University of Twente

Shear Response in Reinforced Granular Soil

Final Bachelor Thesis

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Summary

This study delves into the domain of soil reinforcement, a critical aspect of civil engineering with far-reaching implications for structural stability. It traces the evolution of soil reinforcement from ancient practices to modern techniques, notably highlighting systematically reinforced soil and the recent emergence of randomly distributed/oriented fiber-reinforced soil. While traditional methods have typically relied on inert fibers, the study introduces an innovative approach by exploring the use of living plant roots for soil reinforcement. This novel approach not only promises ecological benefits but also addresses the limitations associated with conventional methods.

The research aims to investigate and compare the performance of granular soil reinforced through living plant roots versus inert fibers. It addresses the fundamental problem of enhancing the stability and strength of granular soils, which are prone to various environmental factors. The study's motivation lies in sustainable engineering practices, aligning with ecological solutions amid a climate crisis. By integrating living plant roots into civil engineering practices, the research aims to establish a symbiotic relationship between the built and natural environments. It also builds upon previous research, contributing to a broader understanding of randomly distributed/oriented fiber-reinforced soil.

Scientifically, this study bridges the knowledge gap by exploring the application of living plant roots for soil reinforcement, shedding light on plant-soil interactions under shear stress. The findings have the potential to shape future soil reinforcement guidelines and to promote sustainable civil engineering practices. The research methodology includes a suite of experimental and analytical techniques, with a focus on laboratory testing using a Direct Shear device. The study details the materials used, including plant species, soil type, and various fibers. It describes the sample preparation processes for soil samples reinforced with active plant roots, inactive Polypropylene fibers, and Nylon fibers, highlighting the importance of simulating root structures. The data processing methods are thoroughly explained, covering parameters like porosity, sample mass, vertical force, rate, water content, and more.

The experiments reveal interesting insight into the performance of root, Polypropylene fiber, and Nylon fiber in soil samples under multiple normal stresses (25N, 60N, and 100N). Root samples exhibit a nuanced relationship between root length density (RLD) and shear strength, with an optimal RLD range identified. Polypropylene fiber samples display inconsistent behavior, influenced by clumping during mixing, while Nylon fiber samples consistently perform well, possibly due to their elasticity. Overall, the study concludes that Nylon fibers offer superior reinforcement compared to root and Polypropylene fiber samples.

In summary, this research expands our understanding of soil reinforcement techniques by introducing living plant roots as a sustainable alternative. It underscores the importance of RLD and offers valuable insights into the performance of various reinforcement materials under different normal stresses, contributing to the advancement of eco-friendly civil engineering practices.

Table of Contents

1. Introduction

Soil reinforcement stands as a fundamental concern in civil engineering, affecting the stability and resilience of structures. The concept of reinforced soil has been in practice since ancient times, but its modern form was developed in 1966 by French architect and engineer Henry Vidal. Today, this is known as ‘systematically reinforced soil’ and most civil engineering applications use geosynthetic sheets or galvanized steel strips as reinforcement, arranged in the directions where the soil is subject to tensile strains (Sanjay Shukla, 2009). The concept of reinforcing soil with fibers, especially natural ones is called ‘randomly distributed/oriented fiber-reinforced soil’ and has recently gained attention in geotechnical engineering. Compared to systematically reinforced soils, randomly distributed fiber-reinforced soils offer strength isotropy and limit potential planes of weakness (Sayyed Mahdi Hejazi, 2012). Traditional techniques have widely relied on the use of inert fibers to enhance soil shear strength. However, with growing emphasis on sustainability and ecological balance, an alternative approach is proposed: the use of living plant roots. The research presented hereby aims to examine and contrast the behavior of granular soil reinforced in two ways: by using living plant roots and inert fibers.

2. Problem Context

2.1 Problem Description

The stability of civil engineering structures is critically dependent on effective soil reinforcement techniques. Granular soils present a significant challenge due to their inherent low tensile and shear strength, and their susceptibility to environmental conditions such as dryness or wetness. Traditional practices often reinforce soil with inert fibers, but these methods have notable limitations. These include resource depletion, high cost, and potential environmental harm.

Moreover, Sayyed Mahdi Hejazi states in his paper that soil reinforcement is a complex process that aims to improve the engineering characteristics of soil, such as shear strength, compressibility, density, and hydraulic conductivity (Sayyed Mahdi Hejazi, 2012). It involves the incorporation of materials with desired properties into the soil, which lacks those properties. The primary purpose of reinforcing soil mass is to enhance its stability, increase its bearing capacity, and reduce settlements and lateral deformation. However, some conventional methods of soil reinforcement can be ineffective or expensive, necessitating ongoing research to develop new techniques.

In light of these challenges, this study explores the viability of living plant roots as a promising alternative for soil reinforcement. Plant roots can improve the mechanical behavior of the soil composite. They contribute to the stability of soil mass by adding strength to the near-surface soils where the effective stress is low. This approach offers several potential benefits, including carbon sequestration, ecological symbiosis, and potential soil enhancement. Therefore, the use of living plant roots for soil reinforcement represents an innovative and sustainable approach to addressing the challenges associated with traditional soil reinforcement techniques.

2.2 Research Motivation

Sustainable engineering practices have never been more critical. During the current climate crisis, ecological solutions are sought to combat synthetic material dependency. The use of living plant roots for soil reinforcement integrates ecological balance with civil engineering practices, creating a symbiotic relationship between built and natural environments. Thus, the motivation for this research is to explore such sustainable practices while addressing a fundamental engineering problem. In addition, this research also aims to continue the research done previously, such as that of Alexey Matyunin where the same problem was tackled (Matyunin, 2022). This will further diversify the range of experimentation to create a broader understanding of the performance of both randomly distributed/oriented fiber-reinforced soil and randomly distributed fiber-reinforced soils.

2.3 Scientific Relevance

This research fills the knowledge gap surrounding the application of living plant roots for soil reinforcement. It aims to unravel the dynamics and performance of roots in granular soil, offering insights into plant-soil interactions under shear stress. The findings could establish a new theoretical foundation, providing design guidelines and setting the groundwork for sustainable civil engineering practices.

2.4 Previous Research

The study of shear response in granular soil has been a topic of significant interest and investigation within the field of geotechnical engineering. Prior research has provided valuable insights into the behavior of fiber and root reinforced granular soils under shear loading conditions and has laid the foundation for understanding the role of reinforcement in enhancing their mechanical properties. Some of these notable papers are the ones by Soriano and by Arciero, that speak about the mechanical response of fiber reinforced sand as well as the importance of fiber orientation (I. Soriano, 2017) (Michela Arciero, 2023). They both provide X-ray topography of the reinforced samples, that together with theoretical background, form a key step in preparing and understanding the results obtained during the experimentation period.

Moreover, the research of Pallewattha and of Matyunin also provides a lot of interesting insights about what to expect and how the experiments should be modeled when testing root reinforced soil samples. The paper of Pallewattha was used for understanding the role of the hydraulic reinforcement generated by water uptake and the theoretical background; whereas the report of Matyunin provided comparable results where the behavior of shear strength in certain root samples supported the findings in this study (Muditha Pallewattha, 2019) (Matyunin, 2022).

3. Theoretical Framework

The theoretical framework forms the bedrock of this research, drawing upon soil reinforcement principles, soil-plant interactions, and relevant scientific literature. Existing studies on inert fiber and plant root reinforcement will be synthesized, forming a theoretical base to draw comparisons and derive hypotheses.

3.1 Soil Shear Strength

Shear strength is a fundamental property of soils and is the maximum resistance of a soil to deformation by shear stress. The shear strength of a soil is typically described by the Mohr-Coulomb failure criterion, which states that the shear stress (τ) at failure is linearly dependent on the normal stress (σ) acting on the failure plane. This relationship is given by the equation (1):

$$\tau = \sigma * \tan(\phi) + c \qquad (1)$$

Where:

- **τ** is the shear stress at failure
- **σ** is the normal stress
- **ϕ** is the angle of internal friction, which is a measure of the soil's inherent resistance to shear deformation
- **c** is the cohesion

In saturated soils, the normal stress (σ) is not the same as the applied stress because the water in the soil pores also bears some of the load. This is described by the concept of effective stress, which was first introduced by Terzaghi (Karl Terzaghi, 1996).

The effective stress (σ') is defined as the difference between the total stress (σ) and the pore water pressure (u). This relationship is given by the equation (2):

$$\sigma' = \sigma - u \qquad (2)$$

Where:

- **σ'** is the effective stress
- **σ** is the total stress (also known as the total normal stress or the overburden stress)
- **u** is the pore water pressure.

Because the experiment will be conducted in unsaturated granular soil, the framework described by Tarantino is applied (Alessandro Tarantino, 2019). Thus, the failure criterion for an unsaturated soil can be written generically as follows in equation (3):

$$\tau = \sigma \tan \phi + f(s, Sr) \cdot \tan \phi \qquad (3)$$

Where:

- **$f(s, Sr)$** is the function of suction and degree of saturation (**$f(s,Sr) = s \cdot Sr$**)

This is the case because plants require consistent watering to foster the development of a robust root system within the soil samples. To ensure uniformity among the samples, identical conditions are also maintained for those reinforced with inert fibers.

3.2 Rooted Soil Shear Strength

The shear strength of rooted soil is a complex phenomenon that is influenced by a multitude of factors. This section aims to provide a mathematical formulation to explain the root failure mechanisms predominantly inspired by a mathematical model by Pallewattha (Muditha Pallewattha, 2019).

The total shear strength of the root-permeated soil can be interpreted based on three different components: (i) shear strength of the soil in a saturated condition, (ii) the increment in shear strength caused by an increase in suction, and (iii) the physical reinforcement provided by the roots. This can be represented by the equation (4):

$$\boldsymbol{\tau_{Total}} = \boldsymbol{\tau_S} + \boldsymbol{\tau_U} + \Delta\boldsymbol{\tau_T} \qquad (4)$$

Where:

- $\boldsymbol{\tau_{Total}}$ is the total shear strength,
- $\boldsymbol{\tau_S}$ is the shear strength of the saturated soil,
- $\boldsymbol{\tau_U}$ is the shear strength increased by soil suction caused by drying out or desiccation,
- $\Delta\boldsymbol{\tau_T}$ is the additional effect on shear strength due to the presence of roots (i.e., both mechanical reinforcement effect and the hydraulic reinforcement generated by root water uptake).

Both U and T are dependent on the soil suction, and they can be considered in tandem as the role of suction and root reinforcement.

The total increase in shear strength due to root effect T may be postulated by:

$$\Delta\boldsymbol{\tau_T} = \Delta\boldsymbol{\tau_R} + \Delta\boldsymbol{\tau_S} \qquad (5)$$

Where:

- $\Delta\boldsymbol{\tau_R}$ is the increase in shear strength only due to root reinforcement (including soil-root interface shear strength).

- $\Delta\boldsymbol{\tau_S}$ is an increase in shear strength due to increase of soil suction only, as derived by moisture extraction induced by the evapo-transpiration process.

This proposed model serves primarily as a conceptual development to complement the experimental observations. While its theoretical components represented by mathematical equations cannot be explicitly calibrated with the measured experimental data, it provides a framework for understanding the complex interactions between roots, soil, and water in the context of shear strength.

In Figure 1 , the shear and normal stress performance of fallow soil compared with that of soil with roots can be seen.

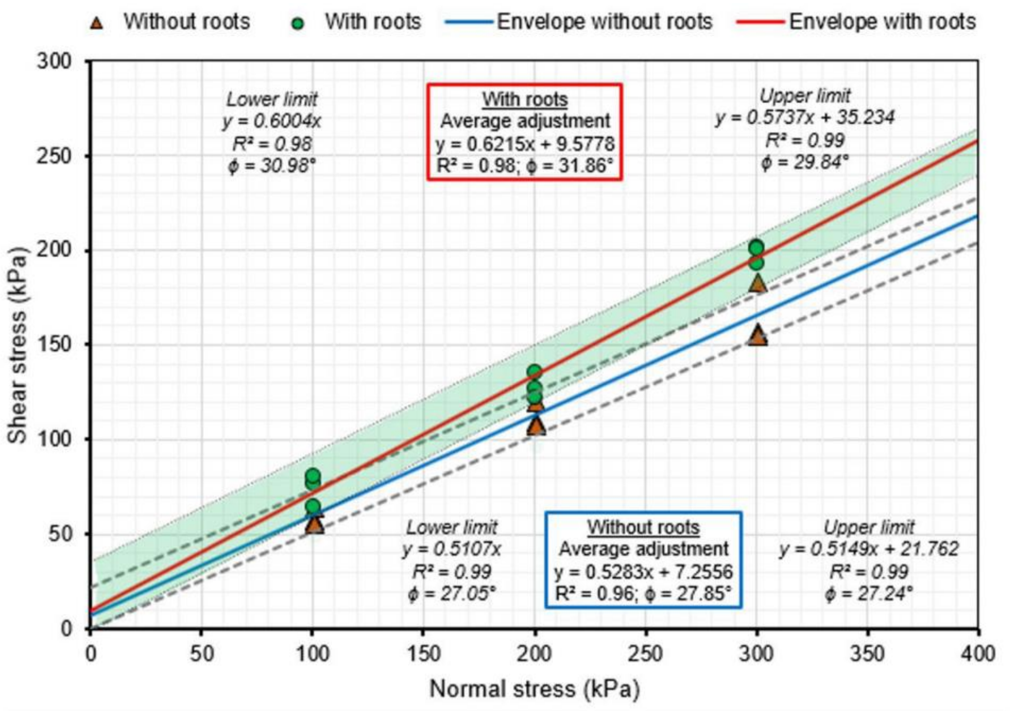


Figure 1: Failure envelopes of sandy soil with and without roots. The shaded area (soil with roots) and the dotted lines (soil without roots) represent the confidence intervals at 95% reliability (Maffra Charles, 2019).

