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Effect evaluation of grass roots on mechanical properties of unsaturated coarse-grained soil

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Abstract

The utilization of vegetation to prevent shallow slope failure and erosion has received significant attention in recent years, since it is recognized that vegetation has the mechanical and hydrological strengthening effect on soils. To accurately evaluate the mechanical properties of grassed soil and effect of grass age, grassed soils with grass ages of 2, 4, 6 and 8 months as well as bare soil are cultivated and prepared. Then, considering that grass layer in nature is usually situated above ground water table in the non-saturation state, a sequence of unsaturated triaxial tests are performed for soil specimens with different grass ages and matric suctions. Experimental results reveal that both grass root and matric suction enhance soil shear strength. The peak shear strength and cohesion of grassed soils tend to increase with increasing grass ages or matric suctions. Moreover, it is recognized that compared with grass root, the matric suction causes a more significant reinforcement effect for increasing total cohesion of soil sample. On the other hand, grassed soil has a higher water retention capacity, and under the same matric suction conditions, the soil specimen with older grass age have higher volumetric water content. Furthermore, the measured total cohesion for unsaturated soil is validated by the proposed calculation equation based on Vanapalli model, and the calculated results fit the measured results well. Calculated and experimental results have good agreement showing the proposed equation can properly reflect the increase in the unsaturated mechanical properties of grassed soil.

Keywords: Grassed soil; Soil strength, Unsaturated soil mechanics, Soil-water characteristic curve; Triaxial test; Coarse-grained soil

1. Introduction

Local environment is altered by vegetation in a number of ways, from motivating microbial abundance and diversity, to modifying soil biophysical, hydrological and mechanical properties [25]. The application of vegetation of soil bioengineering methods as an environmentally friendly restoration technique to prevent surface erosion or debris flow [13], serve as a hopeful substitute to conventional civil engineering solutions to stabilize shallow damage on either artificial or natural slopes. The soil-root enhancement is usually caused by transferring the mechanical energy from the root system to soil particles [4] assumed both root and soil materials [15] composing into plant-soil matrix. It is toilless to explain and interpret the mechanism of root reinforcement, while a major challenge is still existed in performing an accurate method of incorporating and quantifying the organismal influences into the traditional geohazard assessment, which is the defect of soil bioengineering methods [11] comparing to well-developed techniques of programming and calculating traditional civil engineering infrastructures, such as soil nailing wall and soldier pile. The main reason is that the differences in vegetation species, vegetation ages, root volume, and vegetation spacing might lead to noticeable effects [46],[38]. The vegetated soil has distinctly different hydraulic and mechanical properties compared with the bare soil. For the hydraulic property, vegetated soil has a enhanced ability to hold water and a lower permeability coefficient as roots underground block the soil pores and plant evapotranspiration could induce the increase in matric suction. [30],[38]. For the mechanical property, root systems grasp soil particles to prevent surface erosion, and slope stability is improved with roots crossing a possible failure surface [53].

Ni, J. et al. [39] inspected the effect of vegetation roots including the tree and grass on changes of the permeability coefficient as well as soil water characteristic curve (SWCC). A greater water retention ability, matric suction and air entry value of both tree-soil and grass-soil were observed due to the existence of roots. Similar experimental results were found for different plant and soil type [44],[36]. Furthermore, plant evapotranspiration in natural environment, a process of the sum of transpiration that absorbs root water through leaves and evaporates from the soil ground, could directly change the distribution of moisture content and matric suction in the soil ground. From the perspective of unsaturated soil mechanisms, the soil shear strength increases as a result of the increased matric suction caused by the evapotranspiration [35], enhancing the stability of geo-structure, especially during heavy rainfall. Rahardjo et al. [44] contended that

the vegetation layer was available to keep the negative pore water pressure in the soil ground under rainfall condition in the field monitoring results. However, the hydrological reinforcement effects of plant-soil such as matric suction has received less consideration [48] since it is relatively hard to integrate hydraulic impacts of vegetation into the assessment of soil shear strength and complex hydraulic conditions such as soil water content and SWCC also affect the performance of plant-soil fortification. Soil shear strength at the potential failure surface is increased due to the strength enhanced offered by roots. Fan and Tsai [5] conducted a sequence of direct shear test for evaluating the root effects on soil shear strength indicating that a larger shear strength is observed in the root-permeated soil compared with the bare soil without roots. Wu and Watson [52] performed the field strength test on soil specimen with root systems reporting that bare plain soil has a distinctly lower shear strength than that of root-reinforced soil. Moreover, tensile strength tests on roots [9], blade penetrometer tests [33] and centrifuge testing [47] have been adopted to appraise the soil shear strength under vegetation effects. It is noted that plant roots contribute an important increase in soil shear strength. Giadrossich et al. [10] gave a specific review of measurement techniques for mechanical responses of rooted soils. The root-permeated soil shear strength is generally quantified through Mohr circles by drawing Mohr Failure Envelopes with assuming the effect internal friction angle equal to that of the bare soil since the change of effective angle of internal friction is negligible while roots are existed in the soil [12],[8]. “Root cohesion” value is defined as the intercept increment along the deviator stress axis. Some triaxial compression tests for grass-reinforced soil focus on the reinforcement of soil with artificial materials and relatively simply accessed structures [54]. Moreover Karimzadeh et al.[29][28] gave an insight in monotonic and cyclic behaviour and anisotropy effect on root-reinforced soil through conducting triaxial tests with various stress paths, and indicated that the root reinforcement effect is anisotropic because the root-induced change in soil friction angle is found to be path-dependent, with the change in friction angle being minimal along compression, while the friction angle along extension increased significantly and roots can effectively increase the liquefaction resistance. On the other hand, grass layers in nature are usually located above the water table and under unsaturated condition, while strength tests applied on rooted soil have been usually performed under saturated [51] or constant moisture levels [8], which cannot accurately evaluate its mechanical properties by ignoring the effect of matric suction and moisture content. Therefore, researches attempting to mimic natural conditions to explore the effects of the root reinforcement should take the matric

suction and moisture content into account. Mahannopkul and Jotisankasa [32] conducted suction-controlled direct shear tests on root-reinforcement of clayey sand at four different suctions to evaluate the reinforced effect provided by the grass root and matric suction, and concluded that the highest increment in root cohesion with root volume is at the suctions around 10–20 kPa. Rahardjo et al. [44] performed triaxial test for saturated and unsaturated grassed soil specimens, and their results indicate that the presence of root system and matric suctions results in the increase in shear strength of the soil covered with vegetation, and root system mainly increases the effective cohesion of the soil, while they adopted multistage tests for one soil specimen and as the load increases, part of the root system may fail, leading to inaccurate experimental results. Nevertheless, a large proportion of researches up to now focus on the distinction only between bare soil and grassed soil regardless the grass age effect on soil. Kamchoom et al. [27] conducted a sequence of direct shear tests with various grass ages, and indicated that the shear strength of the vegetated soils increased with increased growth duration because of the improvements in root strength and modulus. However, they did not go one step further to determine the strength parameters such as friction angle and cohesion of soil, and did not take the matric suction of the unsaturated condition into account. The root volume and root components such as cellulose and lignin contents, which control root biomechanics, change with grass ages leading to different impact on the mechanical property (shear strength) and the hydraulic property (matric suction) [38][26]. It is essential to take the grass ages effect into account quantitatively to make a comprehensive understand on grassed soil.

The purpose of this study is to evaluate the influences of grass ages and matric suctions on mechanical property of soil. Grassed soils with grass ages of 2, 4, 6 and 8 months as well as bare soil are prepared in the indoor cultivation equipment. Then, a sequence of unsaturated triaxial tests are performed for soil specimen under different grass ages and matric suctions to figure out the influences of grass roots on increasing the unsaturated soil shear strength. Furthermore, a calculation approach considering the effects of grass ages and matric suctions is proposed to validate the measured results and to estimate the unsaturated mechanical property of grassed soils.

