EFFECTS OF NATURAL VEGETATION ROOT SYSTEMS ON THE SHEAR STRENGTH OF SOIL:

Comparison of effectiveness of vegetation root system reinforcement and fiber reinforcement

Final Bachelor Thesis

Supervisors: Vanessa Magnanimo; Floriana Anselmucci

Second Assessor: Rik Gijsman

Student: Alexey Matyunin (s2389134)

University of Twente, Faculty of Engineering Technology, Department of Civil Engineering

Academic year 2021-2022

Summary

This study investigated and compared the effects of root reinforcement and Polypropylene (PP) fiber reinforcement on the shear strength of unsaturated sand. The plant that was chosen to grow and develop in sand is common Maize (Zea Maize L.), since it can freely develop a root system in coarse sand with the addition of a nutrient solution. Sand is chosen as a soil since it is the most available soil for analysis.

Several mathematical models were taken as a basis for this study, namely the Pallewatha et al. (2019) model for rooted soils, the Tarantino and Di Donna (2019) model is used for unsaturated soils and the Maher and Grey (1990) model is used for analysis of fiber reinforced soils. Since in this case it is necessary to develop plant life in the tested samples, the unsaturated soil approach had to be taken.

The tests were performed by means of a Direct Shear Cell device, in which constant vertical stress is applied while horizontal stress changes in accordance to the set shearing rate. In order to not disturb the soil integrity of rooted samples, several shea boxes were 3D printed to use both as a growing container and a part of the testing apparatus. The plants were grown in a growing chamber with constantly maintained temperature and moisture conditions, as well as a simulated daytime cycle. After testing, the rooted samples were exhumed to acquire root volume by image segmentation to determine the volume of the fiber to be used in the comparative testing.

The results of testing rooted samples showed one major trend, which was that plant roots do not perform well in terms of shear reinforcement at high values of normal stress, while at lower values of normal stress plants perform quite well. As well as that, several connections between plant age, the volume of the root and the density of the root were identified as influences on the shear strength reinforcement capacities of the root system, which meant that root behavior could not be predicted linearly by growing period as initially assumed.

The results of fiber reinforced samples were directly compared to the results of the plants from which the fiber volume was acquired to achieve the most direct comparison. In all cases fiber reinforcement underperformed when compared to root reinforcement, which could be due to several factors. One is that rooted samples on top of the mechanical effect of the roots utilize a suction mechanism which results from evapotranspiration of moisture from the soil. Therefore, the general performance of rooted samples was better. However, the underperformance of fiber samples could be due to the stolen void ratio effect and the fact that the chosen fibers were too short to entangle with each other and simulate root performance.

The study was subject to several limitations, the most major of which was the limited time frame since it restricted the number of tests that could be performed on the rooted samples and as a consequence on the fiber reinforced samples. As well as that, some equipment and material problems were present, which resulted in a significantly smaller number of shear boxes being 3D printed.

Further studies could focus on creating a systematic picture of plant root influence on the shear strength of soil, especially with regards to how much influence can be attributed to variables like plant age, suction, root stiffness, root volume and how they are interconnected.

Table of Contents

1. Introduction

Soil reinforcement is one of the most prominent and universal tools used in Civil Engineering right now. The simplicity of its implementation, coupled with the effectiveness and economic feasibility allowed it to spread all over the engineering world and infiltrate many different branches of it. Soil reinforcement is used in infrastructure, construction of flood defences and water management solutions, developments of areas that are to be used in heavy construction and as one of the methods of disaster effect prevention and mitigation. The concept of intentional soil reinforcement has been around for almost as long as the recorded history of civilization can show. Soil reinforcement by adding fibers was used in ziggurats of Babylon, in stabilizing soil by means of limestone or calcium powder by the Romans in road building and in stabilizing the soil in the construction of the Great Wall of China by using tree branches to carry tensile stress (S.M. Hejazi et al., 2012). Meanwhile in 1966 Henri Vidal introduced the idea of soil stabilization into modern engineering by means of adding artificial fibers into the soil itself. He called this idea “reinforced earth”.

According to Shukla et al (2013), the practices of soil reinforcement can be divided into “systematically reinforced soil” and “randomly distributed/oriented fiber reinforced soil” or simply “fiber reinforced soil”. This distinction is made on the basis of the mechanisms that ensure soil stability. The branch of systematically reinforced soils uses materials such as geotextiles (which include geotextiles, geogrids and geocomposites) and sheets or strips of steel. This is very similar in nature to conventional concrete reinforcement by metal bars put in the directions and planes of calculated stress or strain. This is generally applied for soils in the context of limited directions of deformation. An example of this could be soil that is supported by sheet piles on one or several sides. Fiber reinforced soil generally utilizes small strips of natural materials like jute, cane or bamboo, or synthetic materials such as polymers, glass fibers or steel fibers. The most commonly used fiber for the purposes of soil reinforcement is Polypropylene (PP) (S.M. Hejazi et al., 2012). In contrast with systematic reinforcement, which contributes to strength in only limited directions, fiber reinforcement contributes to strength in an isotropic manner, due to the random distribution and orientation of the fibers within a given soil sample. The most characteristic effect of fiber reinforcement is increased shear strength, specifically an increase in peak shear strength and a reduced loss of post-peak strength.

However, the research in this thesis project will be focused on soil reinforcement by means of root systems of various vegetations. Root systems work similarly to fiber reinforcement, especially in plants with a fibrous root structure, in which the roots are of consistent size with each other and are uniformly distributed around a soil sample with random orientation with regards to planes. However, root reinforcements allow for both the mechanical effect (using the roots as a support structure) and the so-called soil suction effect. The principle of the second effect lies in the evapotranspiration processes, under which the plants extract moisture from the soil, thus creating a suction that contributes to the shear strength of the soil (M. Pallewattha et al., 2019). Some uses of plant roots in soil reinforcement are in dikes and other flood defence structures, on banks of rivers upstream from hydro-electric power plants to prevent sedimentation at the dams and stabilization of soil in areas with harsh terrain and rapid changes in vertical elevation.

Within this research, the root system of Maize (Zea Maize L.) will be investigated. This choice of plant is made since this plant develops a fibrous root structure, which are grouped together and are of similar size and length to each other (Anselmucci et al., 2021), which facilitates comparison with fiber reinforced samples. As well as that, as shown by Anselmucci et al. (2021), this plant can develop in sand with addition of nutrients and water, which is incredibly convenient for the purposes of this research. The seeds are to be planted directly into the shear boxes, as to not disturb the sample by transporting it from one container to another. After growth for time periods of 8, 10, 12 and 14 days, the samples will be tested in a Direct Shear Cell device under different normal stresses to assess sample properties for different stages of root development. Samples with the same amounts of PP fiber will be tested under the same conditions of soil volume, normal stress and moisture content in order to compare the effectiveness of fiber-reinforced samples and root-reinforced samples.

1.1. Research Objective

The objective of the research is to explore how soil shear strength can be influenced by the root system of plants by means of in-vivo experimental observations. Specifically, the goal of the research is to quantify the contribution of both the tensile effect and the suction effect that the roots provide to the shear strength of a soil sample. In order for the research to be meaningful, soil samples with artificial fiber reinforcement comparable to the root systems will be investigated as well. A comparative analysis will then be drawn to assess the effectiveness of the root system against the effectiveness of fibers. The shear strength of the soil sample without any reinforcement will also be measured to establish a control reading. The in-vivo experiments will consist of using the Direct Shear device to measure the shear strength of the soil samples.

1.2. Research Question

The following research questions can be posed in this thesis project:

- How effective is the root system of natural vegetation compared to flexible artificial fibers in reinforcing the shear strength of the soil?
- To what extent can natural vegetation root systems be considered a substitution to flexible fibers in reinforcing the shear strength of the soil?

2. Theoretical Framework

This section will be describing the main theoretical concepts behind the research topic.