3.3 Fiber Soil Shear Strength

Flexible fiber soil reinforcement is based on the principle that the addition of fibers to soil can improve its strength, ductility, and resistance to deformation (Michela Arciero, 2023). The reinforcement effect arises from the interaction between the soil matrix and the fibers, which modify the stress distribution, shear resistance, and overall behavior of the soil. This reinforcement can be particularly valuable in scenarios where enhanced stability, reduced settlement, and improved load-bearing capacity are required.

Equations Governing Flexible Fiber Soil Reinforcement

1. **Fiber Volume Fraction (VF):** The volume fraction of fibers in the soil is a fundamental parameter in flexible fiber soil reinforcement. It is defined as the ratio of the volume of fibers (Vf) to the total volume of the reinforced soil (Vs):

$$VF = \frac{V_f}{V_s} \qquad (6)$$

Where:

- VF = Fiber volume fraction
- V_f = Volume of fibers
- V_s = Total volume of reinforced soil

2. **Fiber Aspect Ratio (AR):** The aspect ratio of fibers is the ratio of their length (L) to their diameter (D). It is a crucial factor influencing the reinforcement effect. Higher aspect ratios generally lead to greater reinforcement efficiency:

$$AR = \frac{L}{D} \qquad (7)$$

Where:

- AR = Fiber aspect ratio
- L = Fiber length
- D = Fiber diameter

3. **Fiber Orientation:** The orientation of fibers within the soil matrix can significantly impact their contribution to reinforcement. Fiber orientation can be described using angular parameters and is important in predicting anisotropic behavior.

4. **Shear Strength Enhancement:** The Mohr-Coulomb equation, commonly used to describe soil shear strength, can be modified to account for the effect of fiber reinforcement. The modified equation includes terms related to the fiber characteristics, such as aspect ratio and orientation.

$$\tau = c' + \sigma' * \tan(\varphi' + \delta) \qquad (8)$$

Where:

- τ = Shear strength of the reinforced soil
- c' = Effective cohesion
- σ' = Effective normal stress
- φ' = Effective friction angle
- δ = Angle of internal friction due to fiber reinforcement

Factors Influencing Flexible Fiber Soil Reinforcement

Several factors influence the effectiveness of flexible fiber soil reinforcement, including fiber type, length, diameter, volume fraction, and the method of fiber incorporation. Additionally, the type of soil, its relative density and the stress state are critical considerations.

Stolen Void Ratio

The stolen void ratio represents the increase in the void ratio (ratio of void volume to solid volume) of a soil mixture due to fibers creating a dilation in the soil around them and compacting the remaining soil. It quantifies the contribution of fibers to the overall porosity or void space within the mixture.

Mathematically, the stolen void ratio (e_{stolen}) can be calculated as the difference between the void ratio of the reinforced soil ($e_{reinforced}$)and the void ratio of the same soil without fibers ($e_{plain\ soil}$):

$$e_{stolen} = e_{reinforced} - e_{plain\ soil} \qquad (9)$$

This equation expresses how much the presence of fibers increases the void ratio compared to the plain soil.

The stolen void ratio affects various properties of the soil-fiber mixture, including its compaction behavior, shear strength, and permeability. Generally, a higher stolen void ratio results in greater changes in these properties, such as reduced density and increased porosity.

A paper published by Soriano exploring the 3D fiber architecture of fiber-reinforced sand shows that in most cases, the porosity is higher locally around the fiber inclusion (I. Soriano, 2017). This can be related to a possible wall type effect, in which granular particles near a rigid wall boundary show higher porosity. In fiber-reinforced soils, Larrard estimated the perturbed zone from the face of rigid cylindrical fibers mixed with a granular soil (having an average particle size diameter of the same order of magnitude of the fiber diameter) to be about 10% of the average particle size of the soil (Larrard, 1999).

4. Research Dimensions

4.1 Research Goal

The primary objective of this research is to investigate the shear response of reinforced granular soil using living plant roots, in comparison with traditional inert fiber reinforcement. The goal is to gauge the potential of plant roots in improving the mechanical properties of granular soils.

4.2 Research Scope

The research will focus on sand reinforced with two types of fibers and select plant species. The inert fibers under consideration will vary in material composition and size, allowing for a comprehensive comparison of their performance. Laboratory-scale experiments will be conducted to control environmental variables and ensure replicability. The investigation will concentrate on the mechanical response and interaction of plant roots and inert fibers with granular soil under shear stress. The comparative analysis will extend to the different types of fibers, examining how variations in material and size influence the overall soil response under shear conditions.

4.3 Research Questions

The research intends to answer the following questions:

1. How do living plant roots affect the shear response of granular soil?
2. How does the performance of plant roots compare with inert fibers in terms of soil reinforcement?

5. Methodology

A suite of experimental and analytical methods will be adopted in this research. Laboratory testing will be performed, encompassing sample preparation, reinforcement techniques, and shear strength measurement. Data analysis will involve computational modeling to analyze and interpret experimental results.

5.1 Experiment Description

The primary methodology for this research will be experimental, utilizing a Direct Shear device shown in Figure 5. The device operates on the principle of measuring the vertical and horizontal deformation of soil. This is achieved by first applying a constant vertical stress, followed by an incrementally increasing horizontal stress on one horizontal half of the apparatus to induce a shearing effect. The device records the horizontal and vertical displacements of the soil sample, which can be used to ascertain the sample's shear strength.

5.1.1 Materials

In order to compare future results with the ones in previous papers, such as the research Alexey Matyunin (2022), similar specifications were transferred for this experiment. The similarities consist in the plant species, shear boxes, water content and soil type.

- **Plant Species**: Maize (Zea Maize L.) will be used due to its fibrous root structure and resilience in the initial growing days.
- **Soil Type**: Sand from a Dutch local quarry will be used for the experiment. The sand will be sieved to achieve the granular curved seen in Figure 3.
- **Artificial Fibers**: Two types of fibers will be used for this experiment. The first fiber is Polypropylene, used to reinforce concrete, and the second one is Nylon. Different nylon fiber diameters a chosen to match as close as possible the corelated root diameter composition. The different diameters are: 0.1mm, 0.2mm, 0.4 mm, 0.6mm, 0.8mm, 1mm, 1.5mm.
- **Number of Plant Samples**: A total of 32 plants will be planted to account for potential plant failure and the need for multiple observations.
- **Number of Fiber Samples**: A total of 18 fiber samples will be made to account for each root sample.
- **Tensiometer**: A sensor that is able to record suction levels inside the sample, measured in kPa.
- **Shear Boxes**: 10 shear boxes will be 3D printed and used in rotation with rooted soil samples to maximize time efficiency. The boxes will be modeled in SolidWorks and have dimensions of 61 x 61 x 25 mm.

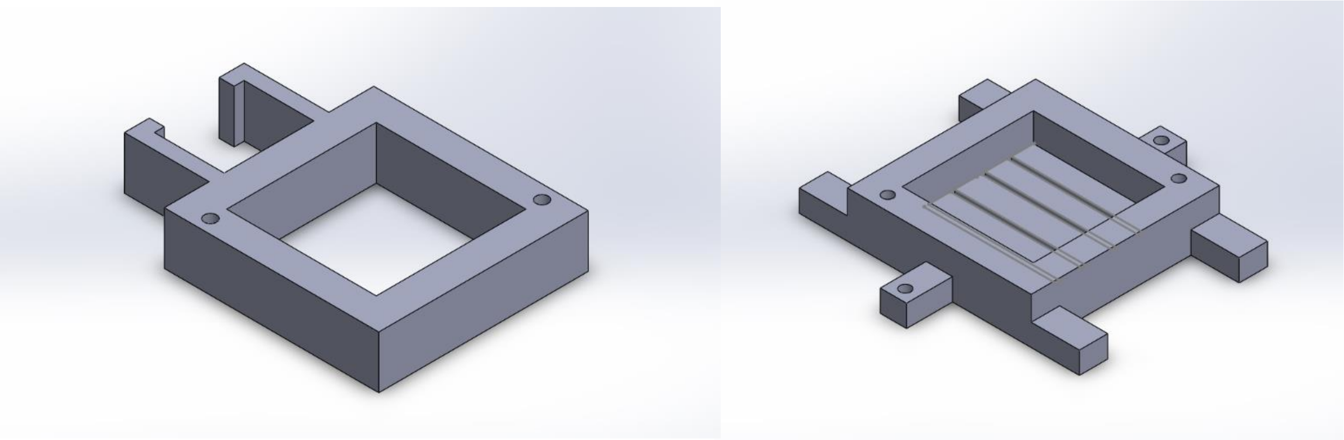
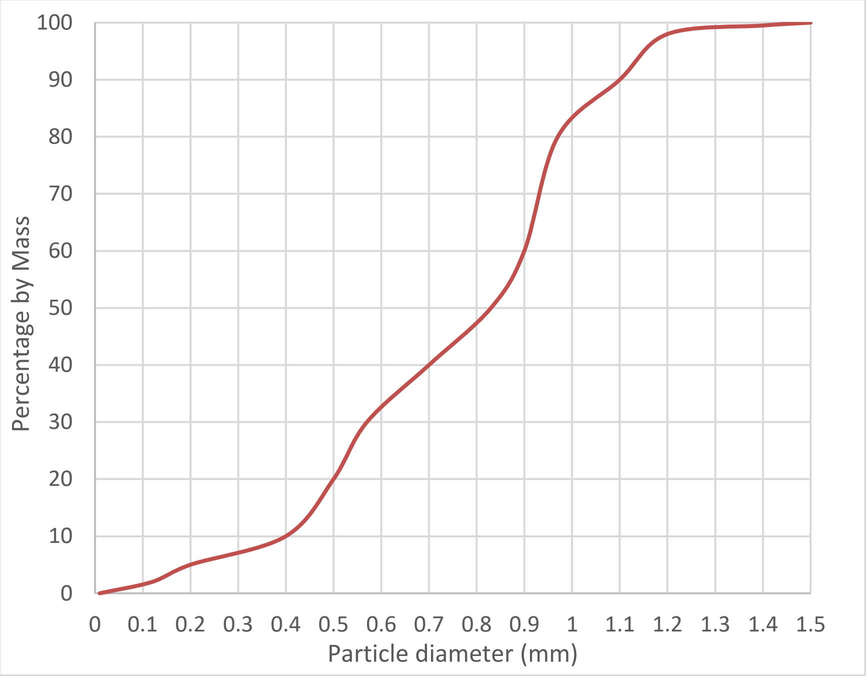


Figure 2: SolidWorks model of the shear box made by Alexey Matyunin

5.1.2 Sample Preparation

5.1.2.1 Soil Preparation

The soil used in the experiments follows the same granular curve as the one used by Alexey Matyunin (2022), as shown in Figure 3. Twelve different diameter classes were chosen for the sieving process. Both the diameter classes and the necessary quantity can be seen in the table below.



Diameter (mm)	Weight (kg)
0.01	0.05
0.125	0.15
0.212	0.1
0.255	0.2
0.3	0.2
0.425	0.3
0.5	1
0.6	1
0.85	2.3
1	0.927
1.25	0.74
1.4	0.2
Total:	10

Figure 3: Sand granulometry and the sieve class weight values for obtaining 10kg of the sand used.

5.1.2.2 Rooted Sample Preparation

Growing a plant in a cell for a Direct Shear test involves a series of steps that ensure the plant roots permeate the soil adequately to influence its shear strength. Appendix B shows photographs of both the roots and the leaves of the root samples that were grown.

Steps of the designed protocol:

1. **Germination**: Begin by germinating the Maize seeds. This should be done in water-saturated cotton discs under controlled temperature conditions, ideally between 18-21 degrees Celsius. This germination period should last for approximately two days.
2. **Planting**: After the germination period, plant the seeds into the 3D printed shear boxes. This is done by carefully pouring the sand through a small funnel into the shear box to make sure the porosity is at 42%. The seed is placed before pouring the last layer of sand to assure that it is not buried too deep nor is it too exposed. The sample is then watered with a syringe as to not disturb the soil, with 22.8 g of nutrient water that represents the 12% water content, and the weight of the sample is noted in the data log. As a precaution, the sample is covered with paraffin to prevent losing water to evaporation.

3. **Growth**: The prepared samples are placed in a growing chamber that provided a controlled environment for plant growth. A day-night cycle was imposed using a timer-controlled cold UV light. A temperature of 24° was always maintained along with a relative humidity of 46%. This growing chamber maintains precise conditions, including temperature, humidity, and light cycles, enabling the maize plants to develop robust root systems within the sand medium over a predetermined growth period.
4. **Testing Preparation**: At the end of the growing period, the paraffine is removed and the sample is photographed. After that, the stem is cut, weighted, and photographed. The sample is then checked to make sure it has the same weight that coincides with 12% water content. If water needs to be added, the sample will be left to absorb the water for at least 10 minutes after which a tensiometer is placed inside the sample for 15 minutes in order to record the suction value that is later acquired from the datalogger.
5. **After Testing**: The sample is removed from the Direct Shear machine and the root is carefully extracted to be weighted, photographed, and measured. The root is divided into 3 classes, namely: the main root, the secondary root, and the lateral roots present on the main root. Each root class's diameter is measured and noted in the data log.