2. Materials and Test apparatus

2.1. Soil type and Grass species

The test material adopted in the experiment is Komaoka volcanic coarse-grained soil (shorten as Komaoka volcanic soil). It is sampled from field cut slopes at Makomanai located in Hokkaido, Japan (Fig. 1). Considering the wide distribution and easy accessibility of this volcanic soil, it is broadly used as a material for building artificial slopes in Hokkaido. Based on the classification method of soil for engineering purposes, Komaoka volcanic soil is categorized as sand-silt mixtures (SM) according to Unified Soil Classification System (USCS) [3]. In the experiment, soil is sieved by 4.75mm of maximum grain size according to the triaxial test specimen preparation method in which the diameter of a specimen may be five times or greater the maximum particle size of a sample for soils having a wide range of particle sizes [23]. The soil specimens for triaxial apparatus have the inner diameter of 70mm and the height of 170mm, so the choosing the maximum particle size of 4.75mm is rational. Fig. 2 displays grain size distributions before and after sieving and the material properties of Komaoka volcanic soil are listed in Table 1 [38].

For grass species, the seed of Tall Fescue, a cool-season perennial species of bunchgrass, taking dominant amount mixed with other two kinds of grass seeds (Kentucky Bluegrass, Creeping Red Fescue) with less amount depending on requirement of gardening technique is adopted in this study. The root system of those chosen grass species have a liner shape individually connecting and twisting with each other, which naturally extensive root system can reach 2 to 3 feet deep, with average diameter of 0.3-0.4mm. These species are pervasively utilized in seasonally cold regions such as Hokkaido for stabilizing soil layers along roads as well as slopes because of their cold resistance. A density of 18 g/m² for the mixed-grass seeds based on gardening standards in Hokkaido, are chosen [38] for cultivating the grassed soil specimen as shown in Table 2.

2.2. Test apparatus

The consolidated drained (CD) test is conducted by the triaxial apparatus to figure out the grass root effect and matric suctions on soil mechanical behaviors. A diagrammatic drawing of the unsaturated soil triaxial apparatus is illustrated in Fig. 3(a). Unsaturated triaxial tests are conducted with this apparatus through utilizing axis parallel translation technique. To keep the unsaturated condition in soil specimen,

pressure membrane method utilizing the hydrophilic membrane filters, rather than pressure plate method with the ceramic plate, is adopted. It can effectively manage the inputted air pressure at the cap and inputted water pressure at the pedestal separately. The reason is that when using the pressure plate method with the ceramic plates in the unsaturated triaxial test with large-size specimens, it takes extremely long time for drainage because of the very low permeability for ceramic disks. Conversely, using pressure membrane method saves time and enhances the efficiency. Several researchers contended that pressure membrane methods are beneficial in reducing test duration [19][21][41]. Therefore, to control matric suction in soil specimen, a micro-porous membrane (Versapor membrane) is used and applied at the pedestal as shown in Fig. 4(a). Versapor membrane belongs to the acrylic copolymer membrane and is generally used for pre-filtration of those materials which are hardly infiltrated such as serum or other solutions. The material properties of Versapor membrane are displayed in Table 3. Once the Versapor membrane is fully saturated, pore water pressure could be measured through this membrane filter while air cannot go through the Versapor membrane because there are many menisciuses formed on the surface of the Versapor membrane to burden the extra air pressure just like shown in Fig. 4(b). Certain matric suctions are controlled in the test through exerting air pressure into the soil specimen that is larger than the pore water pressure. Furthermore, it is worth noting that the AEV of the Versapor membrane is 110kPa so that the matric suction controlled by this method cannot over this value. Then, pore water pressure and pore air pressure are separately controlled during the whole experiment process. The cap of the apparatus is linked up with the pore air pressure path and the pedestal is linked up with the pore water pressure path, respectively, to control the provision and drainage of water and air from both interfaces and the matric suction in the soil specimen. For transferring pore water pressure, the hydrophilic copolymer membrane filter is exerted to the bottom of the specimen attaching to the water supply path. Meanwhile, for transferring pore air pressure, the hydrophobic filter is installed at the top of the soil specimen connecting the air plumbing path. The axial load is applied through a Mega Torque Motor.

The load cell transducer located inside the pressure cell of triaxial apparatus is employed to measure the axial stress (σ_a). The external displacement sensor is installed to measure the axial strain (ϵ_a). The volume of drainage (ΔV_w) before shear process are measured through the double tube attaching to the differential pressure sensors. Furthermore, it is impracticable to measure the volumetric strain (ϵ_v) for unsaturated triaxial

test based on water discharge through double tube burette like the saturated triaxial test. Therefore, an inner cell is installed in the pressure cell and the volumetric strain (ϵ_v) are measured through differential pressure sensors connecting to the inner cell and pressure cell respectively as displayed in Fig. 3(b). Ishikawa et al. [19][22] adopted this method to measure volume change for unsaturated soil specimens showing reasonable accuracy.

In this study, to verify the reliability and availability of the volumetric strain measurement system in unsaturated triaxial tests for unsaturated soil materials, a saturated triaxial test with installing inner cell is performed and the measured volumetric strains by the double tube and inner cell are shown in Fig. 5. The measurement results of the volumetric strain change between the two methods are reasonably consistent. As a result, this volumetric strain measurement system derived from the inner cell is an effective and accurate method to measure the volumetric strain in unsaturated triaxial tests.

3. Laboratory testing procedure

3.1. Grassed soil specimen preparation

The grassed soil specimens are prepared and cultivated by using the PVC mold. PVC molds have the inner diameter of 70mm and the height of 200mm. For effortlessly removing PVC molds to receive the soil specimen for testing, the mold is pre-cut along the shaft, secured with tape and clips. The quartering method [24] is employed to mix Komaoka volcanic soil to establish the identity in grain size distribution. Next, Komaoka volcanic soil specimen in PVC mold is made by the air pluviation method [34] of the oven-dried soil samples. The soil specimen has 170 cm in high and 70 cm in diameter and the dry density for each soil specimen is listed in Table 7. The standard deviation of dry density is 0.011. Thereafter, the mixture of grass seeds matrix is evenly smeared on the top of Komaoka volcanic soil specimens for grass germination. A constant temperature (around 25 °C) is set in the growth room to cultivate all grassed soil specimens. Moreover, to simulate daylight in nature, four fluorescent bulbs are installed to provide enough accumulated illuminance. The grassed soil specimens are watered twice per day with total 300ml water at 8:00 and 14:00. When the grass age reached a specific age of 2 to 8 months, soil specimens are put on the porous stone for several days to allow inside drainage to reach a low volumetric water content for next step, and grass-blade is carefully cut for triaxial test preparation. Then, soil specimens are placed in the refrigerator at -20 degrees

Celsius for 12 hours to give them a tough shape since Komaoka volcanic soil is such a cohesionless soil and it is hard to directly move such soil sample from PVC mold into the membrane for triaxial test without disturbing soil structures as well as soil-root interactions. No frost heaving or expansion in soil specimens is observed when the soil specimens are taken out from the refrigerator because soil samples have low volumetric water content after inside drainage and no root decay is observed since the freezing duration is short. Therefore, it is assumed that this freezing procedure has negligible impact on experimental results. It is followed by strip the mold after taking out the soil specimen from refrigerator. After that, soil specimen is charily placed into the triaxial test apparatus. In addition, bare soil specimens are prepared for comparison with grassed soil specimens. BK and GK denote the bare Komaoka volcanic soil (without grass root) and grassed Komaoka volcanic soil (with grass root), respectively. It is followed by the grass age (e.g. GK2). Consequently, five kinds of soil samples (e.g. BK, GK2, GK4, GK6, GK8) are determined and prepared for triaxial tests. The maximum grass age of 8 months is determined by the grass growth cycle in Hokkaido (April to November). Three replicates are used for each grass ages to capture the natural variability of grass growth on root network. The diagrammatic drawing of the indoor cultivation device is displayed in Fig. 6. Fig. 7 presents the actual grassed soil specimen at grass age of four months as well as its grass root.