Shear Strength of Soil

According to Das & Sobhan (2012), shear strength of soil is defined as internal resistance to failure or sliding in any of the planes in a soil sample. In 1900 Christian Otto Mohr generalized and expanded on the theory presented in 1773 by Charles-Augustin de Coulomb, which was describing the behavior of brittle materials under stress. The theory states that a material fails because of a critical combination of normal stress and shear stress and not from a maximum state of either one. In other words, shear stress can be expressed as a function of normal stress:

$$\tau_f = c + \sigma \, tan\varphi \tag{1}$$

Where τ_f is the shear stress, c is the soil cohesion, σ is the normal stress on the failure plane and φ is the angle of internal friction. In saturated soils, the normal stress is carried both by soil solids (σ') and the pore water pressure (u):

$$\sigma = \sigma' + u \tag{2}$$

The same expression as Equation 1 can be used to define effective stress, using effective friction angles and effective cohesion instead. To give a more comprehensive example, sand and silt soils have a cohesion value of 0, while consolidated clays have a cohesion value of above 0. It is also worth noting that this experiment will be performed on unsaturated sand, but some water will still be present in the soil samples. For this reason, the framework described by Tarantino and Di Donna (2019) is applied. Under this framework, the expression for the shear strength in unsaturated sand is applied:

$$\tau = (\sigma - u_w S_r) \, tan\varphi' \tag{3}$$

Where u_w is the pore water pressure and S_r is the degree of saturation. This is the case because the plants need to grow and develop a root system in the soil samples.

Shear Strength of Rooted Soils

According to the mathematical model developed by Pallewattha et al (2019), the following equation can be used to describe the shear strength of a root-reinforced soil sample:

$$\tau_{Total} = \tau_s + \tau_U + \Delta\tau_T \tag{4}$$

Where τ_s is the shear strength of the soil itself, τ_U is the increase in shear strength due to the suction effect of the soil from drying out and $\Delta\tau_T$ is the increase in shear strength due to the presence of the roots in the soil. The contribution of the roots $\Delta\tau_T$ can be expressed as follows:

$$\Delta\tau_T = \Delta T_R + \Delta T_S \tag{5}$$

Where ΔT_R is the increase in tensile strength due to the mechanical properties of the roots and the soil root interface and ΔT_S is the increase in shear strength only due to suction induced by the evapotranspiration of the plant. From literature, plant suction in laboratory conditions is estimated experimentally, by placing a suction sensor into soil samples of interest. An example of the quantification of the increase of shear strength by means of plant roots is given in Figure 1.

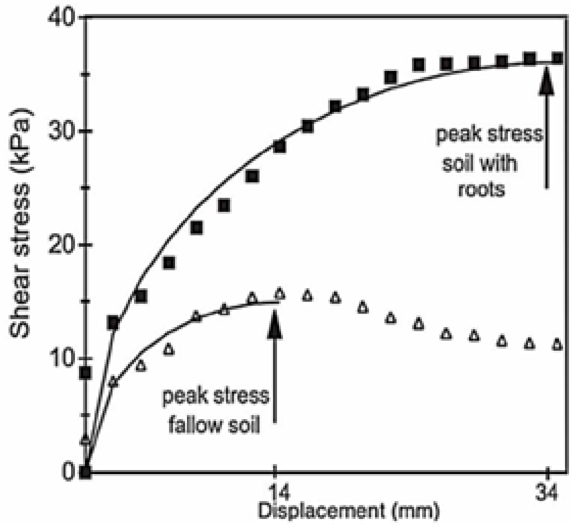


Figure 1 Increase of soil shear strength due to plant roots, taken from Ekanayake & Phillips (1999)

Shear Strength of Fiber Reinforced Sand

The effects that inclusion of randomly oriented fibers has on the shear strength of soil have been extensively described by Maher and Grey (1990), who were in turn building on and expanding the work of Waldron who developed one of the first models of root soil reinforcement. According to Maher and Grey (1990):

$$\Delta S_R = t_R(\sin w \ + \cos w tg\varphi) \quad (6)$$

Where ΔS_R is the shear strength increase resulting form fiber, t_R is the mobilized tensile strength of fibers per unit area of soil, φ is the angle of internal friction of sand, w is the angle of shear distortion. Delving further into the details of the formula is outside the scope of this study, as such this will be left out.

Stolen Void Ratio

The stolen void ratio effect was confirmed by Soriano et al. (2017), by applying X-Ray technology to look at how fibers perform and orient themselves in sand. This effect states that when fibers are introduced into sand, the porosity in the immediate vicinity of the fibers increases in an area of about 3 times diameter of the fiber. This increase in porosity can have a significant effect on the shear strength of a sample, decreasing it. This effect can also be applicable to plant roots, therefore care should be taken in the analysis of final results.

3. Method

3.1. Direct Shear Testing

This section is going to describe the apparatus used in direct shear testing and the standard testing procedure for a soil sample.

3.1.1. Apparatus Description

Within this research, testing of samples will be performed by means of a Direct Shear Cell device. The main principle of the use of the direct shear device is that the vertical and horizontal deformation of the soil are measured by applying an increasing horizontal stress with a set shearing rate in millimeter per minute on one of the halves of the apparatus to cause a shear effect, while applying a constant vertical stress. The monitoring of the vertical and horizontal displacements of the tested sample is done by means of sensors, which are set to monitor the displacement of the top plate for vertical deformation and the displacement of the load application plate for horizontal deformation.

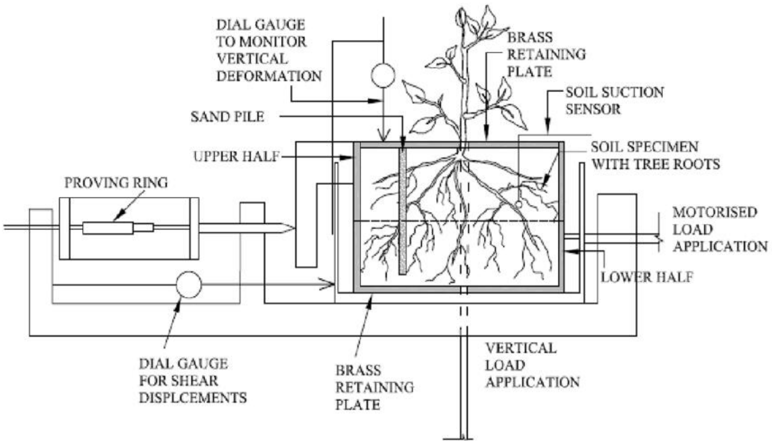


Figure 2 Diagram of a Direct Shear device measuring the horizontal and vertical displacement of a soil sample with vegetation (M. Pallewattha et al., 2019)

The soil samples are put into steel shear boxes with internal dimensions of 60x60 mm and an internal heigh of 35 mm. The bottom of the shear box has ridges of 1mm depth and 1 mm width to ensure and contribute to the soil shearing. The top plate that is placed on the shear box during testing has similar ridges, oriented in the same direction. The shear boxes also have steel pins that hold the top and bottom halves of the shear box together.

Figure 3 Shear box placed in the Direct Shear Cell device. Without the top half (left) and with the top half (right)

The horizontal load on the sample is applied mechanically, by setting a shearing rate on the machine itself. The vertical load is applied by means of metal discs with predetermined weight and associated Newton value placed on a hanger or a lever with a factory-made rate of 1:10. This allows for high flexibility of testing and by combining the hanger and the lever, a wide range of vertical stresses can be achieved. For testing within the scope of this research, five normal stresses were used, as shown in Table 1.

Table 1 Normal stress calculation considering the available weights

№	Force on lever(N)	Force on hanger(N)	Force applied on sample(N)	Stress applied on sample (Pa)	Stress on sample with hanger weight(Pa)
1	0	25	25	6.9	20.6
2	10	0	100	27.8	41.5
3	25	0	250	69.4	83.1
4	35	80	430	119.4	133.1
5	65	0	650	180.5	194.2

3.1.2. Sample testing procedure

The prepared soil samples are placed into the direct shear apparatus in such a manner that the clamp is neatly fit over the horizontal arm and bottom appendages of the box touch the protrusions in the direct shear apparatus. This is shown in Figure 3. Then, the data logger program is initialized on the connected PC. The top plate is placed on the shear box and the hanger is mounted onto the spherical slot on that plate. The vertical sensor is set onto the top of the hanger such that the pin is set vertically. This is done by placing a spirit measure onto the clamp arm that holds the sensor to ensure it is level. The transducers are then reset, to eliminate the zero error. The test is initialized and initial data on the sample is entered into the program, such as its weight, moisture conditions, surface area and height. The necessary weight is applied onto the sample by hanging factory-made metal discs on the hanger and the lever to achieve the desired normal stress.