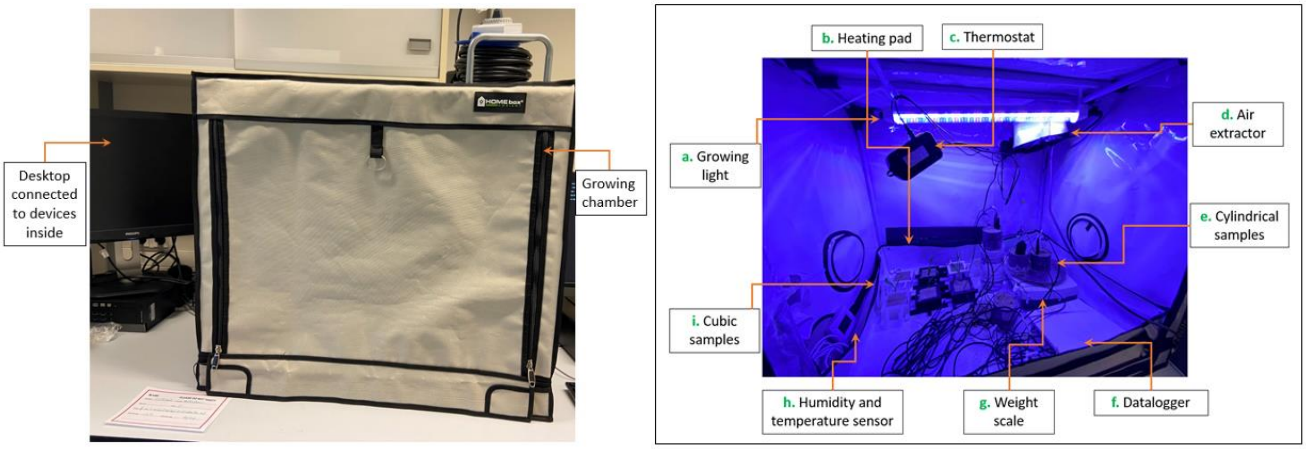


Figure 4: Growing chamber and equipment

5.1.2.3 Polypropylene Fiber Sample Preparation

To make sure the polypropylene fiber sample is as reliable as possible for experimentation the following step in its preparation need to be followed:

1. **Fiber Volume**: Begin by identifying the correct volume that needs to be added based on the volume of the root of the corelated root sample and the density of the fiber.
2. **Fiber Mixing**: Uniformly and randomly mix the fibers into the soil, preventing clumping as much as possible. Add the fibers gradually to the soil mix. Continue adding until uniformity of mixing is confirmed by visual inspection. This is done to simulate the root structure as closely as possible.
3. **Matching Water Content**: The mix is then poured into the shearing box and watered with a syringe to match the 12% water content. This is important for maintaining consistency between the samples.

4. **Testing:** The sample is left to reach a status of equilibrium for a minimum of 10 minutes, and is then weighted and placed inside the Direct Shearing machine.

The properties of the fiber are as follows:

Property	Value
Density	0.00091 g/mm3
Diameter	0.3 mm
Length	2-3 cm

Table 1: Polypropylene fiber properties

5.1.2.4 Nylon Fiber Sample Preparation

To make sure the nylon fiber sample is as reliable as possible for experimentation the following step in its preparation need to be followed:

1. **Fiber Length/Diameter**: Begin by selecting the appropriate nylon fiber diameter from the available classes to match the corelated root sample's root length and diameter as close as possible. A photograph of the fibers is taken for future reference.
2. **Fiber Mixing**: Start pouring the sand in the shearing box and gradually place the nylon fiber both vertical for the bigger and medium diameters, and horizontal for the small diameters. This direction is imposed to better simulate the root structure.
3. **Matching Water Content**: The mix is then watered with a syringe to match the 12% water content.
4. **Testing:** The sample is left to absorb all the water for a minimum of 10 minutes, and is then weighted and placed inside the Direct Shearing machine.

The properties of the fiber are as follows:

Property	Value
Density	0,00115 g/mm3
Diameter	0.1 mm – 1.5 mm
Length	-

Table 2: Nylon fiber properties

5.1.3 Data Processing

All the steps from the experiments have been documented and photographed. A list with all the required data, processing methods, and uses have been listed in Table 3. A more detailed table with all the information, such as sample mass, suction, root weight, and leaf weight can be found in Appendix A.

Data type	Method	Use
Porosity	It is acquired by choosing the proper soil weight (190.3 g) for the given volume (360 mm^2)	The porosity is the same Alexey Matyunin (2022) used, in order to compare the results
Sample mass	It is given by weighing the sample right before testing	Documentation
Vertical force	This can be changed by replacing the weights on the shear	Different vertical forces are used in order to see how the

	machine hanger (25N, 60N, 100N)	samples behave under higher/lower stresses
Rate	This can be changed manually by turning an analog knob on the shearing machine (0.5 mm/min)	The rate is the same Alexey Matyunin (2022) used, in order to compare the results
Water content	It is predetermined and acquired by watering the sample with 23.8 ml to acquire 12% water content	The water content is the same Alexey Matyunin (2022) used, in order to compare the results
Suction	It is given by a tensiometer that is placed and left inside the sample for 15 min right before testing	It is used to identify how much of the shear strength of the sample can be related to the retention properties of the system
Root weight	The root is weighted after testing	Documentation
Leaf weight	The leaf is weighted after it is removed from the sample	Documentation
Root length	It is determined with the use of an image processing software named Fiji after the root has been photographed	Used for determining the needed nylon fiber length and furthermore finding the RLD
Root volume	It is determined by finding the area of each root class and multiplying it with the length	Used for determining how much fiber weight I needed
Fiber weight	It is determined by multiplying the root volume with the density of the polypropylene fiber ($0.00091\ g/mm^3$)	Documentation
RLD	It is determined by dividing the total root length of a sample with the total volume of the sample ($360\ mm^2$)	Used to compare the different root samples and determine a trend

Table 3: Data collected during the experimentation period, how it was acquired, and what it was used for.

5.2 Experiment Setup

Both the root and fiber samples were weighted and checked to make sure they have the correct water content. After the weight was noted into the data log, the sample was placed inside the Direct Shear device and covered with a steel plate that has ridges oriented in the shearing direction. The hanger is then placed over the metal plate and the security screws are taken out. The Direct Shear machine's sensors can be monitored from the computer where the weight, area, and height of the sample are introduced before the testing. Before starting the consolidation stage, the desired normal force is applied on the hanger, namely: 25N, 60N, 100N. After the vertical displacement curve becomes asymptotic the consolidation test is stopped and the device is set to a speed of 0.5 mm/min and all the sensors are reset in preparation for the direct shearing stage. The shearing device is set to take measurements every 0.01 mm and will be stopped manually once the force curve becomes asymptotic. At the end of the final stage, the device is reset to the initial position and the results are saved as a text file on the computer and later transferred on Excel for data analysis.

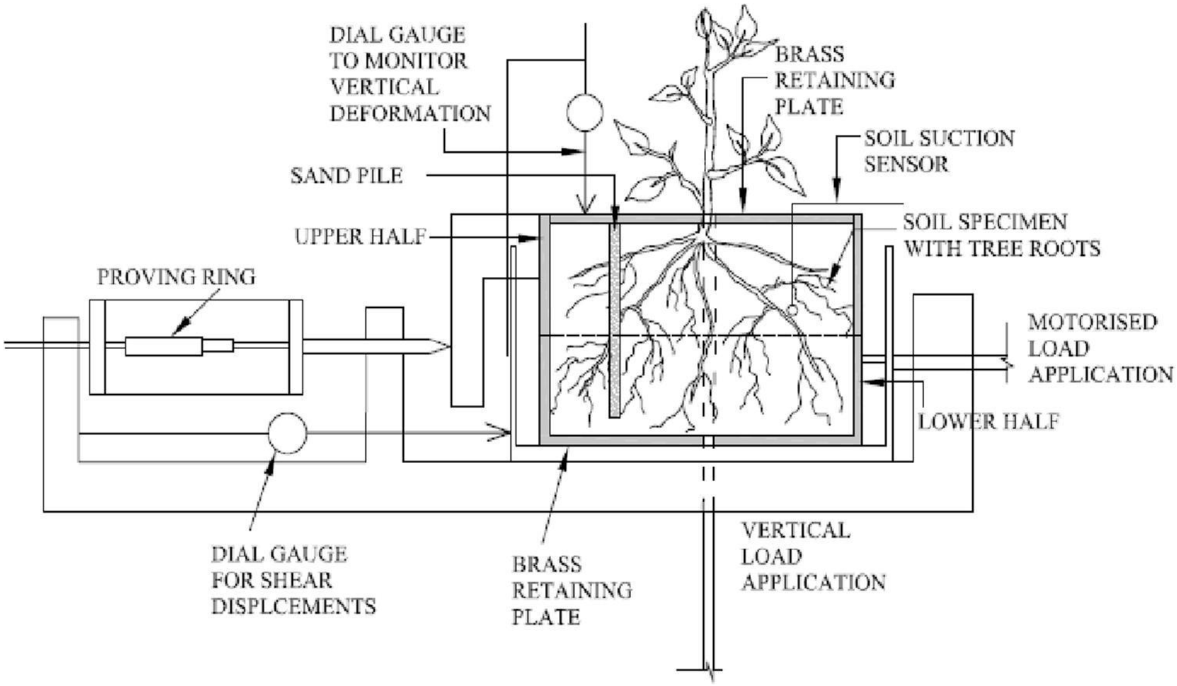


Figure 5: Diagram of a Direct Shear device measuring the horizontal and vertical displacement of a soil sample with vegetation (M. Pallewattha et al., 2019)

6. Results

In this section the results found will be presented. Each sample type will be discussed individually and compared with a reference curve that represents the average of minimum three bare soil samples within their respective vertical force class (25N, 60N, 100N). Moreover, a comparison between the similar RLD samples will be shown in order to determine if there is any trend present.

6.1 Root Sample Results

All root samples have been ranked in order of their RLD (root length density), ranging from green, with the lowest RLD, to red, which has the highest RLD. This is done in order to better understand how the different presence of the root affects the shear strength of the sample.

25N

The first batch made and the one with the lowest normal stress applied shows an improvement in the performance of three rooted samples when comparing it with the bare sample, with only two samples underperforming and one sample behaving the same as the bare sample. When looking at the RLD, it can be said that, generally, samples with more root presence perform better, but it does not constitute a trend as it is not a tight relation. However, when looking at the root engagement, a trend can be noticed, where samples with higher RLD reach their failure locus later, presumably because of the higher quantity of roots being engaged for longer. It is also worth noting that the highest performing sample does not have the highest RLD but comes second at 0.185 cm/cm^3.

Rank	Sample	RLD (cm/cm3)	Color
1	R-001	0.261053	🟥
2	R-003	0.185261	🟫
3	R-002	0.170517	🟧
4	R-005	0.138	🟨
5	R-004	0.054167	🟩
6	R-006	0.053583	🟩

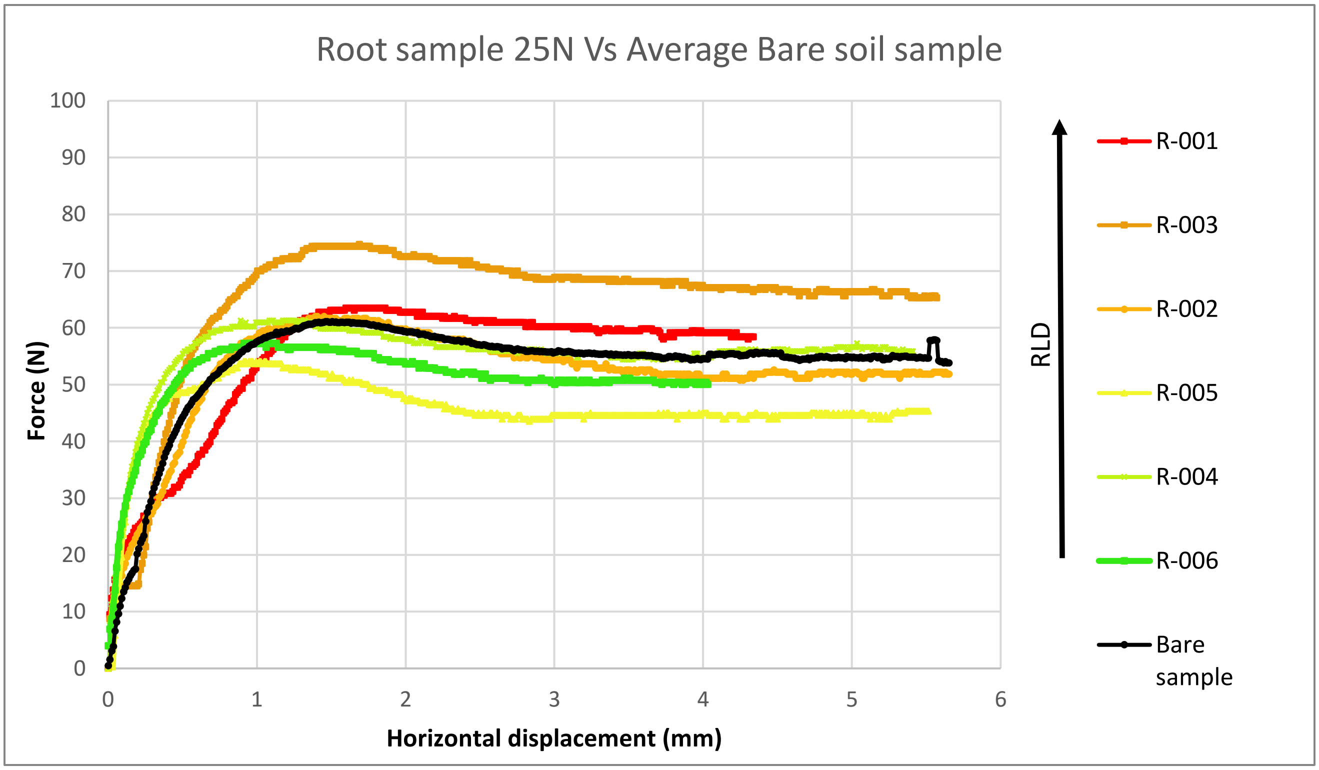


Figure 6: Root samples VS average bare sample with 25N normal stress applied

The underperformance of the last three samples can be explained by the fact that the plants were growing for quite a while and the roots began to dry out, thus shrinking and becoming more susceptible to braking and slippage. This could explain the performance of both the shear strength and the root engagement.