3.2 Consolidation process

After specimen preparation, unsaturated triaxial shear tests are performed through several steps. At first, each frozen specimen is thawed for more than 3 hours in the pressure cell with a pressure of 20 kPa. Double vacuuming method [1] which applied the negative air pressure at the top of the soil specimen to extract the inner air bubble, is employed to saturate soil specimen. Simultaneously, the de-aerated water is injected at the pedestal into the soil specimen. Then, the pore water pressure is increased to 200 kPa while the cell pressure is increased to 220 kPa to make sure that the soil specimen reaches under fully saturated condition with B value beyond 0.96. After the soil specimen is fully saturated, the isotropic consolidation continues with a presetting effective confining pressure of 25 kPa. This confining pressure of 25kPa is chosen based on the past researches of similar triaxial apparatus and soil type (volcanic soil). Accordingly, the pore water pressure of 200 kPa and cell pressures of 225 kPa are supplied. The consolidation process is completed when the axial displacement and drainage volume keep constant.

3.3 Desaturation process

In this study, a suction-controlled unsaturated triaxial test is adopted for evaluating the mechanical property of grassed soil specimens. In the desaturation process, Axis parallel translation technique [16] is employed to govern the unsaturated condition such as matric suction. This method can avoid cavitation effectively, and greatly improve the range of suction measurement that ensures matric suctions in the experiment range from single to several or tens of atmosphere pressure. In addition, the matric suction in soil specimen is exactly controlled through inputting certain air pressure and pore water pressure since pore water pressure can be measured through traditional sensor when it is risen from negative number to positive number. After consolidation process finished, the desaturation procedure would continue with constant preset effective confining pressures. A pore air pressure identical with the original pore water pressure (200kPa) is applied through the valve connecting at the top of the soil specimen. Meanwhile, the pore water pressure is decreased to a preset value through the valve connecting at the bottom of the soil specimen while keeping pore air pressure constant and its value is determined by the preset matric suction. In this research, the matric suctions are set to be 5kPa, 15kPa and 25kPa and the quantity of 25kPa is chosen based on the in-situ measured data of average matric suction and the other two setting matric suctions are interpolated values, so the according setting pore water pressures are 195kPa, 185kPa and 175kPa, respectively. Next, the water in the saturated soil specimen begins to drain out, and the amount of drainage water is recorded for drawing soil water characteristic curves (SWCC). Note that the volumetric change of the soil specimen could hardly be discerned since the net normal stress keeps constant before and during this procedure. Then, the drainage process is kept until the drainage rate is less than 0.01 ml/min because the soil sample reached its equilibrium state of certain matric suction under this drainage rate.

3.4 Shear process

After completing desaturation process, shear process is performed continuously by applying the axial deviator stress (q) under completely drained condition with opening both pore water and pore air pipes. The shear rate in this test is selected to be 0.2 %/min based on the permeability of volcanic coarse-grained soils [19][20]. The shear process is completed as the axial strain (ϵ_a) reached 25%.

After completing the experiment, the root volume for each grassed soil specimens is measured. The grassed soil specimen is taken away from the test device after finishing the triaxial test and soil particles adhering to the grass root are carefully washed away. These roots are placed at room with constant temperature (around 25 °C) for air-drying before the root biomass remains constant. Then, the actual volume displacement approach is employed to measure the volume of grassroots. The treated grass root is submerged in water with a graduated cylinder and the volume of water displaced is recorded to estimate the volume of grassroots (V_r) [42].

4. Experimental results and discussions

4.1 Shear behavior of grassed soil

Relationships between deviator stress (q), volumetric strain (ε_v), axial strain (ε_a) and suction (s) of grassed soils with different grass ages during CD test under unsaturated condition are presented in Fig. 8. There are five kinds of soil samples (e.g. BK, GK2, GK4, GK6, GK8) with three kinds of matric suctions (e.g. 5kPa, 15kPa, 25kPa), and 15 unsaturated triaxial tests in total are performed. The results of saturated triaxial test for bare soil are derived from the additional test, while the results of saturated triaxial test for grassed soil are referred to the past researcher who conducted the triaxial test with similar soil sample and grass seed [38].

From the perspective of grass age, grassed soil has a greater peak deviator stress compared with bare soil under the similar matric suction condition. It is because that the grass roots traverse through the possible failure plane of the soil specimen to generate reinforcement effects. In addition, with higher the grass age, the grassed root volume increases, and then the peak shear strength of the grassed soil specimen becomes greater. The root volume (V_r) under various grass ages is listed in Table 4. Besides, with the increase of grass age, cellulose and lignin contents in grass root system would increase especially in the old root. This thereby leads a larger root strength to make the soil shear strength increased ultimately [2][26]. From the viewpoint of the matric suction, under the similar grass age, unsaturated soil specimen has a larger peak shear strength than saturated soil, and there is an increased tendency for peak shear strength of unsaturated soil specimen of higher matric suction since it owns the stronger capillary action. There has been the strain-softening behavior during the shear process around an axial strain of 10% in stress-strain relationships especially under

the high matric suction condition. Moreover, the volumetric change tendency of saturated soil specimens is generally a compressive response, while the volumetric change tendency of the unsaturated soil specimen is a compressive response first, followed by an expansion response with the increasing axial strain during the shear process. The expansion response increases with increasing matric suction is observed under the similar net normal stress. This might be due to higher suction leading to tighter agglomerates of the soil particle that conducts like "sand" particles [17].

4.2 Relationships between root volume ratio, matric suction and peak shear strength

To quantitatively describe the effectiveness of grass roots in grassed soil specimen, root volume ratio (R_v) is proposed defining as the ratio of the root volume to the whole specimen volume (V_r/V), which is listed in Table 4. Fig. 9 displays the root volume ratio of saturated triaxial test performed by past researcher [38] and unsaturated triaxial test as well as its standard deviation in this research. Two results of root volume ratio are compared for validation. It is indicated that the root volume ratio is higher as grass age increases, and the root volume ratios of saturated triaxial test and unsaturated triaxial test are almost similar. The difference between those two results is negligible meaning that the grass soil samples for unsaturated test have the identical condition compared with the grass soil samples for saturated test used in past research [38], which can be employed as reference for further analysis in following chapter. As root volume ratio rises corresponding to an increase in grass age, the friction force between root and soil particles is increased because there is a broader contact area between the soil-root interface. The root system acts as a tension-carrying fiber that converts increased external stress in the soil matrix into tensile force through interfacial frictions along its surface, thereby exerting a mechanical reinforcement function [14]. This results in better reinforcement effect when grass roots cross the potential failure surface of soil sample [53]. It is noted that the diameters of grass root might be higher when grass becomes older [31]. Therefore, the enhanced shear strength observed in this study are attributed to the higher root volume ratio. On the other hand, more cellulose and lignin contents, which control root biomechanics, deposit in older grass root system [26] and the root tensile strength is reinforced leading to higher soil shear strength under such a condition [2].

The relationships between maximum deviator stress (Q_{max}) with root volume ratio are shown in Fig. 10. Both grass roots and matric suctions provide a support for the increasing of maximum deviator stresses. The

maximum deviator stress increases along with older grass ages and greater matric suctions. Furthermore, it begins to curve and has the tendency to bend toward a near horizontal line under higher matric suction condition. This nonlinearity appears once the air-entry value is exceeded [7] and in this study the air-entry value is less than one, which is smaller than the setting matric suction in the experiment. Meanwhile, it is recognized that in all test results, the peak shear strength of BK under matric suction of 15kPa is larger than the peak shear strength of GK8 in saturated condition meaning that the reinforcement effect caused by matric suctions is more conspicuous than grass roots. Taking the matric suction into account is more suitable and rational for evaluating the strength of grassed soil because grass layer in nature is always situated in unsaturated zone.

4.3 Shear strength of grassed unsaturated soil

Fredlund et al. [7] assumed that the independent stress state variable can be utilized for formulating the linear form of the unsaturated soil shear strength. The unsaturated soil shear strength is defined through the extended Mohr-Coulomb failure envelope in the third dimension of the matric suction. The line of intersection of the extended Mohr-Coulomb failure envelope with the ahead plane is the saturated soil failure envelope. In conventional saturated triaxial test, two tests under two different effective confining pressure are conducted, and then two Mohr circles are plotted with determining the failure envelope to evaluate the mechanical properties of soil specimens such as effective internal friction angle and effective cohesion. On the other hand, it noted that the effective angle of internal friction is similar between the saturated case and unsaturated case in the whole Mohr-Coulomb failure envelope, and cohesion value increases along with the increased matric suction under unsaturated condition. Several previous researchers observed the similarity of effective angle of internal friction for soil specimen under various matric suctions [6][17][43].

