The Relationship between Shear Strength and the Optical Spectral Behaviour of Different Soils

PhD Thesis

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1. Introduction

Terramechanics science aims to study the principles of the interaction between the terrain and machines by studying the performance of the vehicles in the operating environment, modeling the terrain behaviour, measuring the characteristics of terrain properties, and identifying pertinent parameters of the interaction between the vehicle and the terrain. The performance of the machines moving on the terrain is affected by the terrain itself, so studying the behaviour of different terrains under the machines will serve in enhancing the driving and the vehicle performance by improving the effective traction, decreasing the slippage, and limiting or avoiding the sinkage of the wheel/s upon moving on a soft terrain.

By the movement of the vehicle on the terrain, the weight of the vehicle will lead to pressing the wheels downward, so upon moving on soft terrains the wheels will sink, and thus the pressure-sinkage relationship is important to be studied, also when the axle applies torque to rotate the wheel it will be faced by the resistance resulting from shearing the soil (the soil material strength), so might lead to the slippage of the vehicle, thus the shear-slip relationship is also important to be studied when dealing with terramechanics case. The combination of the both upper drags (slip and sinkage) will weaken the consumption of the vehicle's output power leading to many consequences such as non-safe drive, exhausting the vehicle systems (wheels, suspension, brakes, drive train...) and consuming fuel.

This research concentrates on measuring the shear strength of different soil textures. The interaction between the machine specifically between the wheel or track (tractive force) and the terrain will lead to shearing the terrain, so studying the shear force at the interaction level is a required step for studying the vehicle mobility, especially that this load might lead to the slippage of the machine, thus weakens its performance.

Measuring the shear strength of the soil will help in analyzing the shear loads interacting between the machines and the soil terrain mainly the tested soil types, thus the study will be beneficial to some researchers by relying on the obtained data and/or findings to be used in new terramechanics designs or technology. Methods of approach to terramechanics are through empirical, semi-empirical, and theoretical approach. The empirical method relies on experimental results of both the vehicle moving and the terrain, and the outputs are correlated. In case of dealing with too many terrains and different vehicle types such as tracked vehicles, the experiments will consume too much effort and this step requires many experiments, but ends with actual results (might not benefit in tracked vehicles, heavy vehicles). The semi empirical is the combination of both, empirical and theoretical, through having experimental data used in theoretical models, and the theoretical approach relies on theoretical methods.

The target behind the research is that after carrying out laboratory shear tests on different soil samples (different textures) at different moisture contents, and recording the colour reflectance of the different soils (colour influenced by moisture content), the shear strength values (shear strength and its parameters) of each soil texture will be related to its colour reflectance. Relating the shear strength values of a soil to its colour reflectance, provides simplicity in detecting the shear strength values from the colour of the soil. The shear strength values of the soil textures will be measured in the laboratory using the direct shear test, the shearing mechanism that emulates the shear beneath the vehicle tractive element (translational shearing). The colour reflectance will be measured using the visible range spectrophotometer, that measures by sending light wave in the visible band (400-700 nm spectrum).

2. Determining the soil moisture content from its colour reflectance

The main target from this work section is reaching the ability of estimating the moisture content from the colour reflectance of the soil as a preliminary step for linking the reflectance to the shear strength values. Reaching convincing results (after validating field measurements) will help in predicting the performance of a vehicle on soil terrain based on the colour of the soil, upon having the moisture content provided to strength equation.

The spectrophotometer is a modern technology used for measuring the colour of a body (material). The working principle of the used type is by sending light wave which is in the visible band, spectrum (400-700 nm), and based on the collected reflected wavelengths, the colour of the soil is identified. The colour of the soil is described by the reflected wavelengths, which are digital values (quantitative). In most of the soils, the increase in the moisture content of the soil makes the soil darker, but, even though not being able to see the change in the colour by the eye's vision, the spectrophotometer is able to decode the colour of the soil to a digital value.

2.1 Colour reflectance measuring procedure with textures used

The colour of the soil (at different moisture contents) was measured using a visible range spectrophotometer (Konica Minolta CM-700d), see Figure 2.1. The soil is a particulate matter, so the reflectance will not be exactly the same upon repeating the measurement (on same soil at the same moisture content). For this reason, three data records were taken per each measurement (at a moisture content), and the average of the colour reflectance was taken into account.