60N

This is the third batch performed, and it was done as an intermediate step to the 100N batch. It behaved in an unexpected way, with all root samples underperforming. Moreover, in this case it seems like the samples with less RLD are performing better than the ones with higher RLD. Despite this, the best performing sample is the one on second place, same as in the first batch, with a RLD value of 0.175 cm/cm^3. The root engagement is also worth considering, with sample 6 being the only one not following the trend and reaching its failure locus way before the others.

Rank	Sample	RLD (cm/cm3)	Color
1	R-004	0.341	🟥
2	R-005	0.1751	🟫
3	R-003	0.134294	🟧
4	R-006	0.133894	🟨
5	R-001	0.106122	🟩
6	R-002	0.099869	🟩

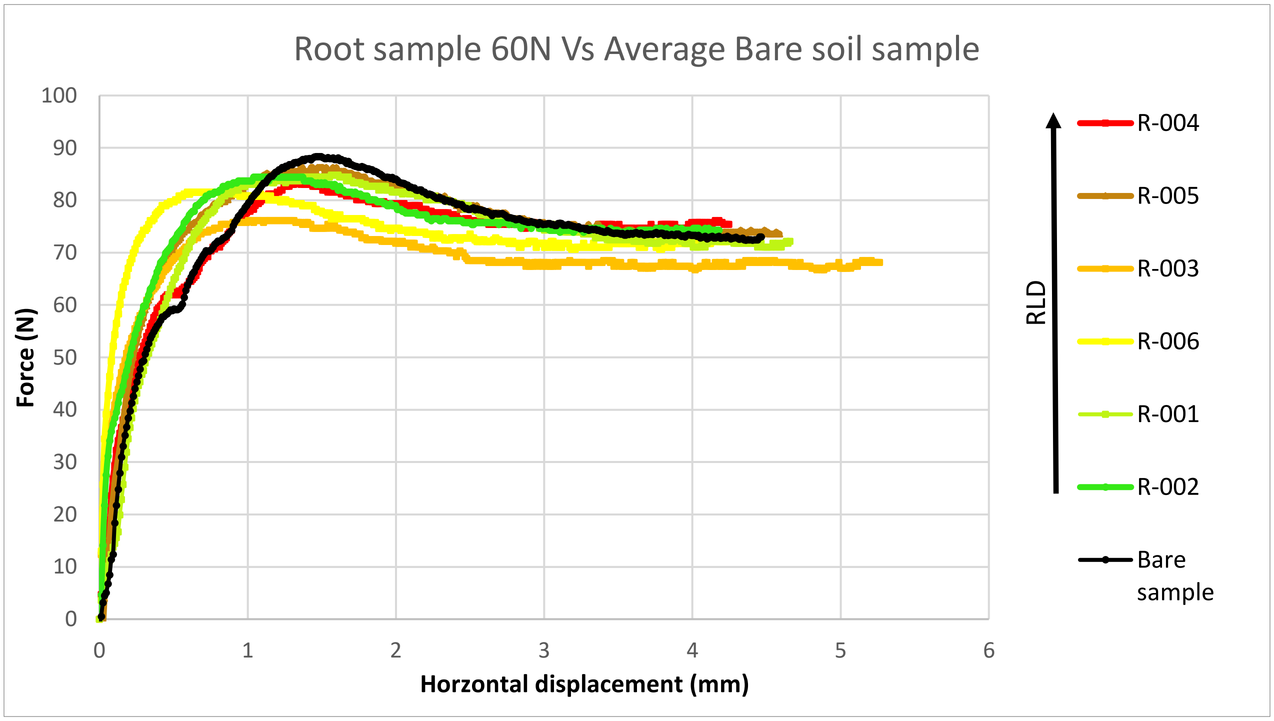


Figure 7: Root samples VS average bare sample with 60N normal stress applied

The overall performance of this batch raises some questions when comparing the root samples to the average bare soil, but looking at the root samples separately, we see that they behave similarly to the other batches in terms of root engagement performance and of the RLD amount of the best performing sample. Nevertheless, an additional five root samples and two bare samples from which a new average will be made have been tested in order to further investigate the total underperformance of the root samples. These results can be seen below, in Figure 8.

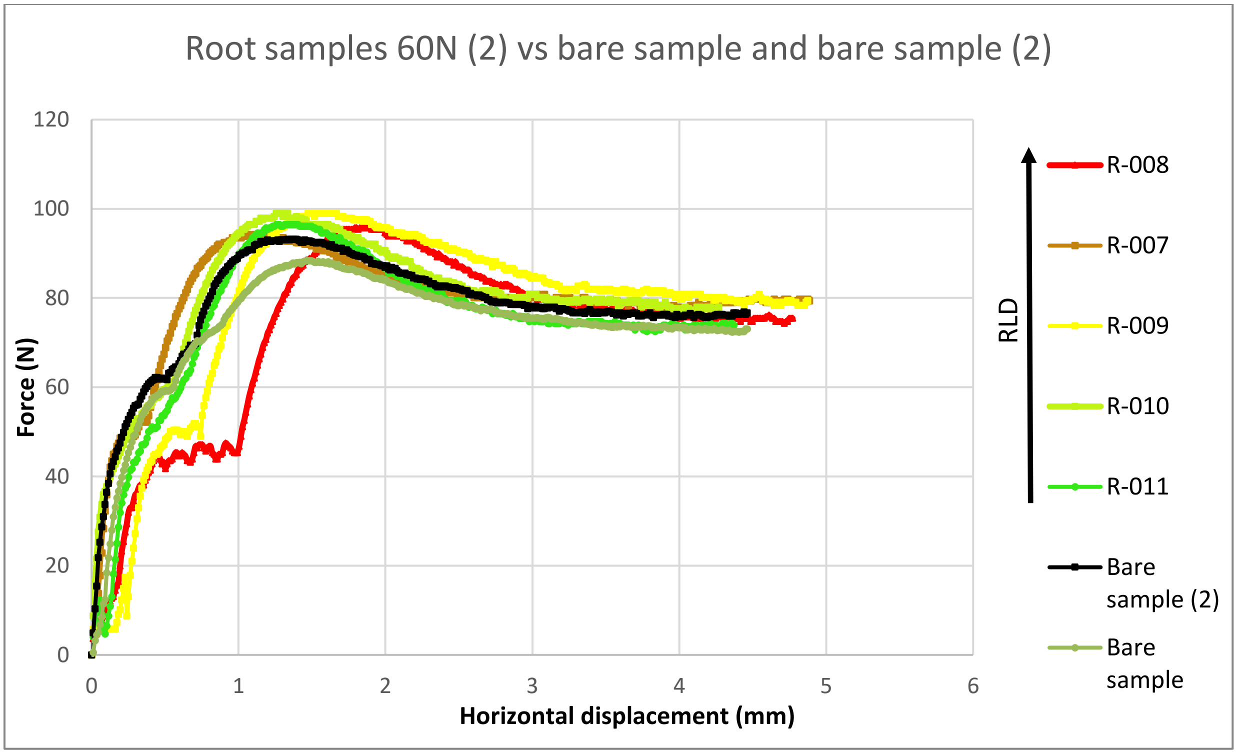


Figure 8: Redo batch of root samples VS average bare sample with 60N normal stress applied

During the growing period of the sample, only two of them made it to maturity (sample R-007 and R-008), one of them had a small main root of about 1-2 cm (R-009) and the other two did not grew at all, only the seed being recovered after the testing. Despite this, all of the root samples performed better than both the bare samples. These results point to the fact that the initial 60N batch was compromised in some way. One explanation could be that reused sand was used when preparing the batch and the heat from the drying process of the sand weakened the properties of the soil. That being said, the results should not be completely disregarded as they still provide valuable insights.

100N

The last batch had the performance of the root samples. Not only did all the root samples outperform the bare sample, but a very clear root engagement can be seen in almost all root samples. This is indicated by the fluctuation of the curve in the first part of the graph where presumably there is root slippage, causing the horizontal displacement without extra force being applied. That being said, the RLD values of the root samples do not show much about their behavior, with sample number 2 having the best shear strength and sample 4 having the best root engagement, both having rather low RLD. A compromise between the two is sample 5 with an RLD of 0.177, which even though it does not have the best performance, it follows closely behind, while also having a much better root engagement, with the failure locus occurring much later than in sample 2.

Rank	Sample	RLD (cm/cm3)	Color
1	R-003	0.227942	🟥
2	R-001	0.224894	🟫
3	R-005	0.177222	🟧
4	R-002	0.106147	🟨
5	R-004	0.060136	🟩
6	R-006	0.057447	🟩

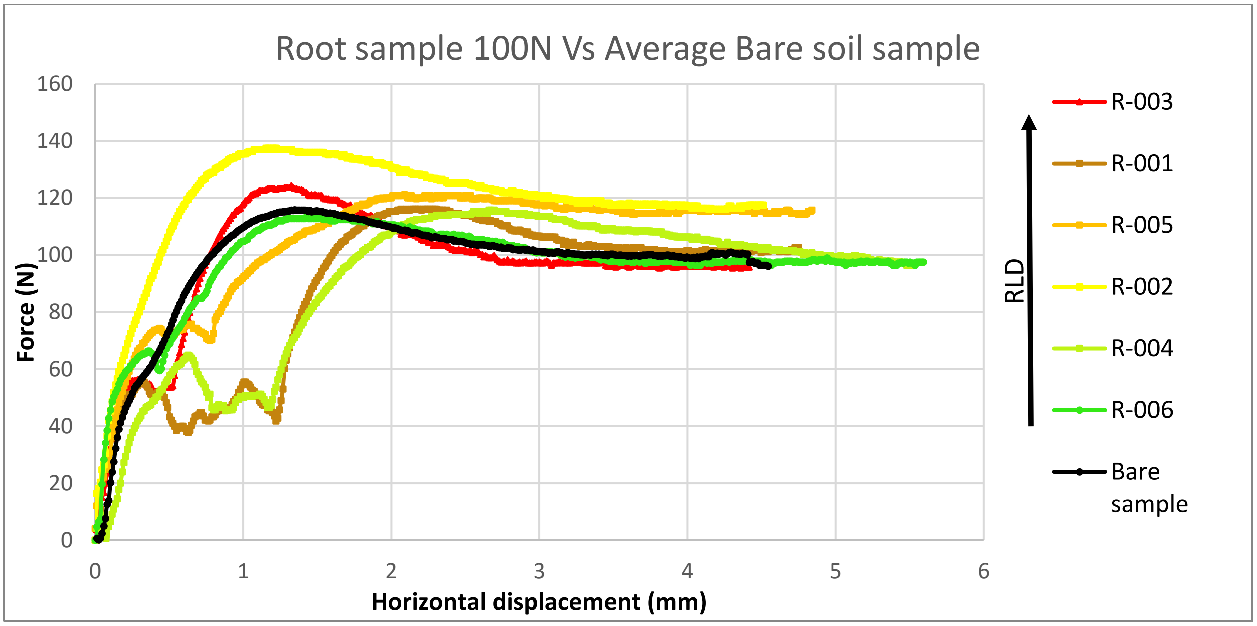


Figure 9: Root samples VS average bare sample with 100N normal stress applied

6.1.1 RLD Comparison

Following the experiments, five classes consisting of samples with similar RLD were formed in order to better understand what the connection between RLD and performance is. The graphs of all classes are listed below for better visualization. The first thing we notice is that samples with similar RLD within the same batch behave almost the same when it comes to shear strength with one exception (R-003-25 and R-002-25); but a couple of differences in root engagement can be seen in the 100N batch samples.

After closer examination, we notice that the best performing RLD class overall is 0.170-0.185, more specifically sample R-003-25, R-005-60, and R-005-100. With R-003-25 and R-005-60 having the highest shear strength in their respective batches, and R-005-100 showing a great shear strength and root engagement.