It means that with the known effective internal friction angle for a specific kind of soil, only one Mohr circle of the given matric suction and the similar net normal stress is sufficient to determine the shear strength of unsaturated soil through translating the envelope line to be tangent with that Mohr circle. It is an effective method to decrease the frequency of unsaturated triaxial test and save the time as well as precious grassed soil samples. Hence, this simplified method is adopted in this research to estimate the unsaturated mechanical property such as total cohesion for bare soil specimens and grassed soil specimens according to the known

effective angle of internal friction measured by past researcher [38].

Various Mohr-Coulomb failure envelopes of bare soil and grassed soils under different matric suctions are displayed in Fig. 11. The results of saturated Mohr circle as well as effective internal friction angles for grassed soil specimens are derived from past research [38]. It is recognized that there is a limitation of this experiment results since only two Mohr circles are adopted for determining the strength parameters such as the effective internal friction angle and the effective cohesion in order to save the precious grassed soil specimens. Total cohesions describing unsaturated mechanical property of bare soil and grassed soils are measured, and Table 7 summarizes the measured total cohesion. From the viewpoint of grass root effect, there is a significant increase in effective cohesion of grassed soil along with the increased root volume ratio. The effective cohesion of bare soil is 1.27 kPa while the grassed soil with 8 month has effective cohesion of 8.51 kPa under the saturated condition. Conversely, only a slight increment of the effective internal friction angle of grassed soil is observed as root volume ratio increase. The effective internal friction of soil under grass age of 8 month is just greater than that of bare soil by around 1.5° (41.2° as compared to 42.7° , respectively). It is because the root-induced change in soil friction angle is minimal along compression path compared with other stress path such as extension [28]. The higher effective cohesion might also contribute to the higher shear strength of grassed soil under higher grass age as mentioned above. In addition, the reinforcing effect generated through grass root can keep its function regardless the matric suction meaning that under unsaturated condition, the grass root can still increase the soil strength by increasing effective cohesion c' . On the other side, as for the matric suction effect, the gradually increased total cohesions along with increased matric suctions are observed under the similar grass ages because of the capillary effect. Furthermore, the matric suction have larger enhancement impact than that of the grass root on total cohesion. The measured results put emphasis on the importance of considering the matric suction for soil specimen in unsaturated triaxial tests.

To check the reliability and validity of the measured total cohesions, the unsaturated soil shear strength is calculated according to Bishop's effective stress principle by Vanapalli et al. [50] as given by:

$$\tau = c' + (\sigma_n - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b \quad (1)$$

where, τ (kPa) is shear stress; c' (kPa) is effective cohesion; σ_n (kPa) is total normal stress; u_a (kPa) is pore air pressure; $(\sigma_n - u_a)$ (kPa) is net normal stress; ϕ' ($^\circ$) is effective angle of internal friction; u_w (kPa) is

pore water pressure; $(u_a - u_w)$ (kPa) is matric suction; ϕ^b ($^\circ$) is angle representing growth rate of shear strength relative to the change in the matric suction ($\tan \phi^b = \chi \tan \phi'$), and χ is parameter correlated with the saturability. The value of parameter χ can be calculated through volumetric water content as follows [50]:

$$\chi = (\theta_w - \theta_r) / (\theta_s - \theta_r) \quad (2)$$

where, θ_s (m^3/m^3) is saturated volumetric water content; θ_r (m^3/m^3) is residual volumetric water content; θ_w (m^3/m^3) is volumetric water content.

Then, the total cohesion describing unsaturated mechanical property for bare soil and grassed soils can be expressed as follow:

$$c_{total} = c'_{soil} + c'_{root} + (u_a - u_w) \tan \phi^b \quad (3)$$

where c_{total} (kPa) is total cohesion; c'_{soil} (kPa) is effective cohesion of bare soil; c'_{root} (kPa) is effective root cohesion (effective cohesion c' is the sum of c'_{soil} and c'_{root} ($c' = c'_{soil} + c'_{root}$)); $(u_a - u_w) \tan \phi^b$ is apparent cohesion caused by matric suction.

For the effective cohesion of bare soil, the value is a constant regardless the grass ages and matric suctions. It is 1.27kPa derived from the saturated triaxial test. However, in the referred past research [38], it is 0.22kPa. The slight difference is attributed to the different sampling position for Komaoka volcanic soil between this study and past research. Therefore, two values are adopted depending on the experimental result sources, and two effective cohesions of bare soil are summarized in Table 7.

For the effective root cohesion, the value increases along with the increased grass age or the increased root volume ratio. Fig. 12(a) and (b) displays the relationship between effective root cohesion against grass age and root volume ratio derived from the past research, respectively [38]. The effective root cohesion, defined as the difference of cohesion between bare soil and grassed soil, was measured by a series of saturated triaxial tests of bare soil specimens and grassed soil specimens with various grass ages, in which the soil sample and grass species are identical to this study. The value can be adapted to be c'_{root} in this study for the computational formula since the root volume ratio between past research and present research is almost similar (Fig. 9). The effective root cohesion is summarized in Table 7.

For the apparent cohesion caused by matric suctions, its value is depended on the matric suction and the corresponding volumetric water content. Table 5 lists various volumetric water contents for soil specimen under different grass ages and different matric suctions, and Fig. 13 displays the measured points of the

volumetric water content and the fitting SWCCs. The fitting SWCCs are matched by using Van Genuchten [49] model shown as follow:

$$\theta_w = (\theta_s - \theta_r) \left[\frac{1}{1 + (\alpha s)^n} \right]^m + \theta_r \quad (4)$$

where α (1/kPa) and n are fitting parameters; m is calculated based on n ($m = 1 - 1/n$); s (kPa) is matric suction.

It is appeared that the fitting results show a relatively great agreement between the SWCCs of the bare soil specimen and grassed soil specimens shown in Fig. 13. Under the similar volumetric moisture content, compared with that in the bare soil specimen, relatively higher matric suctions are observed in grassed soil specimens meaning that grassed soil has the reinforced water retention capacity [30]. It is because that pores in the soil material are taken up by grass roots to cause this phenomenon. Consequently, due to capillary law [45], soil pore diameters decrease and matric suctions increase in grassed soil specimen. Table 6 summarized the parameters of VG model for SWCC fitting as well as fitting errors. It is recognized that the higher grass age results in the greater AEV. This tendency suggests that the existence of the grass root system in soil pores results in the above-mentioned increased water retention capacity. Then, the calculated apparent cohesion is summarized in Table 7, and there might be an increased unsaturated shear strength of grassed soil when grass age is older.

The comparison between measured total cohesion and calculated total cohesion is displayed in Fig. 14. The tendency of both results can relatively fit well. Only the test result of GK8 of matric suction of 25kPa has little deviation because of experimental error. With increasing of grass age and matric suction, total cohesion increases. Furthermore, $\tan \phi^b$, which represents growth rate of shear strength relative to the change in the matric suction, is estimated by the equivalent slope of the linear trend line fitting with those point of measured results in Fig. 14, and the quantities of angle ϕ^b for each grassed ages are listed in Table 7. It appears that angle ϕ^b gradually increases with grass ages to a certain extent (28.5°~32.1°). Rahardjo et al. [44] found that angle ϕ^b increases in the grassed soil compared with the bare soil for certain grass species (Vetiver grass) in low matric suction range (<25kPa), which is similar in this study. Mahannopkul and Jotisankasa [32] observed that angle ϕ^b becomes slight large with increased of root concentration when the root concentration is smaller than such threshold, and as root concentration increases beyond the threshold, the angle ϕ^b becomes slightly smaller. Since the plant growing period in Mahannopkul's research is almost

longer than 1 year, which exceeds the maximum grass age (8 months) in this study, it is considered that the root volume in this study did not exceed the threshold so that the decrease of angle ϕ^b would not be observed. Finally, the measured total cohesion can fit with the calculated total cohesion well to validate the experiment and calculation method mutually and the calculated equation can be utilized to give the assessment on the shear strength for soil under the given matric suction and grass ages as the reference.