The technical usage of the spectrophotometer and the compaction of the soil (either by the instrument lens, or if having the soil already compacted) influence the colour reflectance. The lens of the instrument is applied perpendicularly to the soil surface, so that the lens is touching the soil at equal smooth compaction, having it totally covering the surface. The records are saved in the spectrophotometer and then imported to a computer. The reflectance results (of each soil sample at a moisture content) at the light wavelengths (from 400 to 700 nm with an increment 10 nm) are recorded.

Fig. 2.1. Spectrophotometer CM-700d.

The lens of the spectrophotometer is placed directly on the soil sample, covering all the lens, thus the reflected light is captured by the sensor without losses or any external light noise affecting the measurement.

The measurements were carried out in the same surrounding environment, besides that, the spectrophotometer was calibrated regularly using its white calibration head to avoid any deviations in the results (Spectrophotometer user manual, 2008).

What differentiates a soil from another is its texture, the mechanical composition. For the colour reflectance measurements, five different textures were tested.

Used soil textures in details, the percentage of each mineral, are in the Table 2.1. Soils were sieved before carrying out the measurements on them (physical status: loose soil).

Table 2.1. Textures used, with their minerals percentages (Institute for Soil Sciences TAKI).

Soil texture	Sand (%)	Silt (%)	Clay (%)
Sand	94.53	4.78	0.69
Silty clay loam	14.07	47.46	38.47
Loam sand	90.50	3.20	6.30
Sand	95.68	2.12	2.21
Silty clay	3.34	52.05	44.61

The reason behind choosing these textures is that they are common soils in Hungary, in addition to the difference in their types (for example, sandy soil the coarse particles soil, and silty clay the fine particles soil). The change in physical and mechanical properties of a soil with moistening is dependent on its texture, a reason behind choosing different soil textures (texture affects type).

The moistening process of each soil was by adding water and then stirring till becoming of uniform colour. The moisture content in the soil was measured using the moisture analyzer (HE 53), a gravimetric measurement, operates based on the drying principle (Figure 2.2). The analyzer calculates the moisture percentage by deducting the remaining mass from the initial mass (wet mass), and the value is divided by the initial mass (wet base moisture calculation).

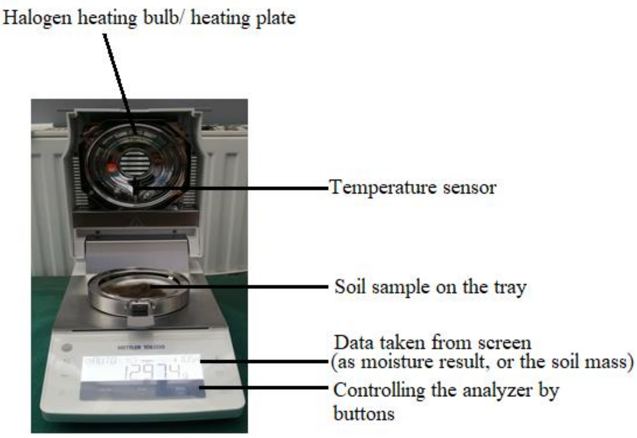


Fig. 2.2. Soil prepared on the moisture analyzer tray before closing the cover (HE 53 moisture analyzer).

In most of the soils, the increase in the moisture content leads to dimming (darkening) its colour, and that can be recognized in the measurements, not only visually by seeing how the colour of the tested soils is changing, but also by the spectrophotometric results.

Empirically and mathematically, the validity of the curves' equations (of the considered reflectance parameters) of each soil was checked by substituting each reflectance value (Z, the averaging, and at 700 nm; obtained from a new measurement at a moisture content) in its equation. The closest estimated moisture value is obtained from the equation of the curve fitting the reflectance at 700 nm as function of moisture content. Upon substituting a new colour reflectance record at 700 nm in the already obtained curve equation (for each soil, 700 nm reflectance results as function of moisture content), the closest moisture value is obtained (relative to the value measured by the moisture analyzer).