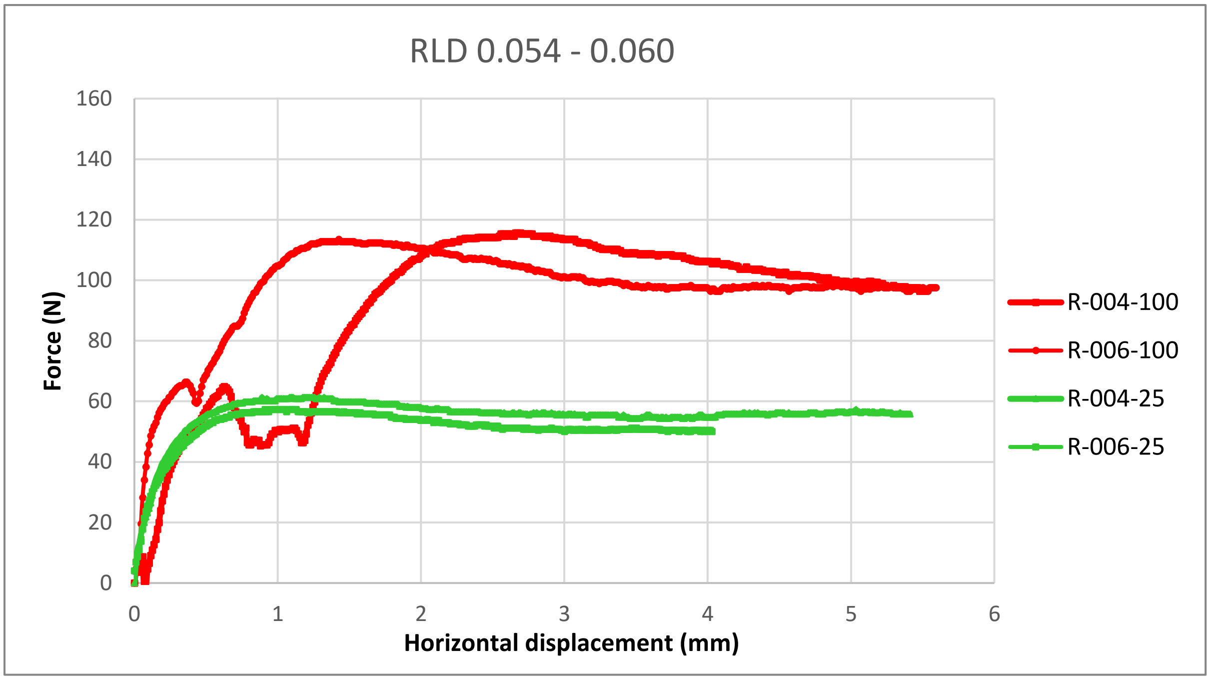


Figure 10: Comparison of different root samples with similar root length density (0.054-0.060)

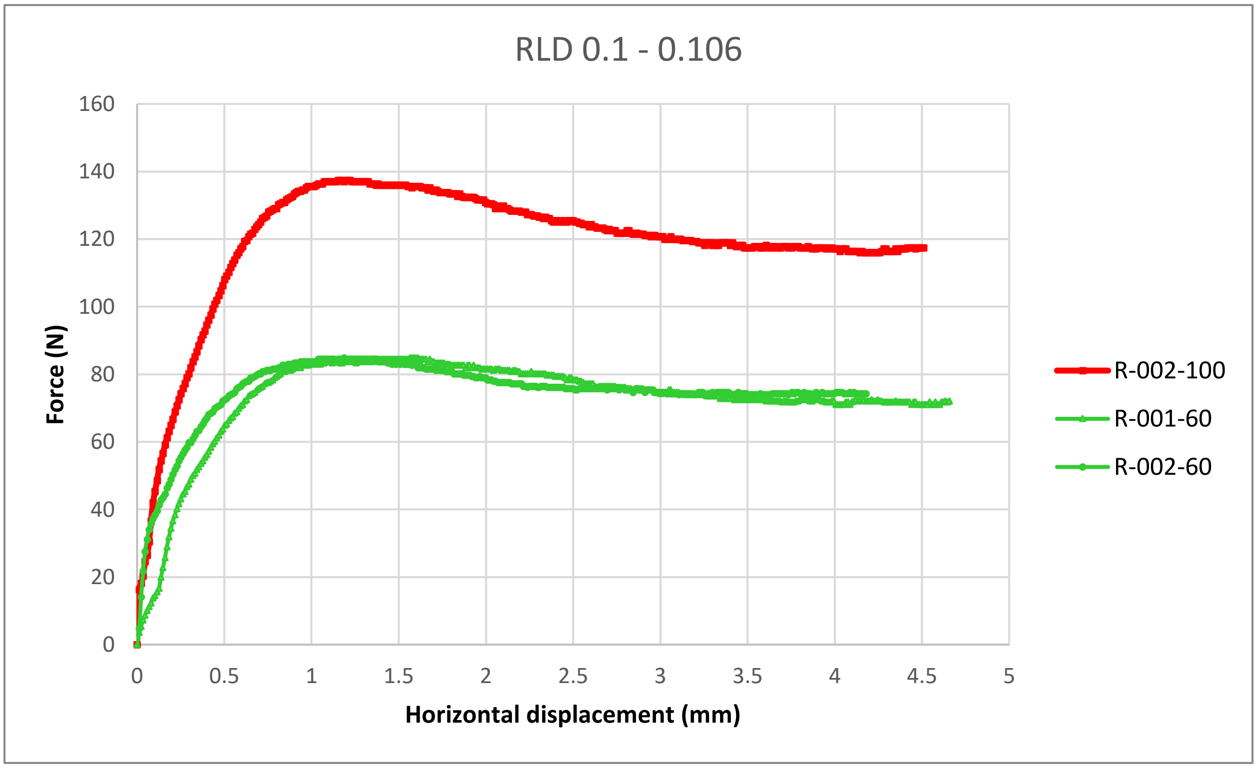


Figure 10: Comparison of different root samples with similar root length density (0.1-0.106)

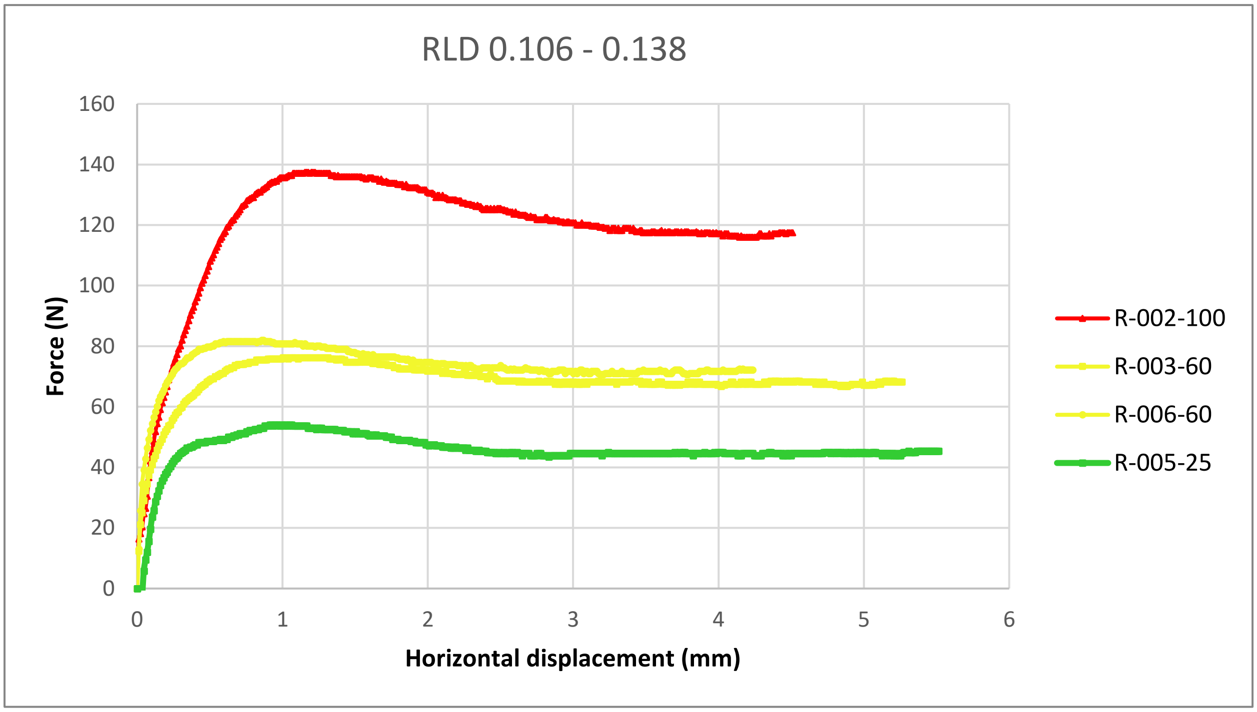


Figure 11: Comparison of different root samples with similar root length density (0.106-0.138)

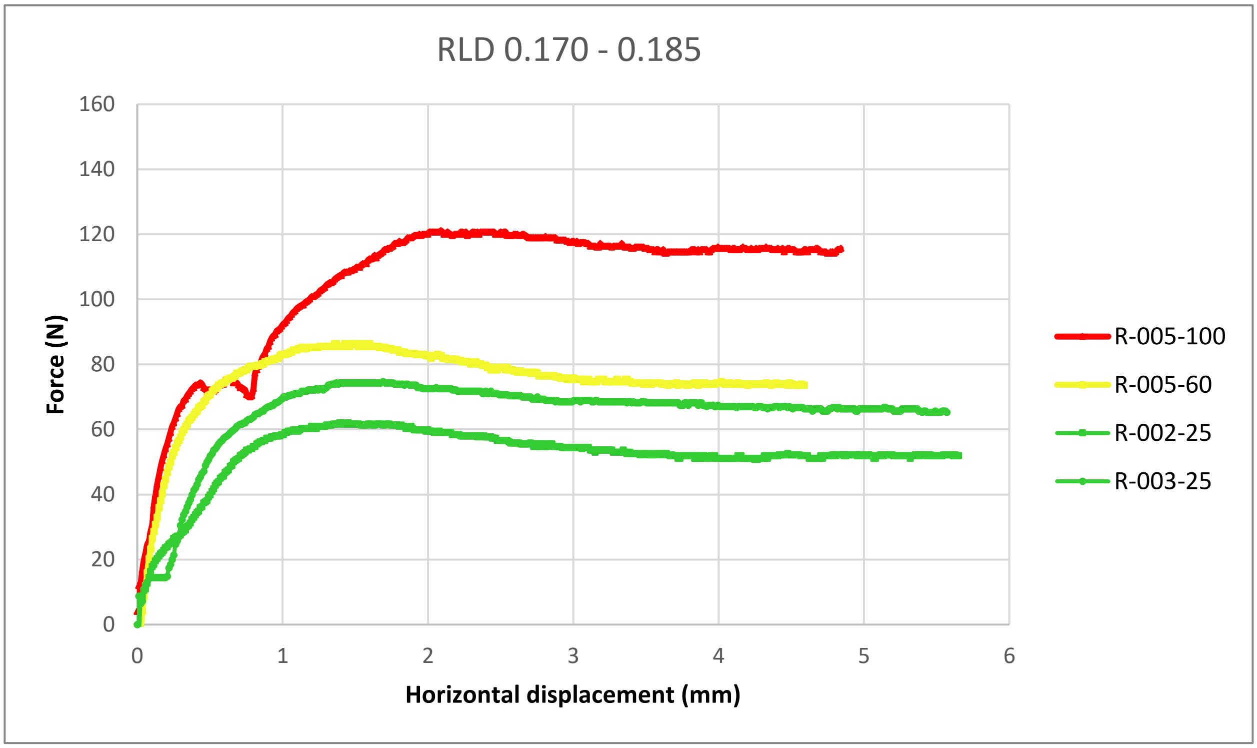


Figure 12: Comparison of different root samples with similar root length density (0.170-0.185)

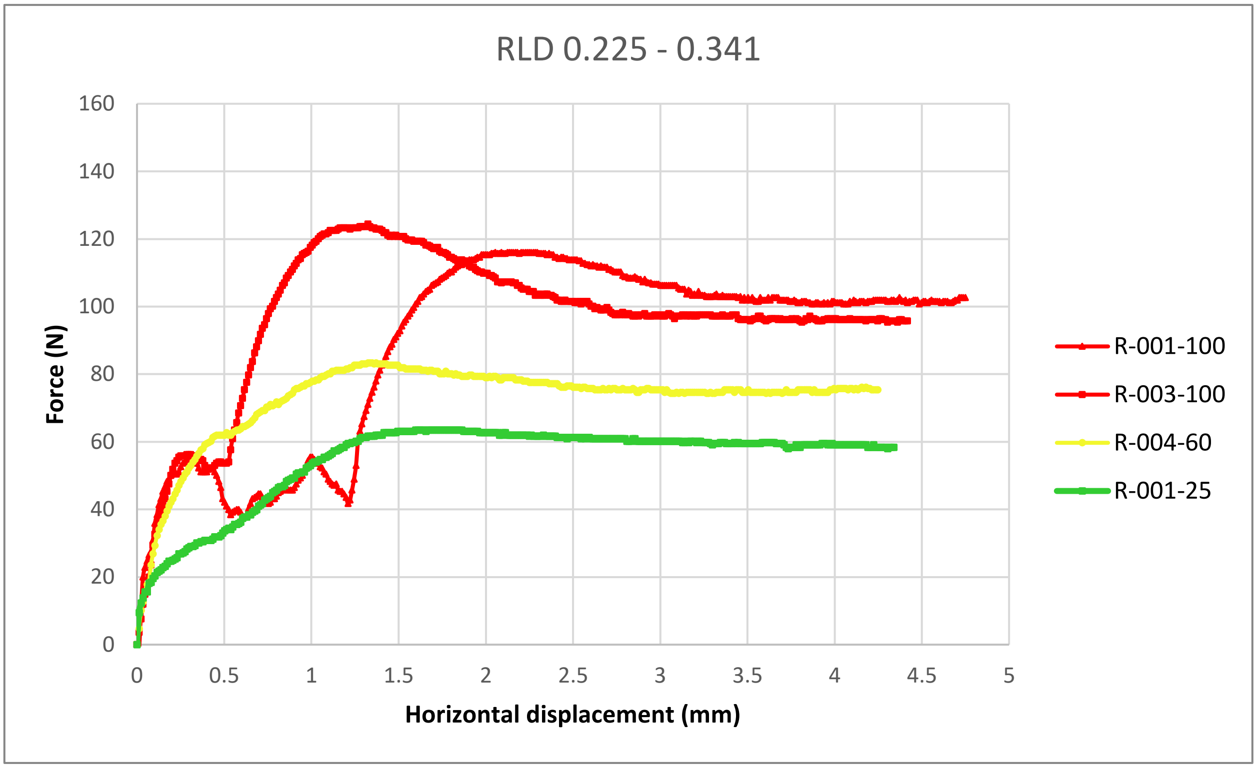


Figure 13: Comparison of different root samples with similar root length density (0.225-0.341)

6.2 Polypropylene Fiber Sample Results

The Polypropylene fiber samples were prepared to mimic the same root volume from their respective counterparts (R-001-25 same as F1-001-25).