5. Conclusions

In present study, a sequence of unsaturated triaxial tests with various matric suctions for soil samples of different grass ages are performed. The findings of this study are summarized as follows:

1. The unsaturated triaxial test results reveal that root-permeated soil shear strength is reinforced. The root volume ratio R_v increases along with time, and there is an increase in effective internal friction angle, effective cohesion and maximum deviator stress (Q_{max}) with the increased root volume ratio.

2. The soil shear strength of bare soil specimen and grassed soil specimens increases under unsaturated conditions with the impact of matric suction. The total cohesion increases with increased matric suctions, while the effective internal friction angle keeps constant.

3. Both grass root and matric suction have reinforcement effect on increasing the soil shear strength, and the reinforcement effect caused by matric suction is more considerable for increasing total cohesion of bare soil and grassed soils than grass root.

4. A higher capability to retain matric suctions is appeared in grassed soils. Under the similar volumetric moisture content, the soil specimen with older grass ages and larger root volume ratio R_v has the greater matric suctions.

5. The unsaturated shear strength of grassed soils calculated based on Vanapalli model shows that the calculated total cohesion fits the measured total cohesion well. The calculation method can be used as a reference for estimating the grassed soil shear strength under unsaturated conditions.

The above findings demonstrate that the strength characteristics and water retention capacity of soil are influenced by the grass roots. The various grass ages lead to the different mechanical behaviours and SWCCs. The grassed soils are further strengthened with the increase in grass ages when the effects of root rot are neglected. Meanwhile, the effect of matric suctions on bare and grassed soil specimens in unsaturated

condition is observed. With higher matric suctions, the shear strength of bare soil and grassed soils increases because of the stronger capillary action. The unsaturated mechanical property of grassed soil at various grass ages and matric suctions can be estimated by using the proposed calculation equation for validation. With respect to the numerical simulation such as slope instability analysis, the estimated unsaturated mechanical property of grassed soil can be applied as the design parameters to access the slope stability of the slope covered by grass layers at different time in one year and different hydraulic domain. However, the opposite phenomenon caused by root systems is generated potentially if the vegetated age increases in one year. Root decay occurs when vegetation becomes old [37],[39]. As a result, the grass might have different influences on soil mechanical and hydrological properties in negative aspects. These contrasted influences should be investigated to access performance of vegetated unsaturated soil slope for long-term period.

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Table 1 Basic properties of Komaoka volcanic soil.

Properties	Komaoka volcanic soil
Specific gravity, G_s	2.445
In-situ dry density, ρ_d (g/cm ³)	0.794
Maximum dry density, $\rho_{d\max}$ (g/cm ³)	1.12
Minimum dry density, $\rho_{d\min}$ (g/cm ³)	0.76
In-situ porosity, n	0.675
Mean grain size, D_{50} (mm)	0.27
Coefficient of uniformity, U_c	3.6
Fines content, F_c (%)	26.0

Table 2 Basic properties of a mixture of grass seeds (kg/100 m²).

Grass seeds	Kentucky Bluegrass	Creeping Red Fescue	Tall Fescue
Weight of grass seeds (kg)	0.2	0.4	1.2

Table 3 Physical properties of Versapor membrane.

Type name	Versapor membrane 450
AEV (kPa)	110
Pore size (μm)	0.45
Water flow*	75
Allowable temperature (water) (C°)	88
Thickness (μm)	94

Note: * Water flow is the maximum water flow under the differential pressure of 70 kPa through the Versapor membrane filter.

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Table 4 Descriptions of root properties.

Soil type	Age of grass (months)	Root volume ratio (cm ³)	Root volume ratio (cm ³ /cm ³)
BK	0	---	---
GK2	2	2.99, 2.61, 2.06 Mean: 2.55 S.D.:±0.38	4.57E-03, 3.99E-03, 3.15E-03 Mean: 3.90E-03 S.D.:±5.84E-04
GK4	4	4.95, 4.42, 3.46 Mean: 4.28 S.D.:±0.62	7.57E-03, 6.76E-03, 5.29E-03 Mean: 6.54E-03 S.D.:±9.43E-04
GK6	6	6.43, 5.68, 5.18 Mean: 5.76 S.D.:±0.51	9.83E-03, 8.69E-03, 7.92E-03 Mean: 8.81E-03 S.D.:±7.86E-04
GK8	8	7.67, 6.42, 6.33 Mean: 6.81 S.D.:±0.61	1.17E-02, 9.82E-03, 9.68E-03 Mean: 1.04E-02 S.D.:±9.35E-04

S.D. stands for standard deviation

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Table 5 Volumetric water content for soil specimens.

Soil type	Suction (kPa)	Volumetric water content θ_w	Effective degree of saturation S_e
BK	0	65.5%	1
	5	44.7%	0.676
	15	39.9%	0.603
	25	37.4%	0.563
GK2	0	65.5%	1
	5	45.8%	0.687
	15	41.6%	0.621
	25	39.9%	0.596
GK4	0	65.5%	1
	5	47.0%	0.710
	15	43.0%	0.646
	25	41.4%	0.621
GK6	0	65.5%	1
	5	49.1%	0.740
	15	45.1%	0.677
	25	43.5%	0.652
GK8	0	65.5%	1
	5	51.2%	0.772
	15	47.7%	0.716
	25	46.4%	0.695

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Table 6 SWCC parameters of VG model.

Soil type	a (1/kPa)	n	m	Air entry value (kPa)	Saturated water content θ_s	Residual water content θ_r	Fitting error R^2
BK	2.932	1.142	0.124	0.21	65.50%	1.48%	0.9925
GK2	2.752	1.131	0.116	0.35	65.50%	1.83%	0.9884
GK4	2.553	1.112	0.109	0.42	65.50%	2.19%	0.9918
GK6	2.325	1.111	0.099	0.53	65.50%	2.38%	0.9937
GK8	2.123	1.096	0.088	0.62	65.50%	2.78%	0.9949

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Table 7 Shear strength properties of bare soil and grassed soils after calibration.

Soil type	Confining pressure (kPa)	Suction, s (kPa)	Dry density ρ_d (g/cm ³)	Friction Angle, ϕ' (°)	ϕ^b (°)	Measured total cohesion, c (kPa)	Calculated total cohesion c (kPa) (Vanapalli model)			
							c'_{soil}	c'_{root}	$c_{apparent}$	Total c
BK	25	0	0.833	41.2	28.5	1.27	1.27	0	0.00	1.27
		5	0.827	41.2		4.08	1.27	0	2.95	4.22
		15	0.814	41.2		9.76	1.27	0	7.90	9.17
		25	0.821	41.2		13.9	1.27	0	12.28	13.55
GK2	25	0	0.840	41.5	29.6	3.16*	0.22*	2.94	0.00	3.16
		5	0.831	41.5		7.16	1.27	2.94	3.05	7.26
		15	0.824	41.5		13.06	1.27	2.94	8.29	12.5
		25	0.835	41.5		17.54	1.27	2.94	13.25	17.46
GK4	25	0	0.813	41.7	30.2	4.55*	0.22*	4.33	0.00	4.55
		5	0.804	41.7		8.71	1.27	4.33	3.16	8.76
		15	0.825	41.7		14.1	1.27	4.33	8.62	14.22
		25	0.829	41.7		19.47	1.27	4.33	13.81	19.41
GK6	25	0	0.842	42.3	31.7	7.17*	0.22*	6.95	0.00	7.17
		5	0.836	42.3		11.32	1.27	6.95	3.36	11.58
		15	0.830	42.3		17.29	1.27	6.95	9.24	17.46
		25	0.818	42.3		22.91	1.27	6.95	14.83	23.05
GK8	25	0	0.825	42.6	32.1	8.51*	0.22*	8.29	0.00	8.51
		5	0.810	42.6		13.14	1.27	8.29	3.55	13.11
		15	0.817	42.6		19.56	1.27	8.29	9.88	19.44
		25	0.842	42.6		24.27	1.27	8.29	15.99	25.55