The consolidation stage is launched, during which the vertical displacement of the sample under stable conditions is measured. This, however does not apply to this research, since sand consolidation is minimal in laboratory conditions. After that, the shearing stage is launched, where the displacement rate and the shearing rate are input into the software. For this research the shearing rabe is set at 0.5 mm per minute and the reading rate is 0.01 readings per mm. The steel pins are removed from the shear box and the transducers are again reset to zero in case they were offset during the previous stages. The actual shearing process is started after that. The shearing process continues until the software indicates that the readings limits was exceeded. During the testing, the graphs of vertical deformation against horizontal deformation and horizontal force against horizontal deformation are plotted automatically, an example is shown in Figure 4. These graphs, however are only temporarily showed for reference and are not saved.

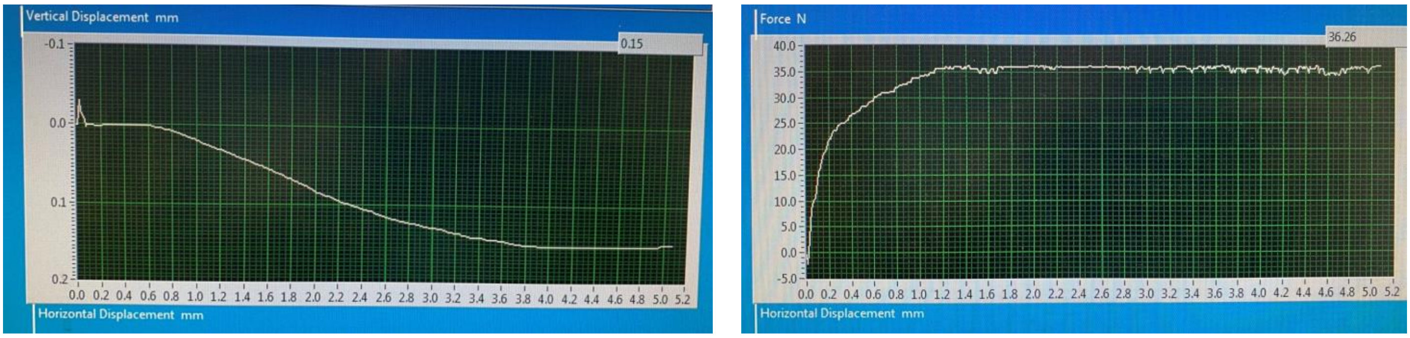


Figure 4 Example of automatically generated graphs.

After the shearing process is concluded, the weight is removed from the hanger/lever and by setting the machine to the “reverse” option, the sample is returned to its original position, so that it can be safely removed from the machine.

The results are saved on the PC connected to the data logger as a text file and contain readings of the horizontal force applied, horizontal deformation and vertical deformation. The text files are then imported to Excel for further analysis.

3.2. Sample preparation

This section is going to describe the procedures involved in preparation of different samples in the scope of this study, accompanied with descriptions of materials used and their quantities.

3.2.1. Soil description and preparation

As mentioned earlier, the soil to be used for this study is sand. Specifically, coarse sand needs to be used, since it facilitates the root development. For this purpose, the sand composition is taken from research performed by Anselmucci et al. (2021), since it also involved the growth of Maize in sand samples. The particle size distribution of the sand is shown in Figure 5. The sand that is to be used for testing is field sand, that was made available in University of Twente laboratory storage.

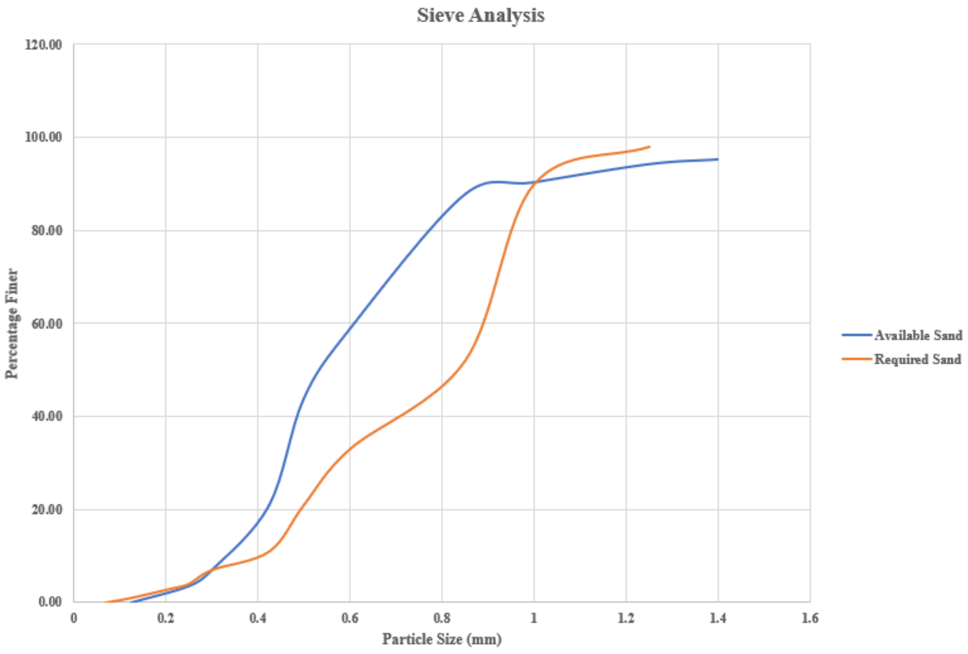


Figure 5 Granulometry for required sand and available sand.

As visible on the granulometric curve, the available field sand is much finer and has a completely different composition as compared to the required sand from Anselmucci et al. (2021). For this reason, it was decided to sieve large amounts of available sand and split it according to particle size. In order to not contaminate the sand with cement residue that was still on some of the buckets in the laboratory, large plastic bags were laid over the buckets. The buckets were also labelled according to particle size.

Figure 6 Buckets containing sand divided by particle size ranging from 1.5 mm to 0.125 mm.

3.2.2. Rooted sample preparation

Before the preparation and planting of the rooted samples, several steps had to be taken. Since only a limited number of steel shear boxes was available and the number of plants to be planted was large, it was decided to 3D print the required number of shear boxes. For this, a simplified model of the steel shear box was made in SolidWorks and printed using the equipment at the University of Twente. Initially, pieces of rigid pipe of appropriate diameter were used to keep the top and the bottom half of the plastic box from sliding, however after running several tests on these boxes with that setup it became evident that when inserting the box into the shear apparatus, the top half of the box could get lifted and sand particles could get between the two halves. This resulted in a falsely increased shear strength of a sample; therefore, it was decided to use screws and dowels to hold the two halves together.