25N

The first batch showed promising results for the Polypropylene fiber samples, with the majority of the samples performing better than the root samples. Moreover, the fiber samples show greater fiber engagement, with the failure locus being closer to 2 mm rather than to 1 mm and fiber slippage occurring in 4 out of the 6 samples. That being said, root sample R-003-25 still has the highest shear strength when compared to the fiber samples.

The trend of the Polypropylene fiber samples seems to be the opposite of the root samples, with higher volume of Polypropylene fibers resulting in a lower shear strength. This trend together with the fiber slippage can be explained by the clumping of the fiber when mixing the sample. Larger amounts of Polypropylene fibers have a larger chance of forming clumps that will lead the sample to have higher porosity and thus a lower shear strength. Fiber clumping also explains the fiber slippage, as it occurs when the clump is ripped, and the soil moves without any extra force needed.

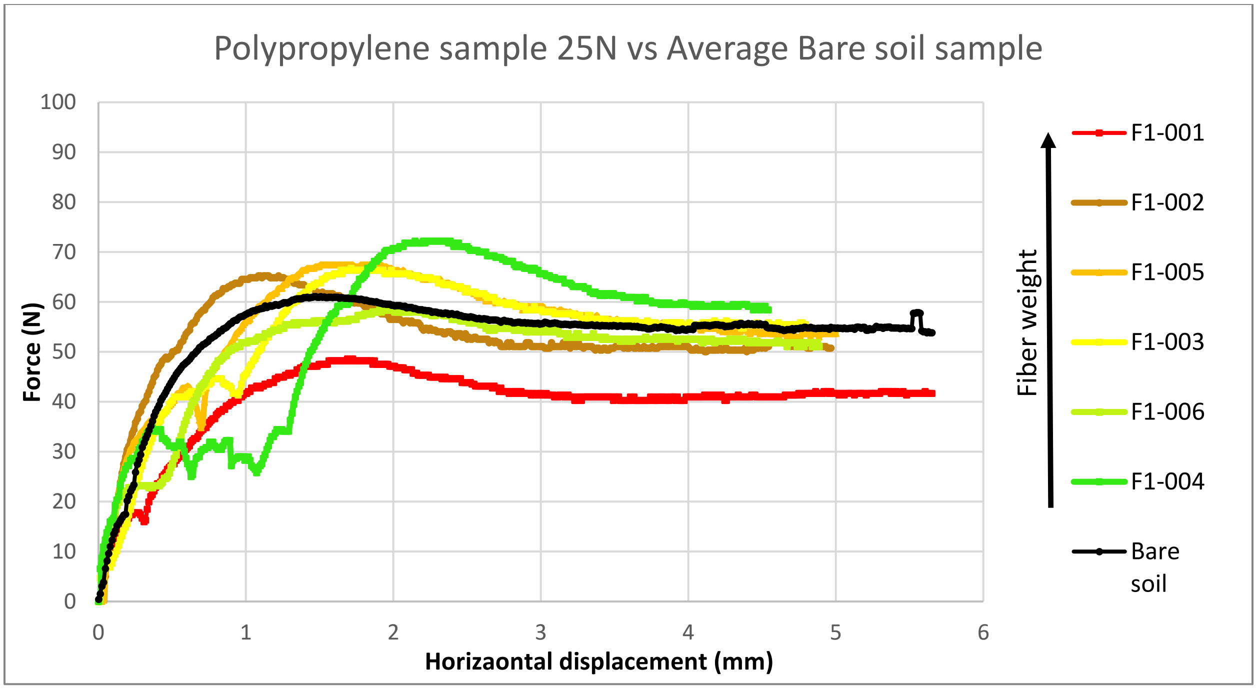


Figure 14: Polypropylene samples VS average bare sample with 25N normal stress applied

60N

The second batch made with Polypropylene fibers shows the opposite trend compared to the previous batch, with higher fiber presence resulting in higher shear strength. The fiber engagement is also less present in this batch. This is probably a result of better mixing of the fibers with the soil that lead to less clumping and thus a better performance overall.

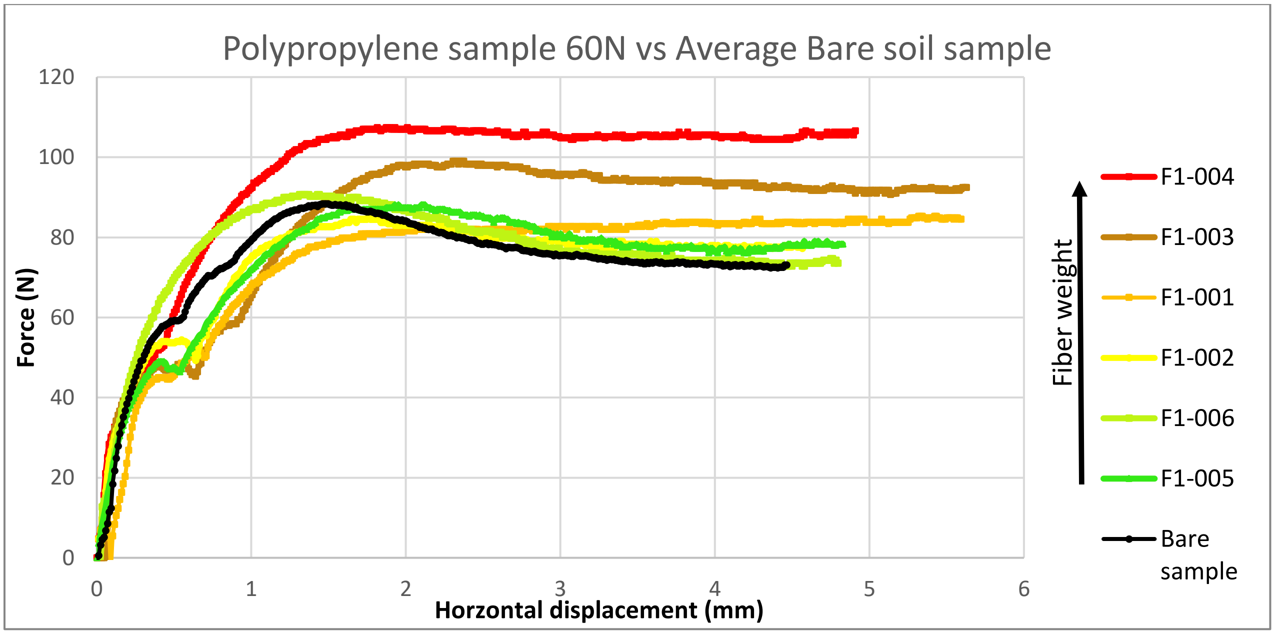


Figure 15: Polypropylene samples VS average bare sample with 60N normal stress applied

100N

In the last batch, almost all samples behaved the same, and also as the bare sample. This can only mean that the fiber played almost no role in the shear strength of the sample at this normal stress, with only small deviations from the bare sample being recorded.

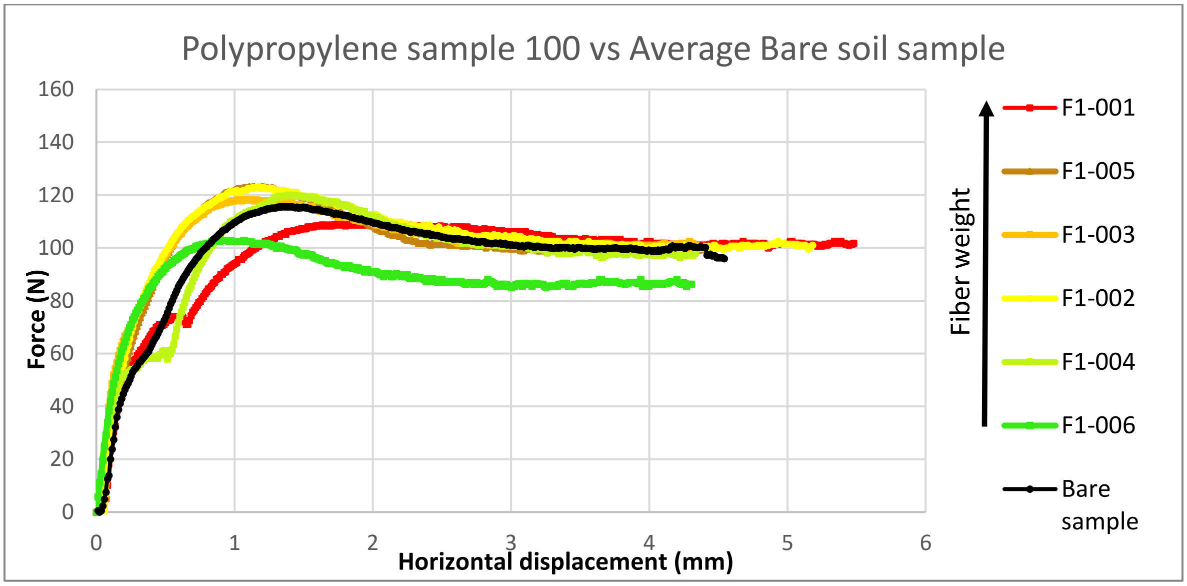


Figure 16: Polypropylene samples VS average bare sample with 100N normal stress applied

6.3 Nylon Fiber Sample Results

The Nylon fiber sample were ranked by RLD, same as the roots, each Nylon fiber having the same RLD as the coinciding root sample (e.g., F2-001-25 same RLD as R-001-25). The samples were prepared by matching each root class length and diameter with the available Nylon fibers. An orientation was also imposed to the fibers, with thicker fibers representing the main and secondary roots being placed vertically, and the thin fibers representing the small roots being placed horizontally. By doing so, the engagement of the fibers was encouraged.

25N

The first batch shows a clear overperformance of the Nylon fibers, with all the samples performing better than the bare sample. Furthermore, the appearance of a trend can be argued, where higher RLD shows an improvement in performance either in shear strength or in fiber engagement. The top performing sample, which has the highest shear strength, also has the best fiber engagement by far.

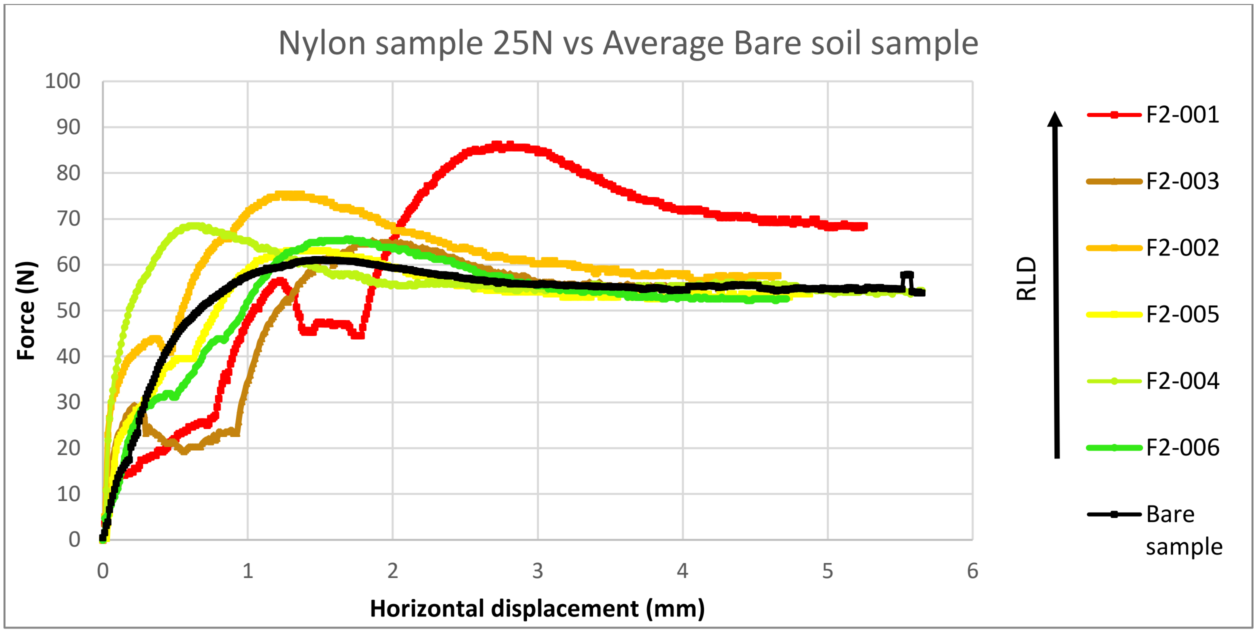


Figure 17: Nylon samples VS average bare sample with 25N normal stress applied

60N

The second batch further solidifies the findings from the first batch. It follows the same trend, where higher RLD leads to a better performance with the exception of F2-005. The exception can be explained by fiber slippage, where the orientation of the fiber did not lead to its engagement, so it did not add to the shear strength of the sample. It is worth noting that all the failure loci of the fiber samples happened before the bare sample, indicating that the fibers were not as engaged as in the first batch.