* stands for results from past research

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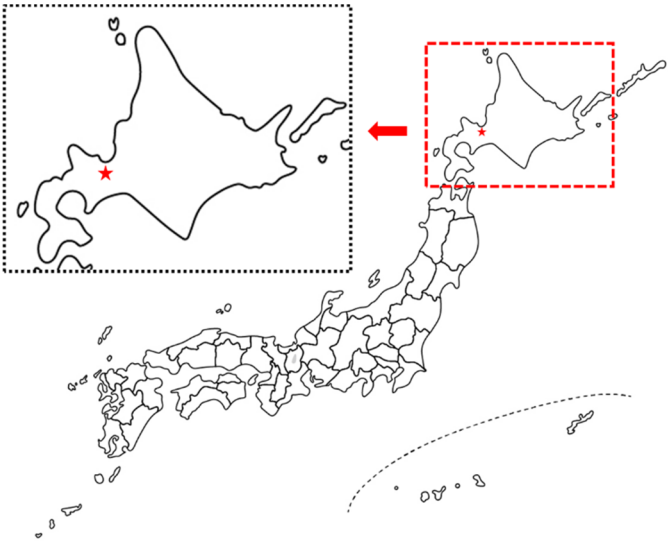


Fig. 1. Location for sampling Komaoka volcanic soil.

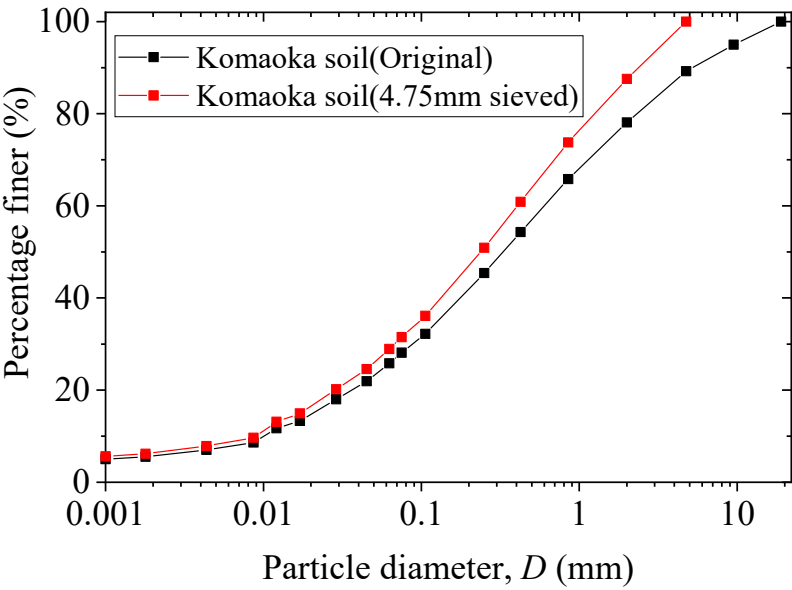
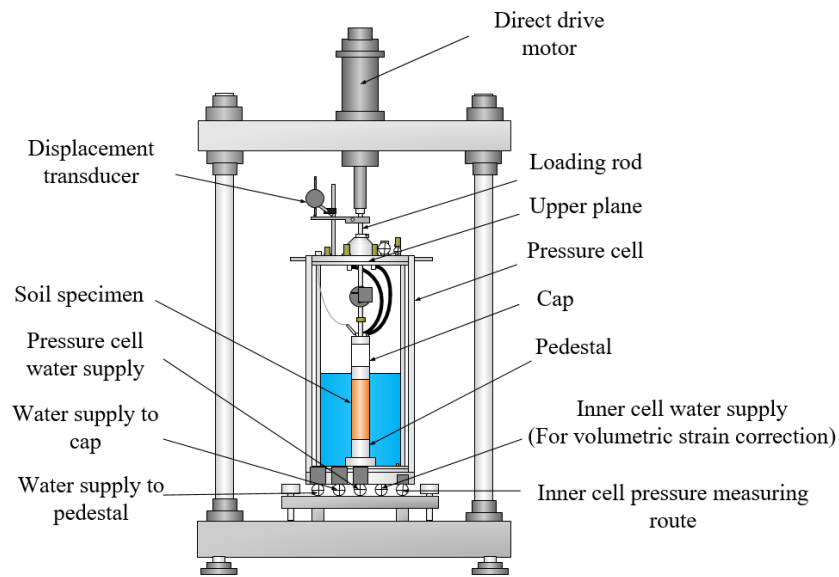


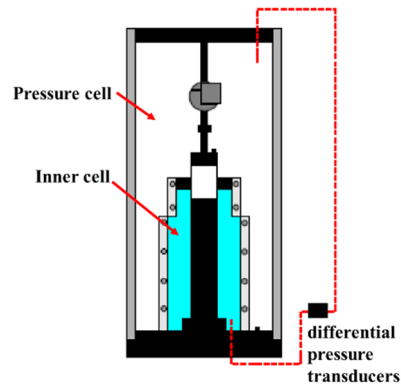
Fig. 2. Grain size distribution of Komaoka volcanic soil.

(a)



9

(b)



10

11

12

13

Fig. 3. (a) Schematic diagram of triaxial test apparatus; (b) Schematic diagram of volumetric strain measurement devices.

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15

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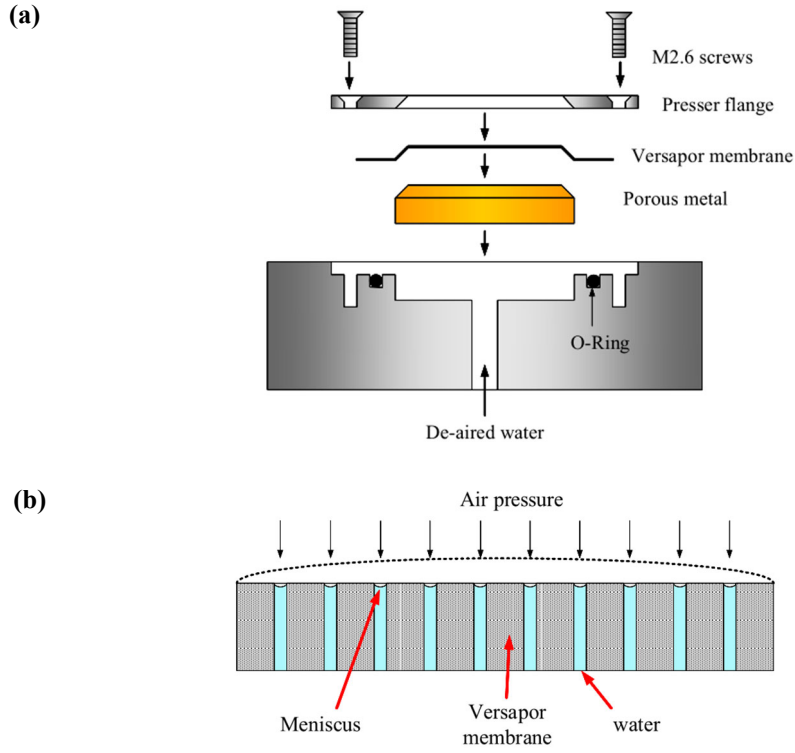


Fig. 4. (a) Installment of Versapor membrane; (b) Mechanism of Versapor membrane.

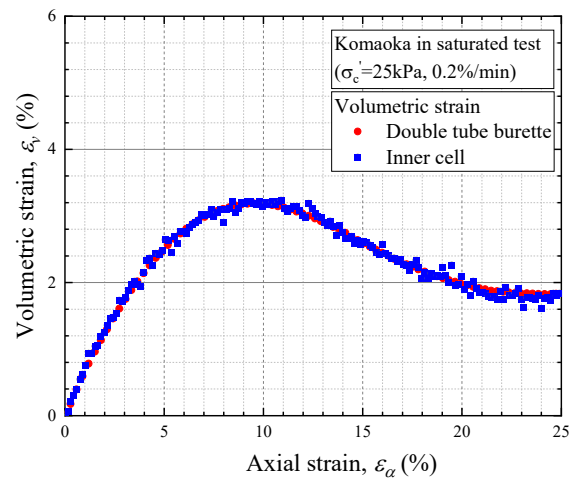


Fig. 5. Comparison of ε_v obtained from different measuring methods.