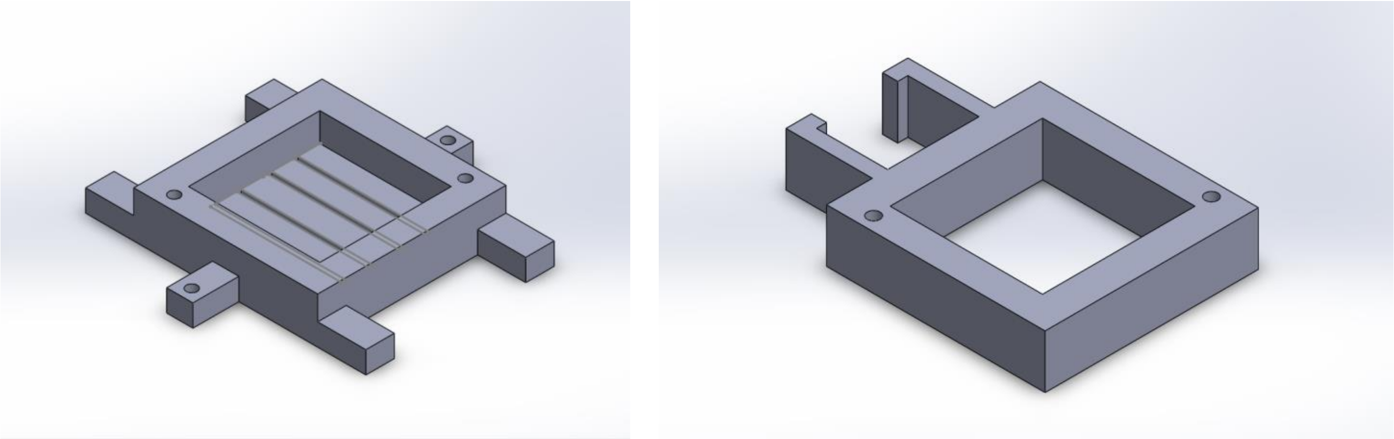


Figure 7 SolidWorks model of the shear box

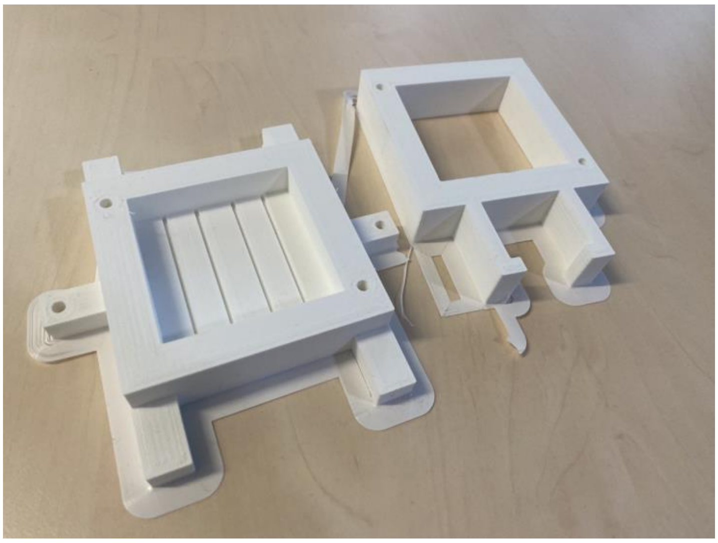


Figure 8 3D Printed shear box

In order to maintain consistency during the whole testing process, sand was transferred into the shear box by means of a funnel to achieve 43% porosity. This amounted to 190.32 grams of sand per shear box. After transferring, a small conical indent was made in the sand and a seed that has been germinating for 2 days was added. Seed germination takes place by first placing Maize seeds in demineralized water for 4 hours and then transferring them into a demineralized water saturated napkin. The seeds are kept under those conditions for approximately 2 days. After planting, 12% moisture conditions are applied on the sample by adding 22.84 g of water mixed with nutrients. The sample is then covered with Parafilm to minimize water evaporation and keep moisture conditions as constant as possible. Following that, the sample is given a number and is placed into the growing chamber, where constant temperature and moisture conditions are maintained. The samples are then kept in the growing chamber for 8,10,12 or 14 days in order to acquire a range of results for different growth periods, root system volumes and root-length densities (RLDs). During the growing period each planted sample is monitored for weight as often as possible, in order to add moisture if necessary.

Figure 9 Rooted samples covered in Parafilm in the growing chamber

After the sample has grown for the necessary amount of time, the stem and leaves are cut from the plant to prepare it for testing. After shearing, the root system and the seed are exhumed to be weighed and measured. The volume of the root system is acquired by means of the image segmentation process.

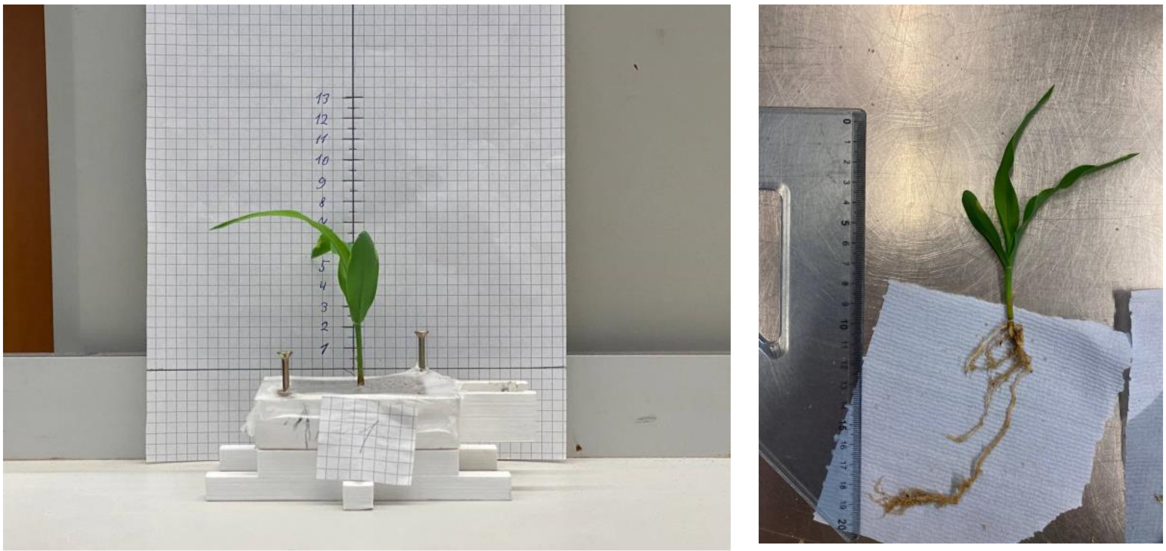


Figure 10 Plant picture before testing (left) and exhumed plant after testing (right). Ruler is laid next to the plant for image segmentation.

3.2.3. Fiber sample preparation

Fiber-reinforced samples are prepared on the basis of root volume that was acquired from the exhumed plant samples. The Polypropylene (PP) fiber that was used is the industry-standard fiber 2-3 cm in length and 0.3mm in diameter. The same volume of polypropylene fiber is used as the volume of the root in the exhumed sample. As well as that, the same normal stress is applied in order to maintain consistency in the analysis. After pluviation for 43% porosity, the 12% of moisture is introduced into the sample by means of a syringe. After the soil was moisturized, the polypropylene fiber is manually mixed into it until uniformity of mixing is confirmed by visual inspection. The sand mixed with fiber is disposed of after testing.

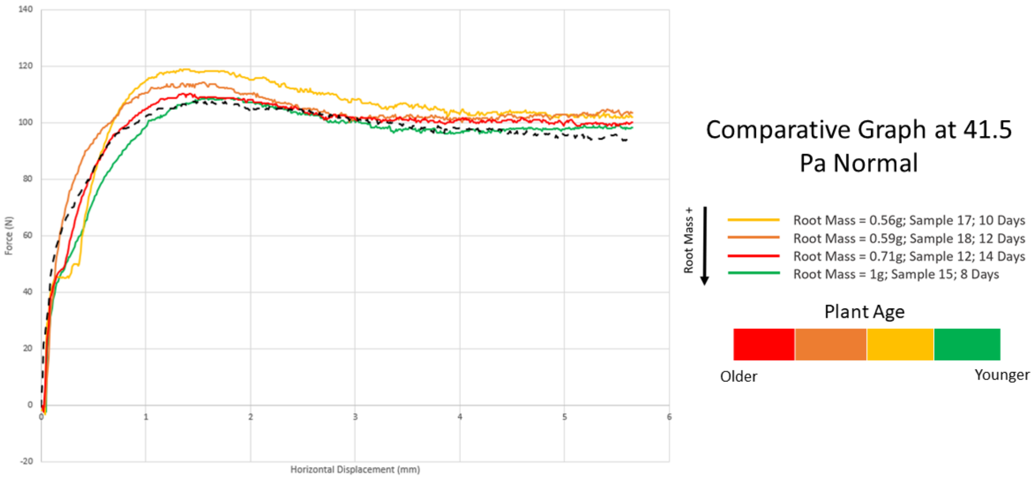
4. Results

This section contains description and analysis of results acquired in the course of direct shear testing.