2.2 Reflectance curve at 700 nm (moisture content estimated from the colour reflectance)

Each of the below curves (Figures 2.3-2.7) shows the reflectance results at 700 nm plotted as function of moisture content of a tested soil texture.

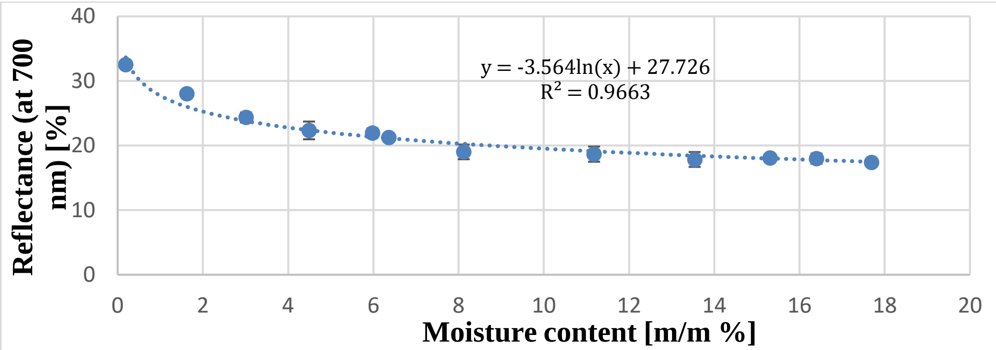


Fig. 2.3. Colour reflectance (at 700 nm) as function of moisture content, sand soil (94.53 % sand, 4.78 % silt, 0.69 % clay).

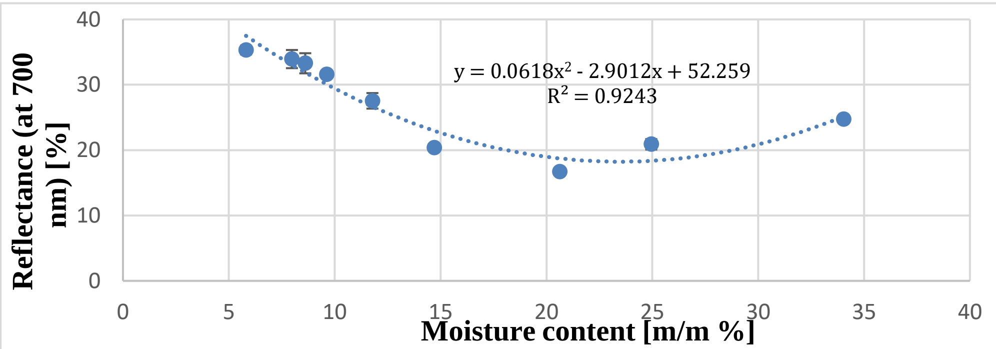


Fig. 2.4. Colour reflectance (at 700 nm) as function of moisture content, silty clay loam (14.07 % sand, 47.46 % silt, 38.47 % clay).

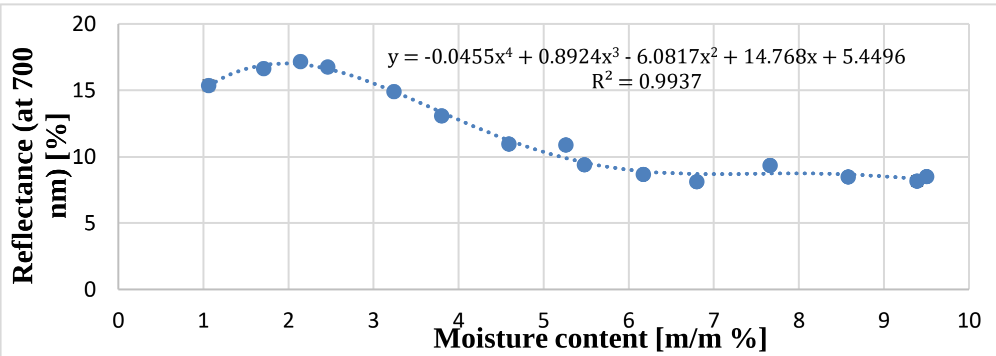


Fig. 2.5. Colour reflectance (at 700 nm) as function of moisture content, loam sand soil (90.50 % sand, 3.20 % silt, 6.30 % clay).