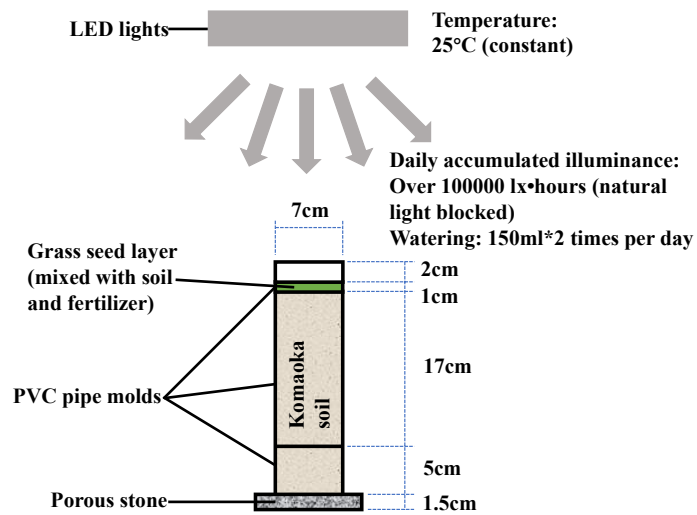


Fig. 6. Schematic diagram of indoor cultivation.



Fig. 7. Specimens after cultivating and after trimming and freezing.

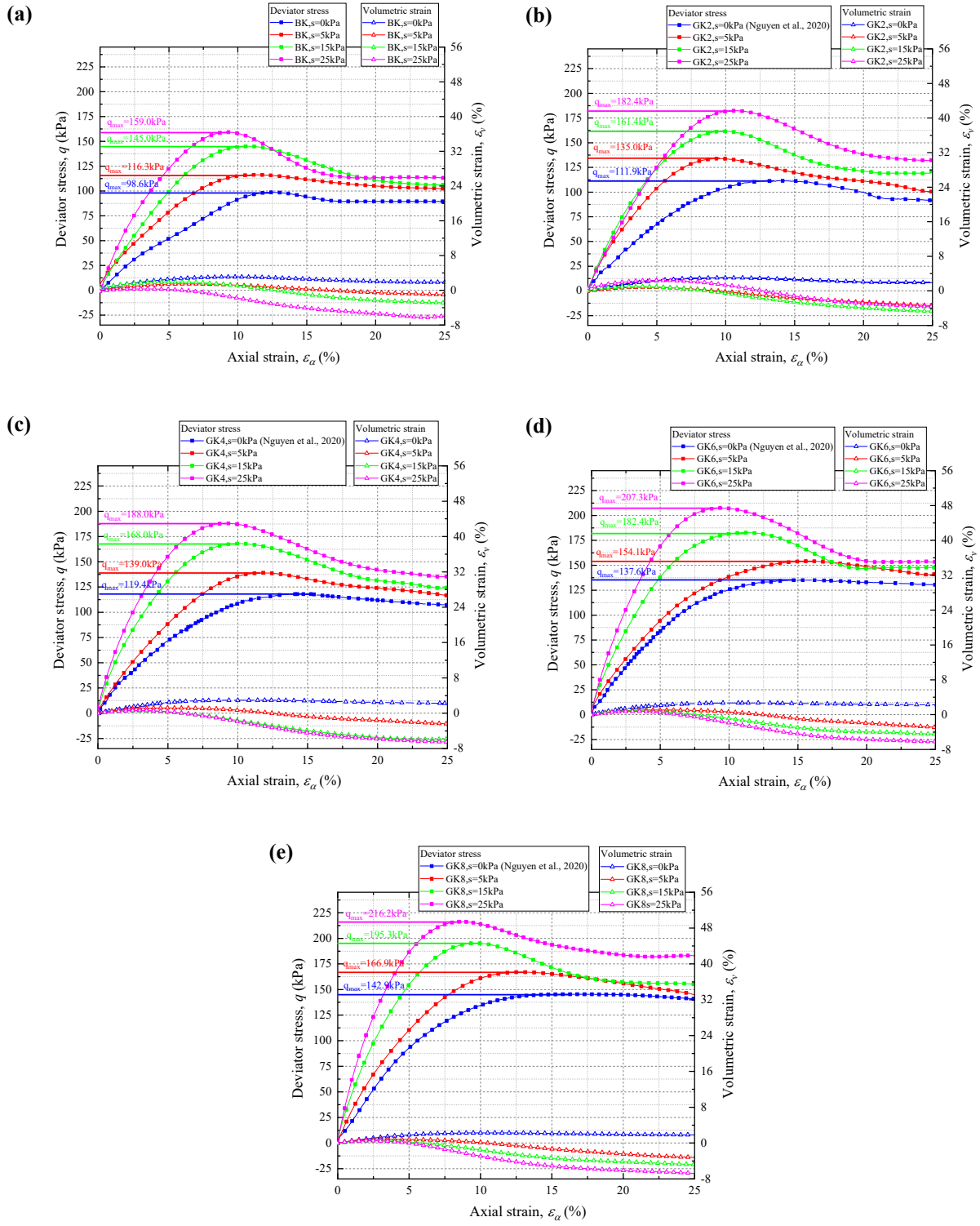


Fig. 8 Shear behaviors of soils at effective confining pressures of 25 kPa under matric suction of 0 kPa, 5 kPa, 15 kPa and 25 kPa. (a) BK; (b) GK2; (c) GK4; (d) GK6; (e) GK8.