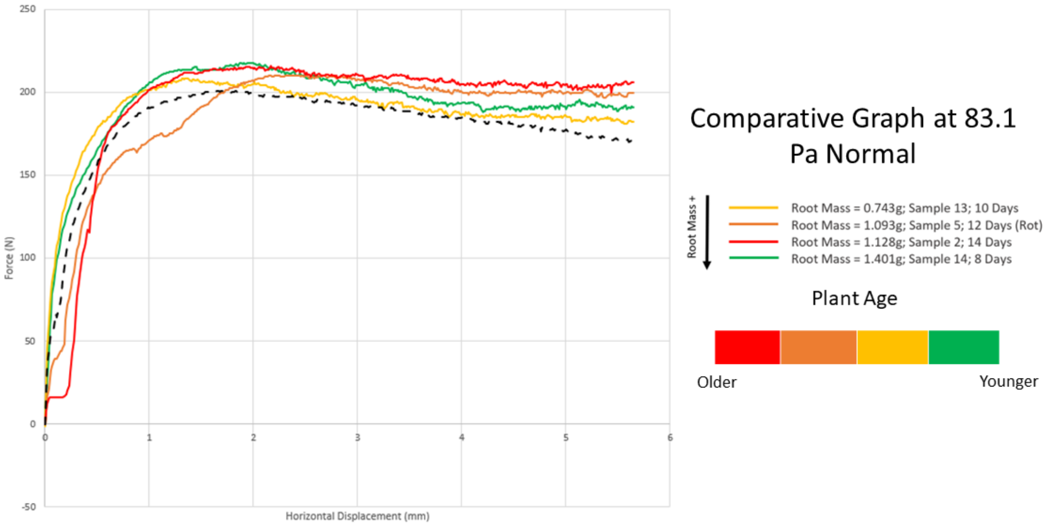
4.1. Rooted sample results

4.1.1. General results

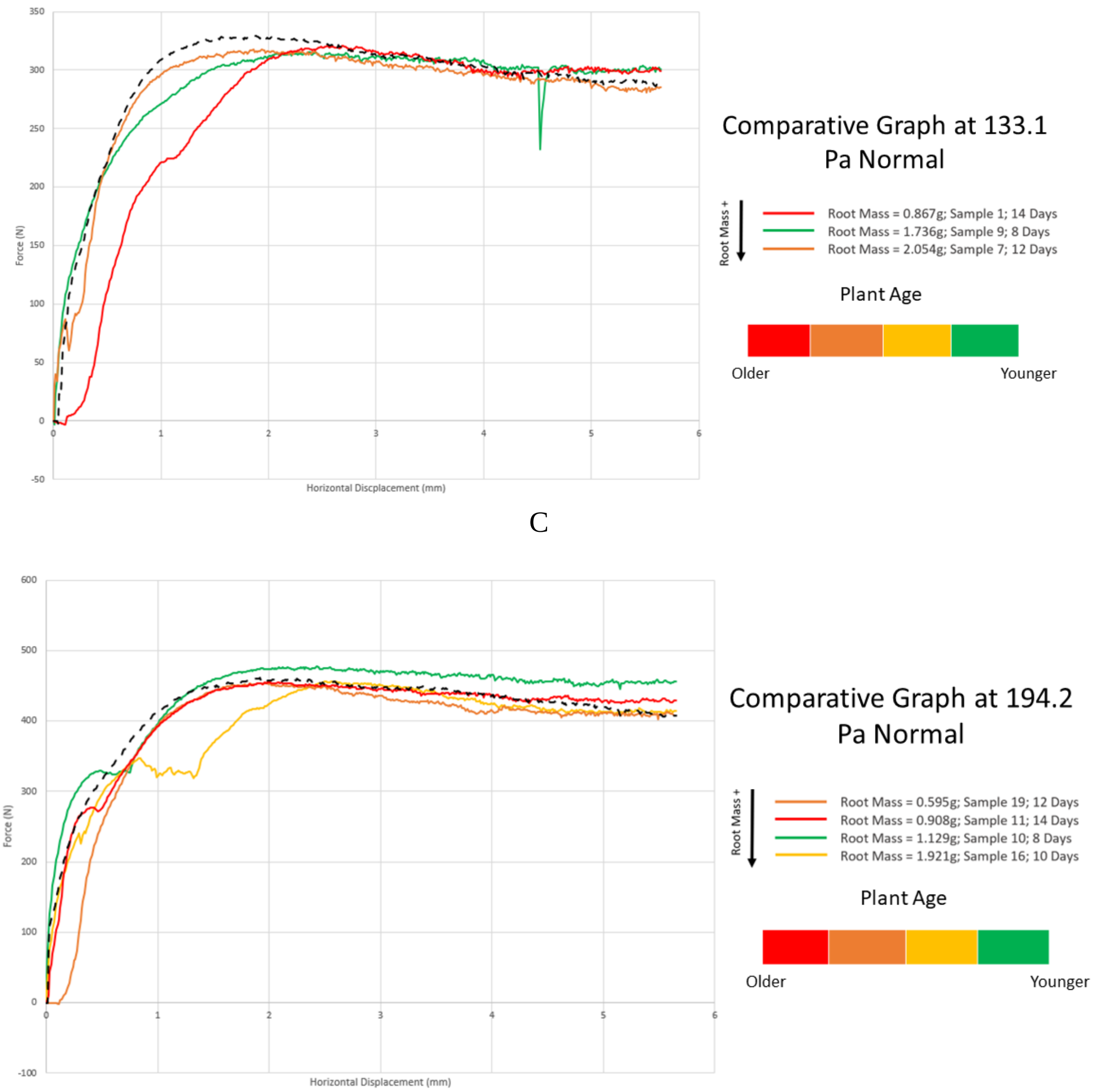
As stated in previous sections, direct shear tests were run on several plant samples with growth periods of 8, 10, 12 and 14 days and under normal stresses of 41.5 Pa, 83.1 Pa, 133.1 Pa and 194.2 Pa. This was done to get the widest possible look into the performance of rooted samples. Initially, when it was assumed that a plant’s age was directly proportional to the development of the root system and as such, performance under shear stress, this experimental setup with 4 growing dates and 4 normal stresses was done to acquire a friction angle for each growing period and somehow compare it to the friction angle acquired from fiber samples and the control. However, the actual results show a more complex relationship between plant characteristics and its performance under shear strength.



A



B



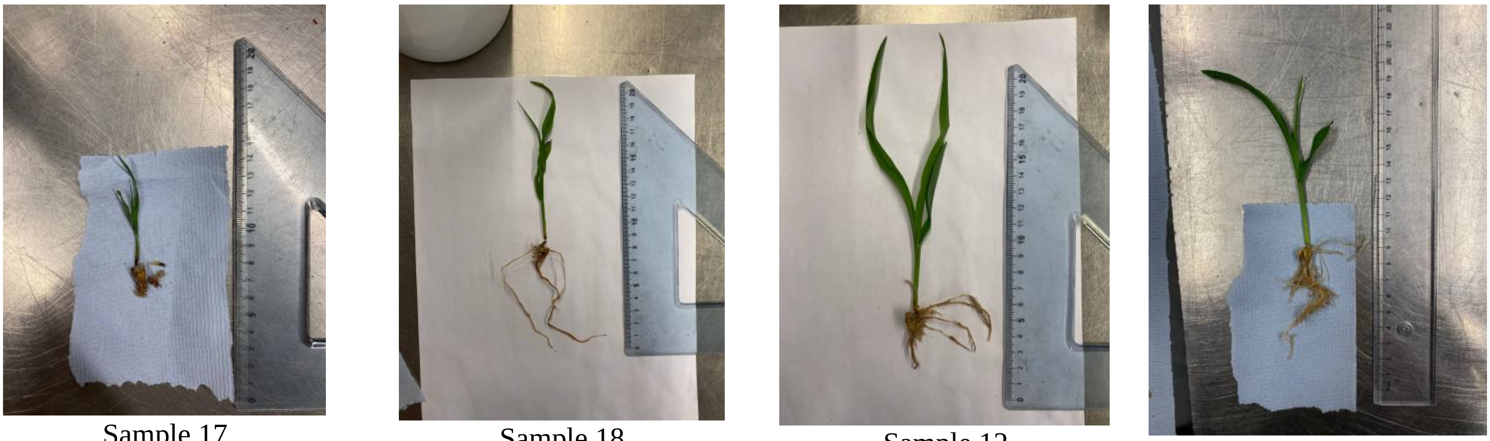
C

D

Figure 11 Comparative graphs A-D showing performance of plants grown for different time periods under the same normal stress. The dashed line is the control sample.

The first and most apparent conclusion that can be drawn from the comparative graphs in Figure 11 A-D is the fact that a higher plant age does not directly indicate a more developed root system or an increase in shear strength performance. Therefore, the analysis framework should be shifted to accommodate for other factors in play such as the increase in root stiffness and suction effect with age, actual development of the root system and the condition of the plant at the time of testing.