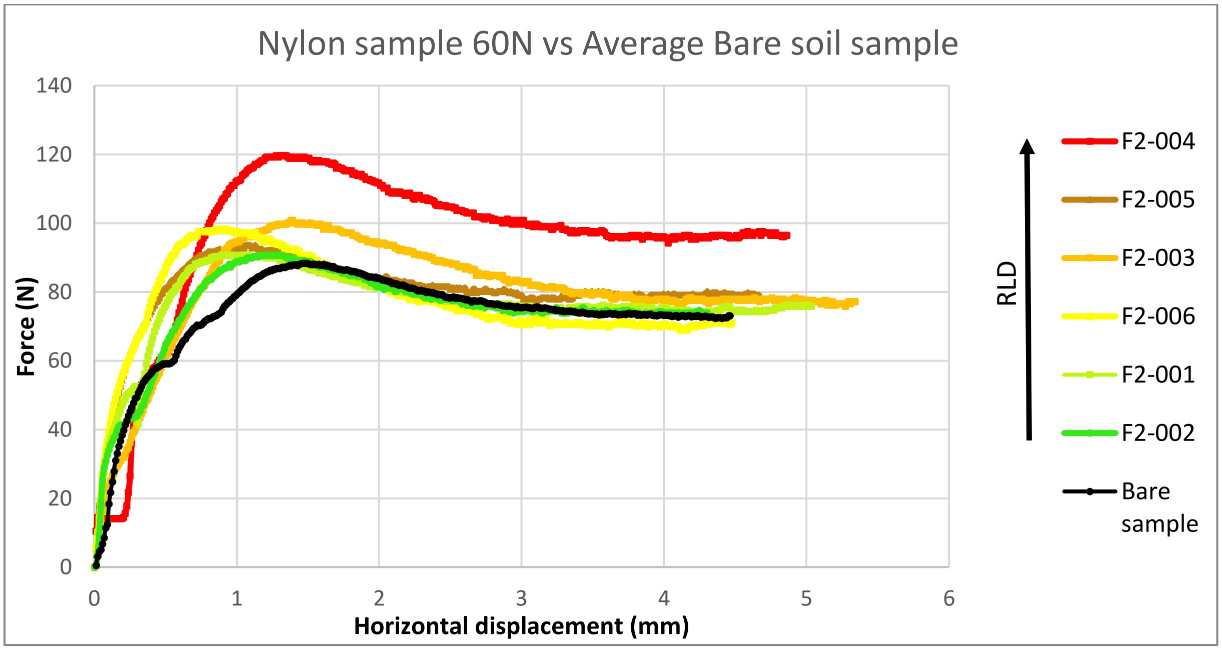


Figure 18:Nylon samples vs average bare sample with 60N normal stress applied.

100N

The final batch follows the same trend as the other two batches, being the clearest case out the three. A clear increase in the shear strength can be seen with the increase of RLD, with the top two samples having very similar RLD (0.227 and 0.225), and so, a similar performance.

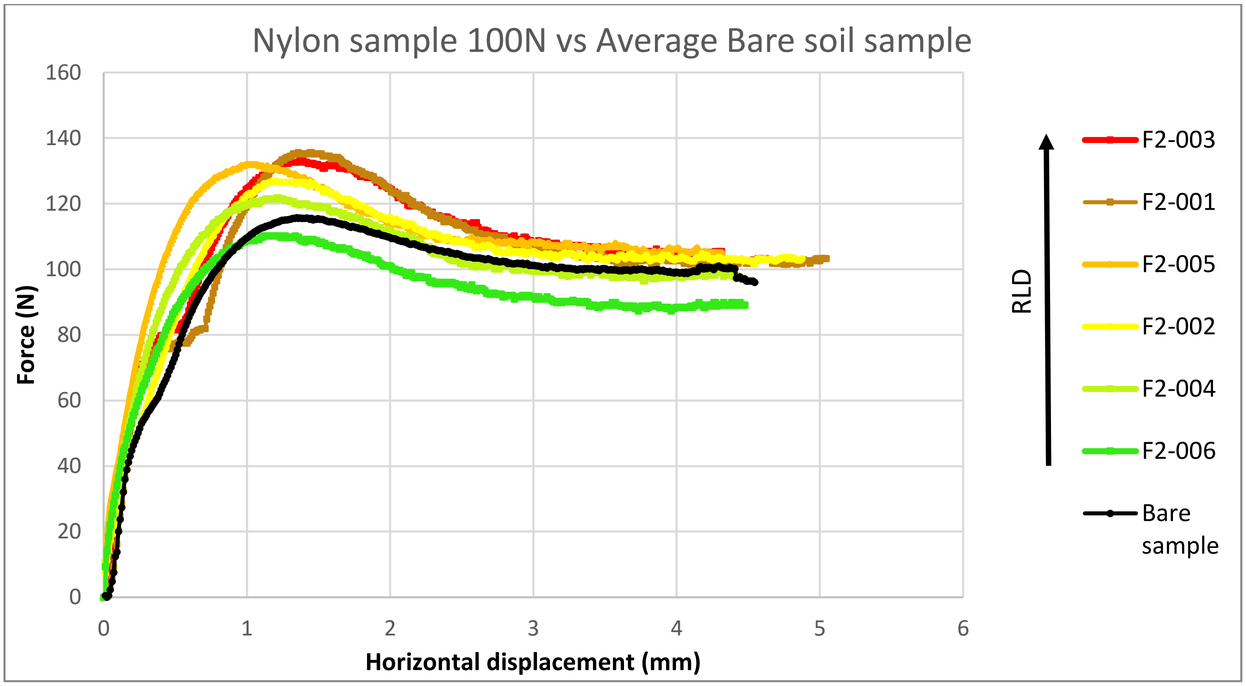


Figure 19: Nylon samples VS average bare sample with 100N normal stress applied

7. Discussion

7.1 Root Sample Discussion

The first observation made during this study was that an increase in normal stress results in a higher shear strength of all sample types. This is totally expected as higher stress usually denotes higher friction between the particles. Furthermore, it appears that root engagement also increases with higher normal stresses, with almost no apparent root engagement in the first batch and gradually showing a positive shift in the failure locus in the second and third batch.

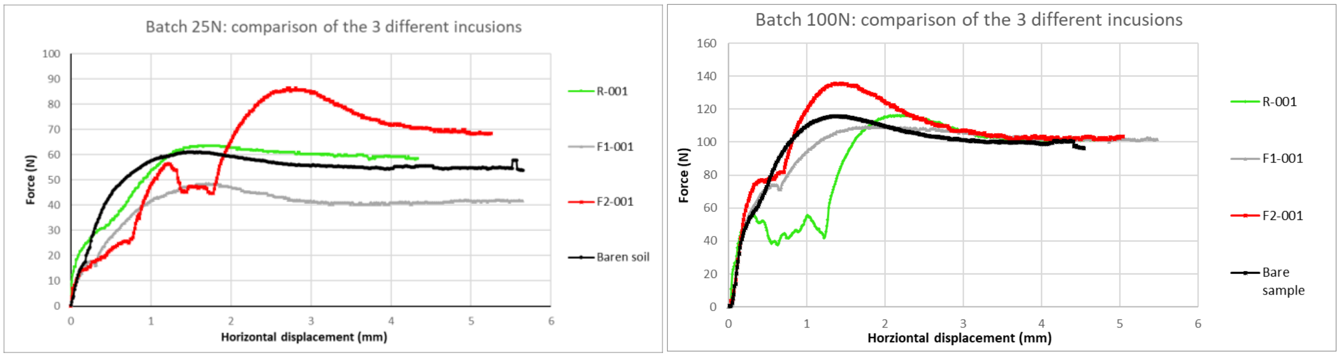


Figure 20: Results showing the increase in shear strength and root engagement

The ranking of the rooted samples by their RLD values also proved to provide a lot of insights. While finding that higher RLD does not necessarily mean a better shear strength, it can be observed that the root samples which performed best belonged to the same RLD group as seen in Figure 12. This leads to believe that there is an optimal root inclusion for a given soil volume that in this case lies between RLD 0.170 - 0.185.

The 60N batch proved to be the most complicated to analyze, especially alongside the second 60N batch. While in the first batch all the root samples underperformed but behaved as expected when compared with each other, the second batch had all root samples overperforming. Moreover, even the compromised samples performed better than the bare sample. Even so, these results do not disprove the statements made earlier and it is only proof that further research needs to be made to comprehend the behavior of the roots under certain normal stresses.

7.2 Polypropylene Fiber Sample Discussion

The Polypropylene fibers behaved contrary to the root samples, with higher fiber inclusion leading to a worse performance. This has been theorized to be an effect of clumping, where fibers tend to stick together during the mixing process. While the behavior of these trends is clearly visible in the first and last batch, the 60N batch shows completely opposite behavior, with higher fiber inclusion leading to better results and the fiber samples performing way above the bare sample. This could indicate that the 60N normal load imposes different behavior in the soil that further affects the performance of roots and fibers. Moreover, it seems that the performance of the fibers also diminishes with the increase of normal stress, as seen in Figure 21.

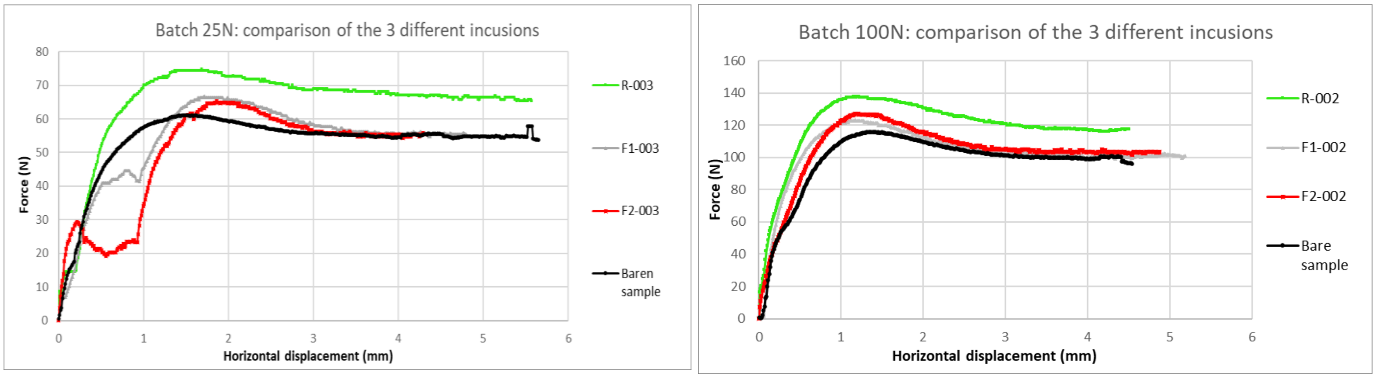


Figure 21: Results showing the loss in performance in polypropylene fiber samples

7.3 Nylon Fiber Discussion

The Nylon fiber samples are the best performing overall. In all cases they follow the trend where higher fiber inclusion leads to a better performance. Moreover, it’s the only sample type that showed consistency in the 60N batch. It is difficult to indicate how much shear strength is credited to the imposed fiber orientation, as there is no alternative orientation available for comparison, but an explication for the overperformance can be given by the increased elasticity that the fiber possesses.

7.4 Comparison with Alexey Matyunin’s Results

The experiments were made with the same parameters Matyunin used in his previous study, in order to compare and verify certain findings. For the two comparable batches that both this research and Matyunin’s research have, namely the 25N and 100N batch, it can be said that they behaved similarly, with slight performance variations. While the root samples in both batches displayed similar shear strength on average, the same cannot be said about the root engagement. The root samples from the 100N batch of this study showed a much clearer root engagement when compared to Matyunin’s results shown in Figure 22. There were no Polypropylene fiber samples results by Matyunin at 25N normal stress and only one for the 100N, so a broader comparison is difficult to achieve. Nevertheless, the fiber samples results shown by Matyunin support the fact that Polypropylene fibers show a weaker performance compared to that of roots.