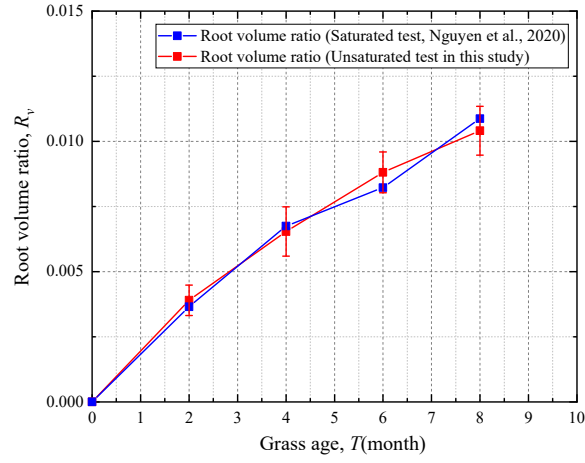


Fig. 9 Relationship between grass age and R_v and comparison

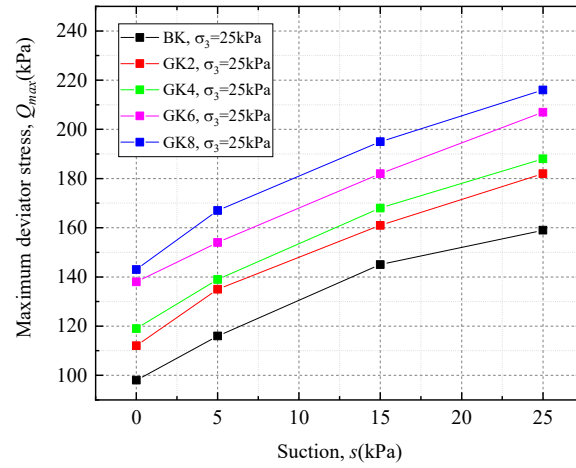


Fig. 10 Relationship between peak shear strength and grass age

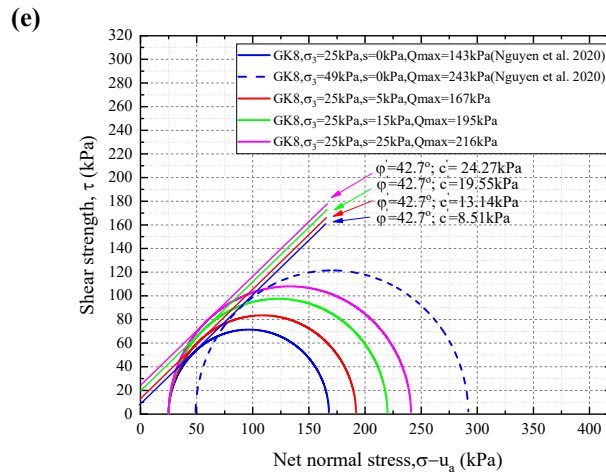
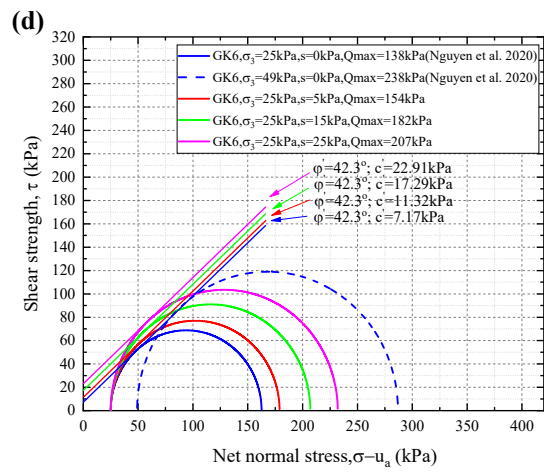
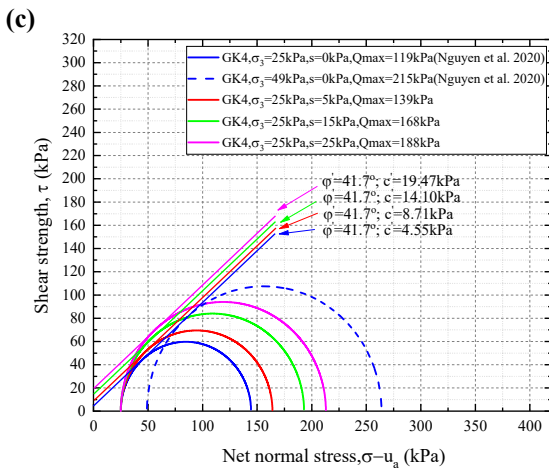
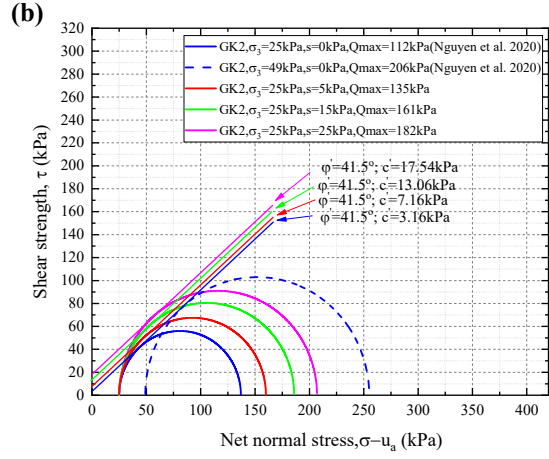
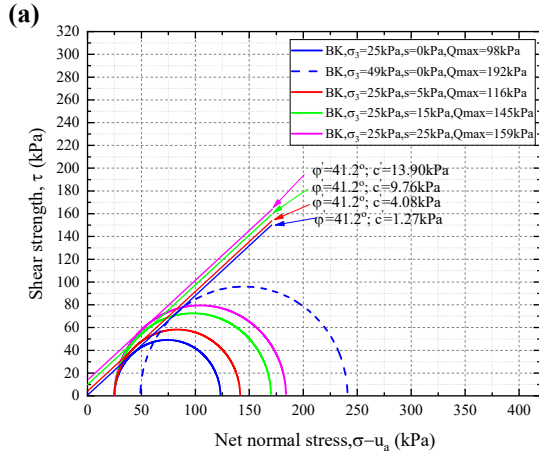


Fig. 11 Mohr-Coulomb failure envelopes of bare soil and grassed soils under different matric suctions. (a) BK; (b) GK2; (c) GK4; (d) GK6; (e) GK8.

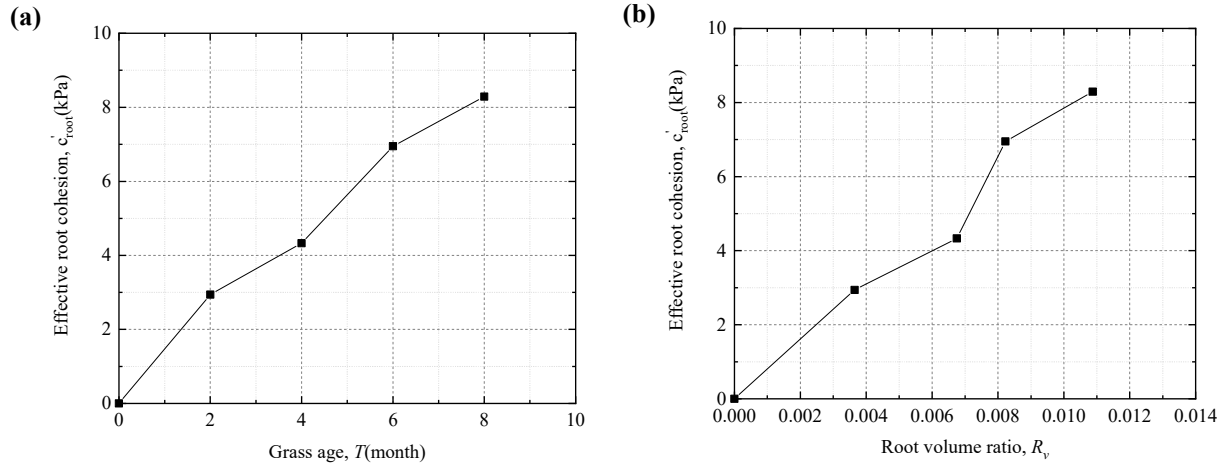


Fig. 12 (a) Relationship between effective root cohesion and grass age; (b) Relationship between effective root cohesion and root volume ratio (Nguyen et al. 2020).

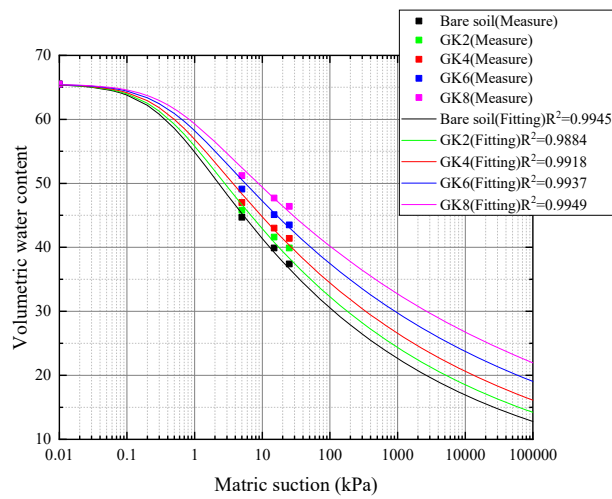


Fig. 13 Measured points of θ_w and fitted SWCCs by Van Genuchten (1980) model of bare soil and grassed soils.

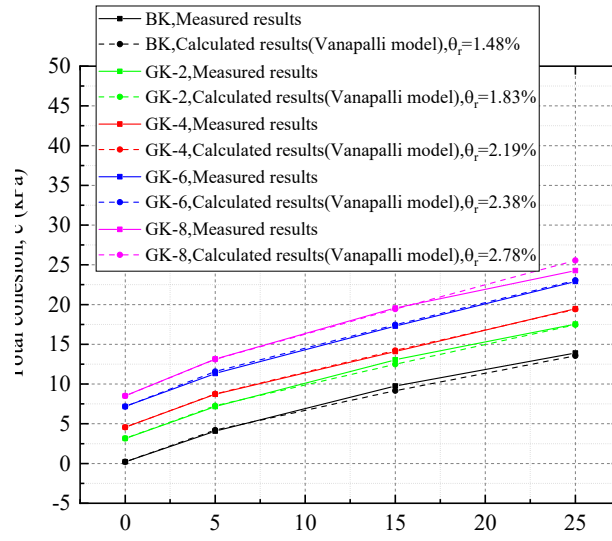


Fig. 14 Calculated total cohesion and measured total cohesion.