Figure 11 – A shows a trend that can be reasonably expected from rooted samples: presence of roots shows an objective increase in shear testing performance, which is specifically visible at the peak region of the graph. However, it also becomes clear that an increased root mass does not imply a better shear performance either. From this graph the inverse seems to be true, with plants at a higher root mass performing closer to the control than plants with a lower mass. That means that to draw necessary conclusions it is also important to look at the root system of each individual sample.



Sample 17 Sample 18 Sample 12 Sample 15

Figure 12 Samples used in testing shown in Figure 12-A. The root mass increases from left to right.

Looking at the individual samples can reveal more conclusions that will be useful in analysis of further results. The best performing sample, sample 17, shows the least developed root system, which is paradoxical at first glance. However, this could be explained in two ways: 1) The seed could have been buried too deep in soil and either intersected the shearing plane or caused enough compression of soil around it to intersect the shearing plane. This would also explain the under-developed root system; 2) As evident by the development of the stem and the root, the plant stopped growing at one point, which led to it rotting, which could have influenced the shear strength of the soil in its own way. This effect will be discussed at a later section. We can also see that the root growth of sample 12 was directed outside of the shearing box and not inside, which led to a significant decrease in its performance. Sample 15, while showing the most developed root system is the youngest one, with only 8 days of growth, therefore its performance can be explained by a lack of root stiffness, which can only be acquired by means of prolonged growth. Sample 18 as a consequence performs the best and that can be reasonably explained. It has a fairly well-developed root system, which has an increased stiffness as a result of age. From the roots and the graph we see that the roots were not sheared in the testing process, but acted as added reinforcement by means of extension.

Figure 11 – B continues the trend of rooted samples showing higher shear strength than the control. At the same time, the graph also shows new and interesting relationships between variables that would confirm some of the earlier assumptions, especially when considered in conjunction with the actual samples themselves.

Sample 13 Sample 2 Sample 14

Figure 13 Samples used in testing shown in figure 12-B. The root mass increases from left to right.

The most interesting relationship to be considered here is that of Sample 2 and Sample 14. Both plants have a well-developed root system with a distinguishable main root and many auxiliary roots, but a difference in behavior under shearing is also visible. While sample 14 shows a slightly higher peak than sample 2, the post-peak performance of sample 2 is significantly better, which can only be explained by the 14 day age of sample 2, which leads to increased root stiffness and an increase in the suction effect.

While the samples tested in Figure 11 – C do not uncover any new relationships by themselves, a new general behavioral trend can be seen, that can be attributed to an increased normal stress. The graph shows that the higher the root mass of the plant, the closer it performs to the control value, with no samples surpassing the control in performance. This can be used to conclude that at this normal stress the plants are ineffective in reinforcing the soil and only strive to compensate for this by increased root mass.

The trend set by graph C continues in Figure 11 – D, with rooted samples underperforming or performing on the same level when compared to the control sample. The notable and obvious exception in this case is sample 16, which exhibits behavior unseen in all other samples.

Sample 19 Sample 11 Sample 10 Sample 16

Figure 14 Samples used in testing in figure 12-D. The root mass increases from left to right.

As evident by graph behavior and the picture of the root system, the main root system of sample 16 got sheared in the process. This explains why the graph behaves so erratically when compared to other samples. Meanwhile, the behavior of other samples in graph D is consistent with all other samples shown before.

In order to confirm the contribution of plant roots to soil shear strength at lower values of normal stress, another set of tests was carried out at a normal stress of 20.6 Pa.

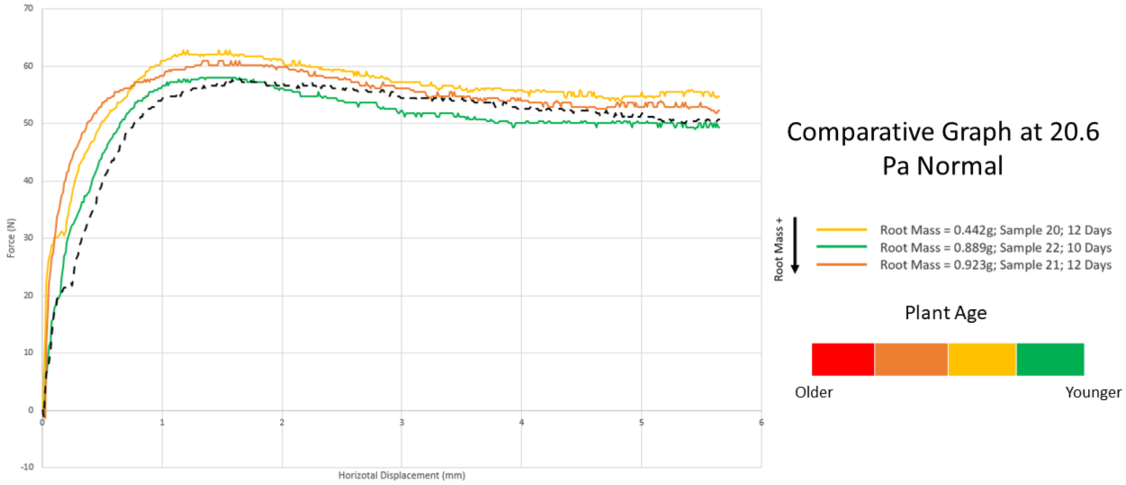


Figure 15 Comparative graph at 20.6 Pa normal stress. The dashed line is the control sample.

The graph in Figure 15 confirms a trend that was uncovered in Figure 11 – A and – B for lower normal stresses, where rooted samples perform progressively better than the control sample. As well as that, samples of higher root mass perform closer to the control line, which is also consistent with data that was seen before. As well as that, while samples 21 and 22 are very close in terms of root mass, sample 21 performs objectively better due to its older age, which also confirms some of the conclusions made before.

4.1.2. Performance of rotten samples

As stated in the previous section when discussing results from Figure 11 – A, rotted samples show anomalous behavior, inconsistent with what can be expected from samples with an underdeveloped root system. There could be several explanations for this phenomenon. One possible reason is that the seed was buried too deep during the planting process and as such failed to developed. This, in turn, also placed the seed in the way of the shearing plane, which is why those samples produce results comparable to normally rooted samples. Another explanation could be rooted in the processes that take place around a rotting seed.

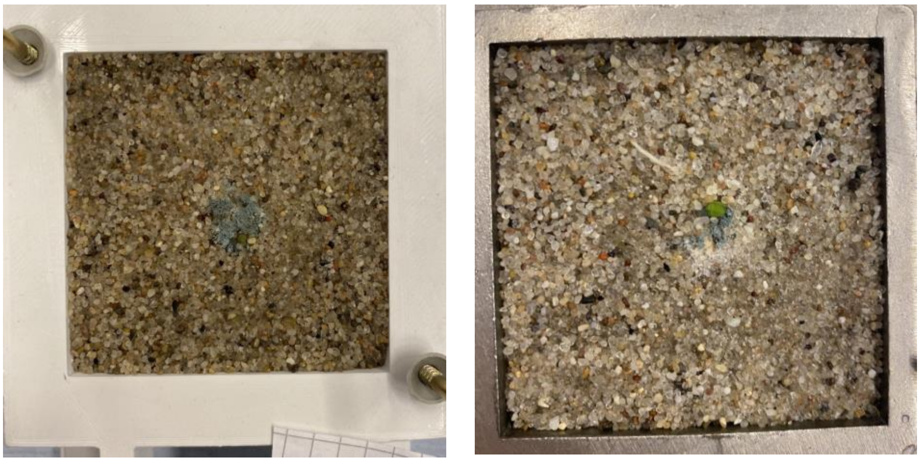


Figure 16 Samples showing mold growth around the seed.

