figure. 7: Stress-strain curves for constant test speed and varying gauge lengths

Further, Figure. 8 shows that the difference between Ultimate Tensile Stress and Yield Stress progressively becomes smaller as gauge length increases.

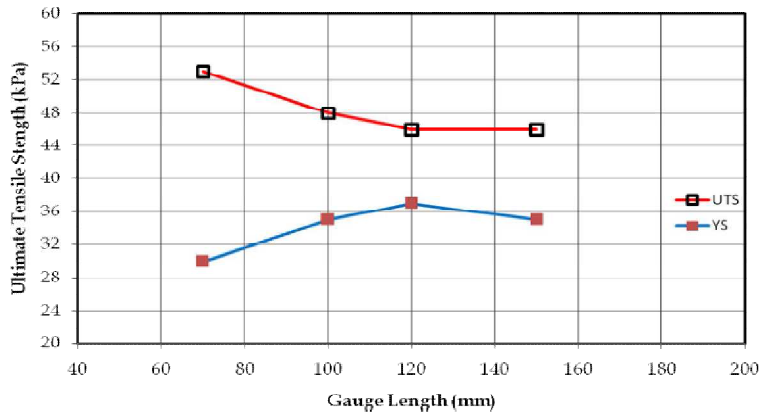

Figure. 8: Ultimate Tensile Stress and Yield Stress against gauge lengths

CONCLUSION

The following conclusions from this study can be made:

1. With increasing strain rate, Ultimate Tensile Stress tend in general to increase. As speed was increased from 2 – 16mm/min, elongation was reduced by almost half. Ultimate Tensile Stress increased by 17%.
2. Changes in strain rate do not significantly affect the Young's Modulus of Elasticity.
3. Vegetation roots thus increase their Yield Stress and the Ultimate Tensile Stress during sudden ground movements. A characteristic where strain rates are increased, such as during earthquakes or during landslide occurrence, can offer more resistance to forces causing instability in slopes.
4. A 13% decrease in strength is observed for increase in gauge length from 70 – 150mm and a corresponding increase in elongation of 32%. These results show that shorter gauge lengths are stronger for those gauge lengths that approach the 'zero' gauge length plain strain concept between soil particles and vegetation roots. This implies that roots act like other reinforcing materials in slope stabilization works.
5. Young's Modulus of Elasticity fairly remained constant regardless of the gauge length used.
6. In general, strain rate and specimen length variation significantly alter the stress strain

behavior of the vegetation root specimens causing substantial changes in the yield stress and specimen failure mechanism, favoring those factors that increase the factor of safety of a slope against land sliding.

Further work

In order to conclusively assess the behavior of plant roots in relation to the contribution to soil stability, a number of further researches are necessary. The following are the areas which need immediate attention in addition to this research;

1. Comparison of tensile strengths of fibers from different plant species used in slope Stabilization.
2. A fundamental biological and geotechnical study of how different plant species increase slope stability. This research will provide a fundamental understanding of how roots from different plants species interact with soil to stabilize slopes, quantify the impact of root reinforcement on slope failure experimentally, and therefore determine which root system structures are most beneficial for slope stabilization. This will enable environmentally friendly technologies for slope stabilization by vegetation through cross-disciplinary research that links plant root biomechanical properties with modeled slope behavior. The creation of reduced scale root analogues will allow different root architectures to be investigated sequentially to assess their importance.

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