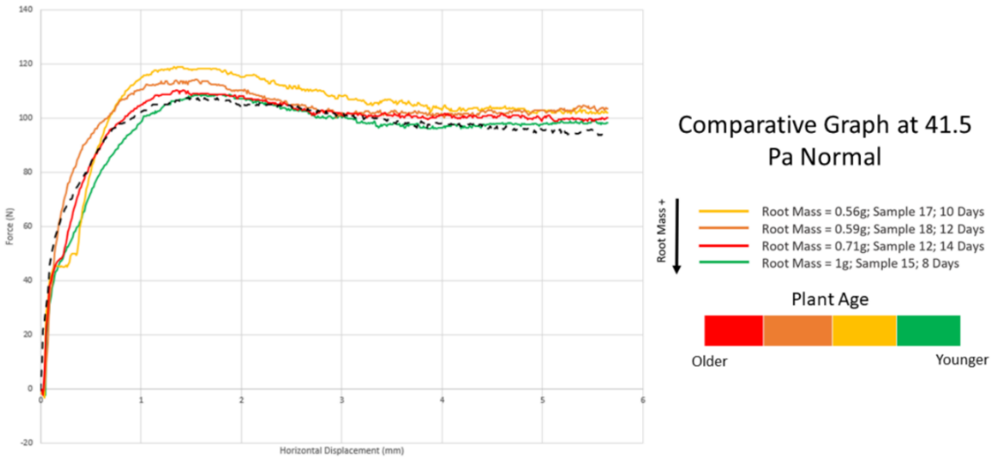


Figure 22: Alexey Matyunin's results of the root samples at 100N normal stress

8. Conclusion

This study focused on the behavior of roots, of Polypropylene, and of Nylon fibers in granular soil for different normal stresses, namely 25N, 60N, and 100N. The results of each individual sample as well as the comparison between different sample types and batches have been analyzed in order to extrapolate possible trends. As a result of this analysis the following conclusions can be drawn:

- A higher root length density (RLD) does not necessarily translate to increased shear strength. There exists an optimal range of RLD for roots, which is likely to result in improved performance. In this study, this optimal range was found to lie between 0.170 and 0.185.
- In this particular case, the Polypropylene fiber samples exhibited generally inferior performance compared to the root samples. It is important to note that the mixing process might have influenced the outcome, and that different mixing techniques could yield different results. Matyunin's (2022) research also yielded comparable findings, where it was noted that several limitations posed challenges in arriving at a definitive conclusion. Despite this, both results show that Polypropylene fibers display weaker reinforcement properties when compared to root reinforcement.

- The Nylon fiber samples exhibited the best results out of all sample types. This is also true in the case were the other samples showed strange behavior (the 60N batch). This leads to believe that Nylon is the superior reinforcement out of the three sample types when it comes to shear strength.

In civil engineering practices, the choice of reinforcement materials can significantly impact the performance of soil structures. This study highlights the superiority of Nylon fibers in enhancing shear strength in granular soil, consistently outperforming both root and polypropylene fibers. While optimal root length density (RLD) falls within a specific range, the results suggest that Nylon fibers offer reliable reinforcement capabilities across various normal stresses. This makes Nylon fibers a top choice for applications where shear strength is crucial, such as stabilizing embankments and retaining walls in construction projects.

However, even though mechanically, the Nylon fibers enhance the shear strength of the soil, plant roots also have a hydraulic contribution. The presence of vegetation can induce volumetric expansion in dense soils before shear failure, effectively redistributing stresses and delaying shear failure, ultimately contributing to improved soil stability. The plant roots influence extends to soil moisture content through transpiration and evapotranspiration processes. Maintaining optimal soil moisture levels enhances both cohesion and shear strength and improves the water retention capabilities of the soil. Furthermore, by anchoring the soil with their root systems, vegetation serves as a bulwark against soil erosion caused by wind and water forces. This erosion control proves indispensable across various applications, including slope stabilization.

Moreover, in cases where sustainability and ecological factors are paramount, root reinforcement can be a great option, especially in eco-friendly engineering projects aimed at soil stabilization and erosion control in natural habitats and restoration efforts. The versatility of these reinforcement materials allows engineers to make informed decisions based on the specific requirements of each project, ensuring both structural integrity and environmental responsibility.

9. Recommendations for Future Research

During this study a number of limitations have been met when it came to understanding the inner mechanics between roots, fibers, and soil. These limitations can be overcome in future studies by introducing a 3D X-ray machine to scan the sample before testing. By introducing this step, a better understanding of how root/fiber orientation affects shear strength and root/fiber engagement can be achieved. It could also help uncover new trends that can only be observed through 3D mapping.

Moreover, a better understanding of how fiber orientation affects the shear strength performance of granular soil could be gained by exploring different mixing methods. During this study, only the Nylon fiber had an imposed orientation, and it is uncertain how exactly this affected the sample performance. This is why it could be worth repeating these same experiments but with different fiber orientation.

Finally, in future research, a guideline could be made by creating a database with results such as those presented in Figure 1. Multiple normal stresses can be tested and plotted accordingly in order to have a better understanding of how samples will behave.

10. Acknowledgements

I would like to thank Dr. Vanessa Magnanimo, and especially Dr. Floriana Anselmucci for their unwavering support, guidance, and dedication that have been instrumental in the successful completion of this research. Dr. Anselmucci not only provided invaluable insights but also ensured that every aspect of my project ran smoothly. Their expertise, attention to detail, and tireless commitment greatly enriched my work. From coordinating meetings to offering timely feedback, Dr. Anselmucci has consistently gone above and beyond to facilitate my progress.

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Appendix A

25 N	Sample mass (grams)	Suction (kPa)	root weight (g)	leaf weight (g)	**60 N**	Sample mass (grams)	Suction (kPa)	root weight (g)	leaf weight (g)	**100 N**	Sample mass (grams)	Suction (kPa)	root weight (g)	leaf weight (g)
R1	337.04	-1,55	1.195	0.386	R1	285.1	1.9	0.656	0.475	R1	313.07	-2	0.998	0.427
P1	311.93				P1	329.38				P1	301.9			
N1	297.14				N1	332.72				N1	299.59			
B1	332				B1	337.65				B1	302.04			
R2	268	-3.3	0.782	0.505	R2	332.08	-2,07	0.718	0.31	R2	329.24	-2.2	0.377	0.063
P2	297.59				P2	347.77				P2	303.62			
N2	330.48				N2	338.19				N2	297.48			
B2	296.6				B2	288.7				B2	297.17			
R3	311.61	-2,95		0.164	R3	302.55	-2.3	0.725	0.493	R3	300.56	-2.1	0.683	0.586
P3	296.47				P3	292.11				P3	302.3			
N2	313.96				N2	319.08				N2	297.52			
B3	296.6				B3	333.07				B3	301.92			
R4	309.49	-2,53	0.378	0.266	R4	334.08	-1.8	1.08	0.957	R4	317.39	1.94	0.465	0.274
P4	314.04				P4	347.9				P4	302.19			
N2	348.1				N2	328.61				N2	296.9			
B4	297.94				B4	347.95				B4	297.32			
R5	279.62	-6,5	0.666	0.325	R5	312.58	-2	0.707	0.636	R5	341.56	1.8	0.615	0.318
P5	303.66				P5	319.24				P5	302.8			
N2	302.9				N2	333.4				N2	296.61			
B5	301.76				B5	-				B5	302			
R6	292.41	-7,65	0.303	0.097	R6	348.45	-2.16	0.73	0.518	R6	301.56	1.7	0.553	0.371
P6	302.17				P6	314.85				P6	297.08			
N2	297.5				N2	348.3				N2	291.5			
B6	297.66				B6	-				B6				

Table 4: Table containing the mass, suction, root weight and leaf weight of all samples

Appendix B

Batch 25N

Figure 23: R-001-25

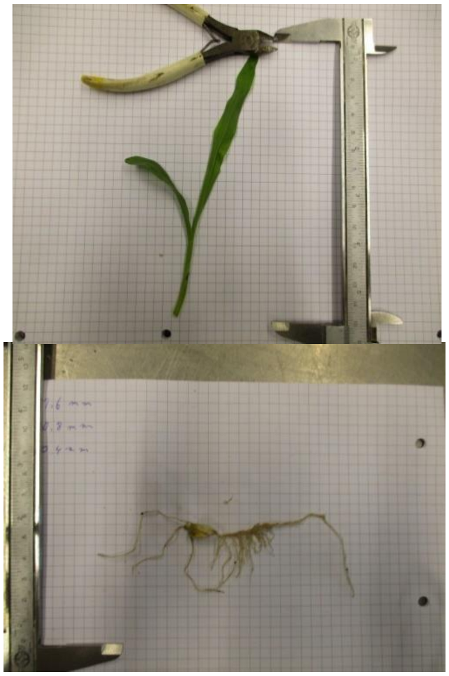

Figure 25: R-002-25

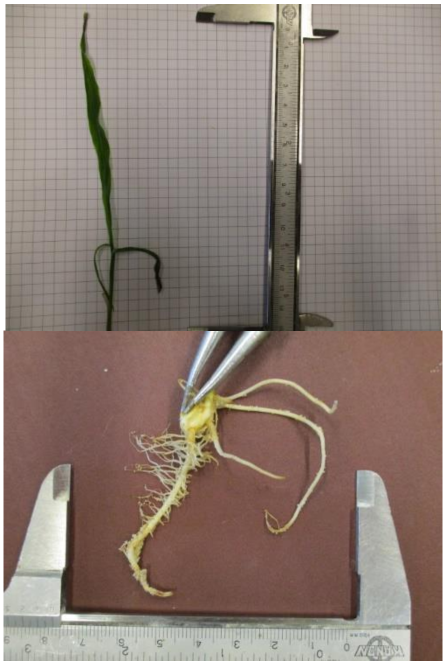

Figure 24: R-003-25

Figure 28: R-004-25

Figure 27: R-005-25

Figure 26: R-006-25

Batch 60N

Figure 32: R-001-60

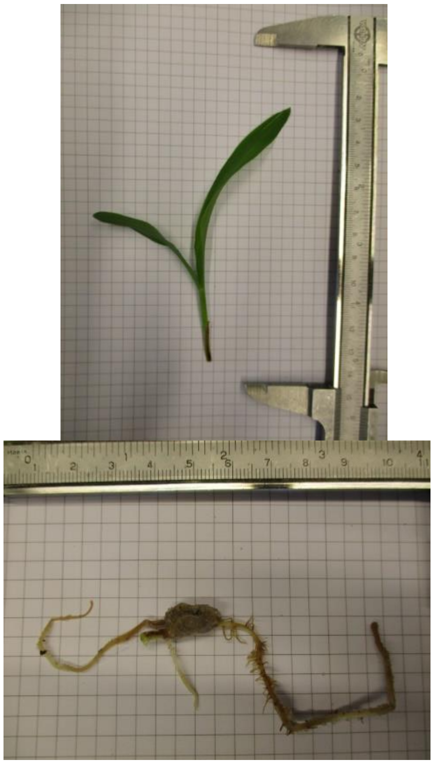

Figure 31: R-002-60

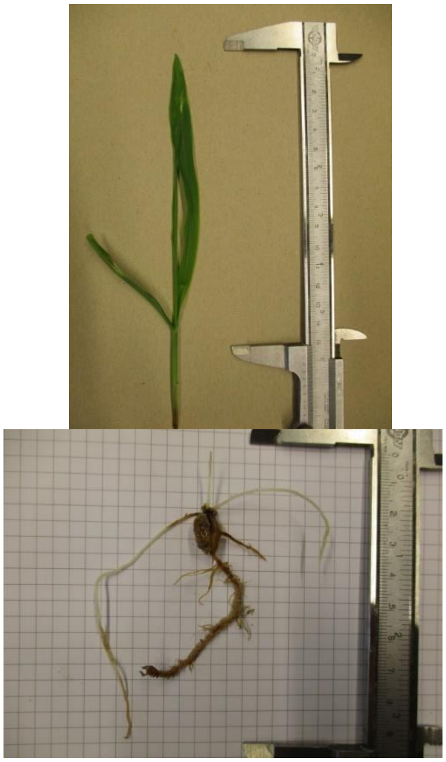

Figure 30: R-003-60

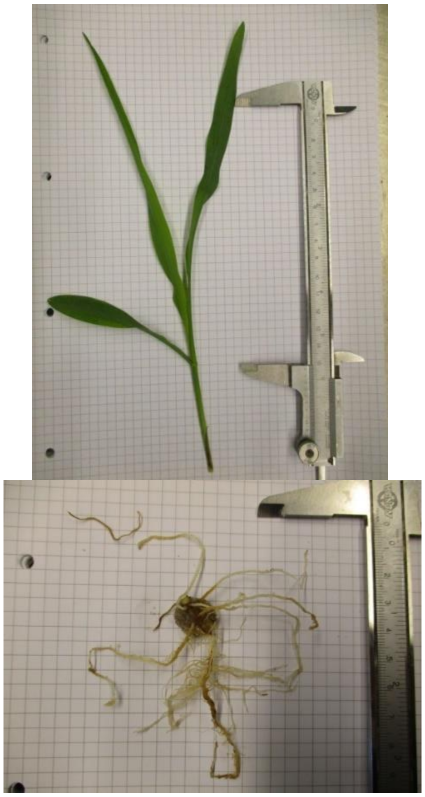

Figure 34: R-004-60

Figure 29: R-005-60

Figure 33: R-006-60

Batch 100N

Figure 38: R-001-100

Figure 39: R-002-100

Figure 40: R-003-100

Figure 37: R-004-100

Figure 35: R-005-100

Figure 36: R-006-100