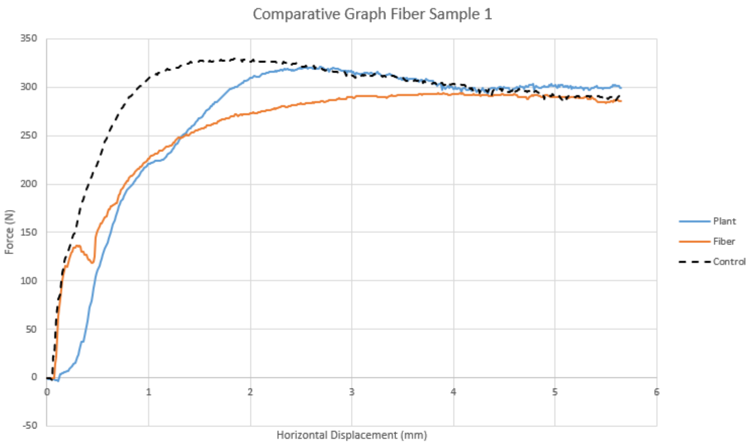
As seen on Figure 16, some of the samples that stopped growing due to various reasons developed mold around them. This mold acts as an adhesive, which became evident when exhuming the samples and looking at the amount of sand that was aggregated around the seed. This essentially forms a clump of cemented sand, which even after drying in the oven is hard to break apart. The study of mechanisms that cause this to occur is outside the scope of this study, however this can help explain some of the results that occur for underdeveloped rooted samples.

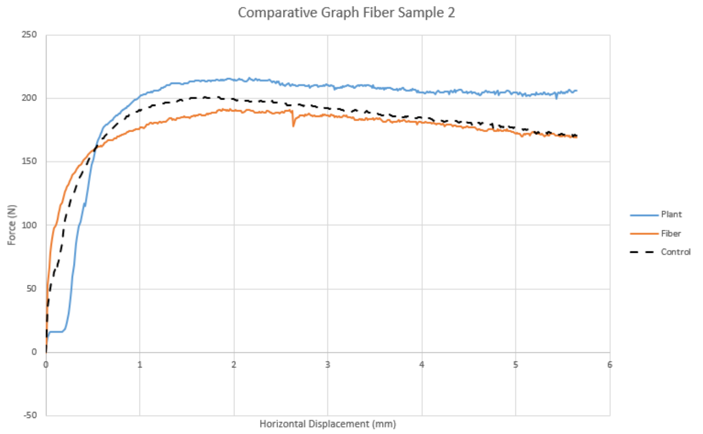
4.2. Fiber sample results

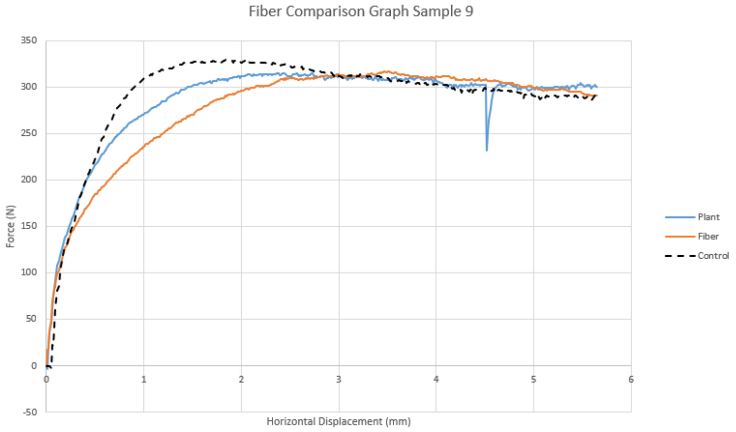
As stated, fiber samples are prepared by using the same volume of fiber as the volume of root that was acquired by image segmentation. Due to this and the complexity of variable relations with rooted samples, the fiber results will be in direct comparison to the samples that were used to determine the volume. The Rooted samples were chosen for comparison and analysis since they all have a well-developed root system and thus would produce a meaningful analysis when compared to industry-standard fiber.

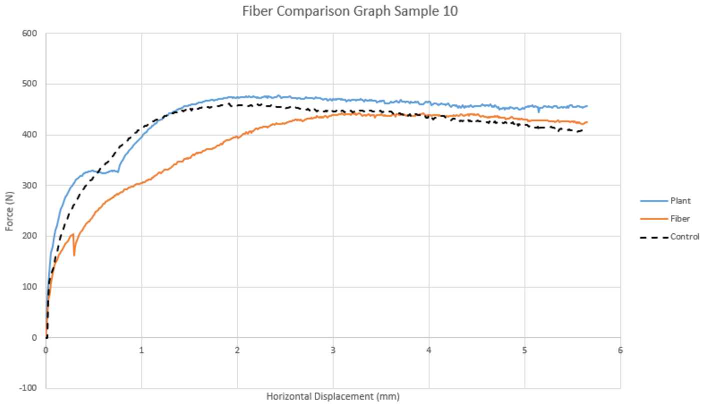
Table 2 Samples used for comparison of root effectiveness versus fiber effectiveness

Sample №	Root Mass (g)	Root Volume (cm^3)	Fiber Mass (g)	Normal Stress (Pa)
1	0.867	0.4665	0.4245	133.1
2	1.128	0.299	0.2721	83.1
9	1.736	0.744	0.677	133.1
10	1.129	0.2289	0.2083	194.2
13	0.743	0.1307	0.1189	83.1
14	1.401	0.2772	0.2522	83.1
15	1	0.1542	0.1403	41.5









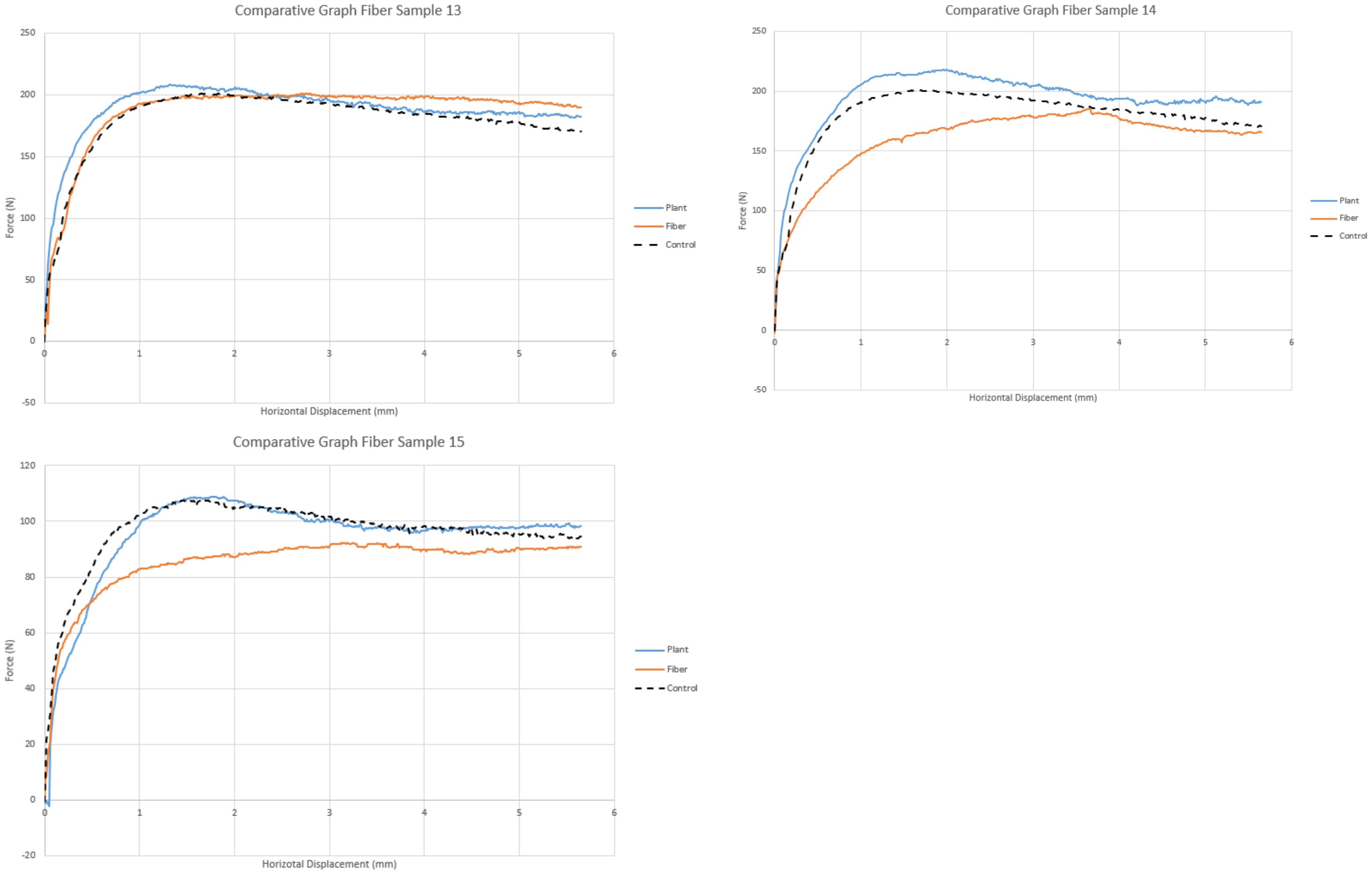


Figure 17 Comparative graphs for fiber samples and rooted samples.

The main trend that becomes apparent after viewing the graphs is that in every case, despite the same volume, the fiber sample either underperforms or performs the same as the rooted sample. As well as that, the main difference in performance is the peak region of the graph, whereas post-peak the graphs usually converge to similar or close values. Fiber displaying lower shear strength is consistent across all samples, regardless of fiber volume or normal stress. The convergence seems to occur only at higher normal stress values, that is, however, inconsistent.

5. Discussion

5.1. Discussion of rooted samples

As stated before, the main and most obvious trend that becomes apparent from results acquired from rooted samples is that they do not display effectiveness in terms of shear strength when it comes to high values of normal stress. In most cases, the rooted samples even perform worse than the control samples with just soil and 12% moisture content. The most likely explanation for this is slippage of roots under high normal stress, which actually weakens the soil by creating excessive voids. Some evidence of this can be found in Figure 11 – C and – D, where in the pre-peak part of the graph the gradient suddenly becomes 0 and the graph becomes flat, signifying that no increase of force is taking place to cause deformation, which most likely implies root slippage. Essentially, this leads to the conclusion that wile plant roots are an effective method of soil reinforcement at lower values of normal stress, they are not applicable to situations where high values of normal stress are present. For example, reinforcement of soil for construction of heavy-duty infrastructure like roads and railway lines would not be suitable use of plant roots as a reinforcement measure. Within this scenario, plant roots would perform significantly better in conditions with lower normal stress, but which still require a shear strength increase. One use which is already popularized is dikes and other flood defense structures, where greenery is commonly planted and allowed to grow.

The most major limitation regarding testing of rooted samples in this study is the limited timeframe. This has to do with the uncertainty which arises when dealing with plant growth. While during the whole study only 4 out of 22 plants irreparably died, many others experienced issues with growth, which lead them to rot within the container. With more time, a significantly larger number of planted samples could be tested, allowing not only for a broader view of plant behavior in these conditions, but also repetition, which could help eliminate errors and anomalies taking place. As well as that, another limitation that stems from the time limit is the maximum growth period that was utilized during this study. Since the tested growth periods were very close together, the differences between them did not always become apparent. A wider growing time frame could allow for more comprehensive results.

5.2. Discussion of fiber samples

The concerning issue with the acquired fiber results is that in most cases they severely underperform the control value. While a better performance of rooted samples could be expected, it was not expected that fiber samples would display such low levels of shear strength. This could be due to several factors. One of them is the fact that the used fibers were 2-3 cm long, which meant that they could not entangle with each other enough to simulate roots and further contribute to the shear strength. Another explanation could be the so-called “stolen void ratio” effect described by Soriano et al. (2017), which states that in the direct vicinity of fiber, sand porosity increases. This can significantly contribute to slippage, and as such, reduce the shear strength of fiber reinforced samples.

The fiber limitations are very closely related to the rooted samples limitations, namely the time frame. With a larger timeframe image segmentation could be performed on more planted samples and as such would lead to a wider variety of results, providing more insight.

6. Conclusion

Within this study, effects of plant roots and fibers on the shear strength of soil were investigated. This was done by means of direct shear cell tests on rooted samples grown for 8, 10, 12 and 14 days and on fiber samples with normal stresses of 41.5 Pa, 83.1 Pa, 133.1 Pa and 194.2 Pa. The results of study outlined specific performance patterns for both fiber and roots that could be useful in application in actual construction situations:

- Plant roots within the scope of the study did not perform well under high values of normal stress and as such, plant roots should only be used in reinforcement of soils that do not experience high normal stress, such as dikes and other flood defense structures.
- Under the conditions created in this research, the fiber reinforced samples performed worse than root reinforced or controlled samples, which leads to the conclusion that Polypropylene fiber was not an effective solution for shear strength in this study. However, the fiber samples were subject to a high number of limitations and as such, no distinctive conclusion can be made on the fibers as a general means of reinforcement.

Recommendations for further research

Surprisingly enough, the topic chosen for this report is very underrepresented in the academic discourse and as such it allows for a wide variety of further research to be done to explore, analyze and compare different methods of soil reinforcement as compared to plant root reinforcement. Further research on this topic should focus on creating a systematic picture of plant root influence on the shear strength of soil, especially with regards to how much influence can be attributed to variables like plant age, suction, root stiffness, root volume and how they are interconnected. Another possible venue of research could be to more closely investigate the effect molding and rotting of organic materials like seeds and roots can have on soil reinforcement and how that effect could be quantified. As well as that, for a more comprehensive view of how fiber reinforcement affects the soil, different types of fiber should be used in the investigations, with the first varying parameters being fiber length and fiber diameter.

Acknowledgements

I would like to thank my supervisors, Vanessa Magnanimo and Floriana Anselmucci for their productive and enthusiastic approach to research, along with the support they provided me through the course of the study.

I would also like to acknowledge Roman Sergeev MSc of the Moscow State University's Department of Geology for inspiration on the research and support in systematization of the main geotechnical concepts.

Reference List

F. Anselmucci, E. Andò, G. Viggiani, N. Lenoir, C. Arson, L. Sibille,
Imaging local soil kinematics during the first days of maize root growth in sand, Sci Rep 11**,** 22262 (2021).
https://doi.org/10.1038/s41598-021-01056-1

J.C. Ekanayake, C.J. Phillips,
A method for stability analysis of vegetated hillslopes: an energy approach, Canadian Geotechnical Journal, Volume 36, 1999, Pages 1172-1184
https://doi.org/10.1139/t99-060

S. M. Hejazi, M. Sheikhzadeh, S. M. Abtahi, A. Zadhoush,
A simple review of soil reinforcement by using natural and synthetic fibers, Construction and Building Materials, Volume 30, 2012, Pages 100-116, ISSN 0950-0618,
https://doi.org/10.1016/j.conbuildmat.2011.11.045.

M. Mazzuoli, R. Bovolenta, R. Berardi,
Experimental Investigation on the Mechanical Contribution of Roots to the Shear Strength of a Sandy Soil, Procedia Engineering, Volume 158, 2016, Pages 45-50, ISSN 1877-7058,
https://doi.org/10.1016/j.proeng.2016.08.403.

M. Pallewattha, B. Indraratna, A. Heitor, C. Rujikiatkamjorn,
Shear strength of a vegetated soil incorporating both root reinforcement and suction,
Transportation Geotechnics, Volume 18, 2019, Pages 72-82, ISSN 2214-3912,
https://doi.org/10.1016/j.trgeo.2018.11.005.

S. Shukla, N. Sivakugan & B. Das,
Fundamental concepts of soil reinforcement — an overview, International Journal of Geotechnical Engineering, 2009, 3:3, 329-342,
10.3328/IJGE.2009.03.03.329-342

I. Soriano, E. Ibraim, E. Andò, A. Diambra, T. Laurencin, P. Moro, G. Viggiani
3D fibre architecture of fibre-reinforced sand, Granular Matter 19**,** 75 (2017).
https://doi.org/10.1007/s10035-017-0760-3

A. Tarantino, A. Di Donna,
Mechanics of unsaturated soils : simple approaches for routine engineering practice. Italian Geotechnical Journal (4), (2019), ISSN 0557-1405,
https://doi.org/10.19199/2019.4.0557-1405.005

D.M. Wood, A. Diambra, E. Ibraim,
Fibres and soils: A route towards modelling of root-soil systems, Soils and Foundations, Volume 56, Issue 5, 2016, Pages 765-778, ISSN 0038-0806,
https://doi.org/10.1016/j.sandf.2016.08.003.