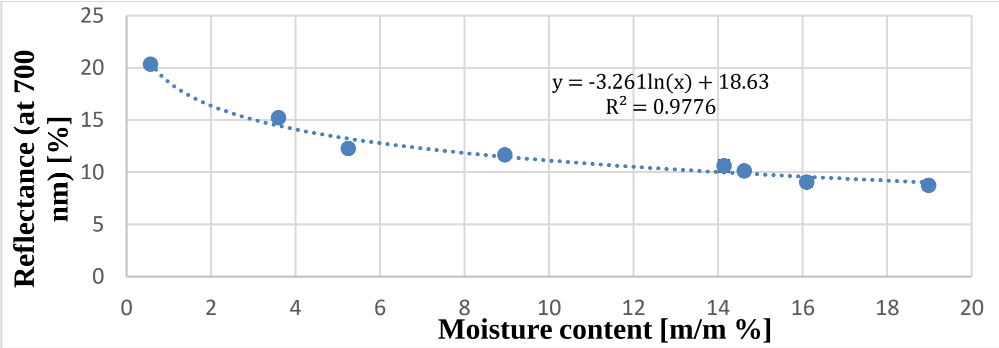


Fig. 2.6. Colour reflectance (at 700 nm) as function of moisture content, sand soil (95.68 % sand, 2.12 % silt, 2.21 % clay).

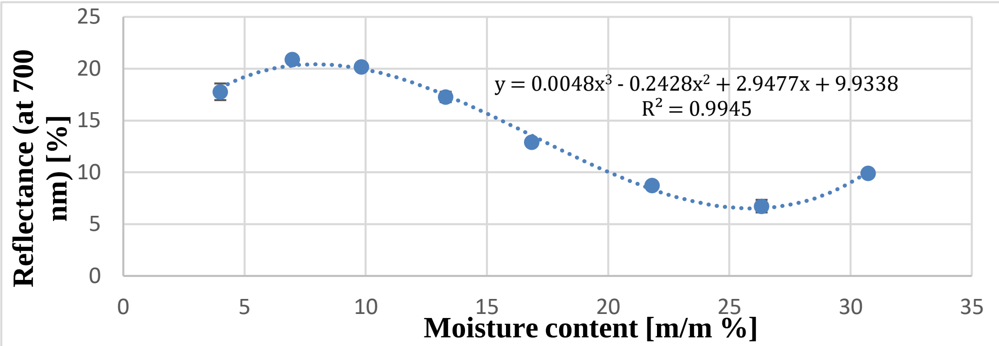


Fig. 2.7. Colour reflectance (at 700 nm) as function of moisture content, silty clay soil (3.34 % sand, 52.05 % silt, 44.61 % clay).

2.3 Reflectance (at 700 nm) results' discussion

In Figures 2.3 till 2.7, it is clear that with the increase in the moisture content, the reflectance is decreasing (on average). Based on the above results, it can be considered as a general rule which was also mentioned (confirmed) by researchers (Zanetti et al., 2015), (Bowers and Hanks, 1965), that on most of the soils with the increase in the moisture content the colour becomes darker, thus leading to decreasing the spectrophotometric reflectance value.

In the soil textures that contain high clay and silt portions (mostly clay, particles of high cohesion), the silty clay loam and the silty clay, after reaching the minimum point in the curve at a moisture value, beyond the minimum point the tendency shows a slight increase in the reflectance. The reason behind this behaviour is that at a moisture content that is close to the minimum point moisture content, the colour reaches an approximately constant level and what is dominating the spectral reflectance at this stage is the behaviour of the soil. With the presence of silt and clay, mainly clay, at high moisture content these fine particle change the soil matter from a particulate matter to a one body bonded paste. Thus, having the sent light wave reaching the soil, the sent wave is no more scattered and absorbed at the particles' level (maybe a small portion), leading to increasing the reflectance. When having the soil as powder (granulated), the specularly reflected wave is a small fraction of the incident light, and the rest part of the incident light penetrates into the soil mass encountering surfaces of minerals and organic particles (Torrent and Barrón, 1993). The material behaviour of the soil at this stage (a moisture range in each of the two soil textures) is a paste like material. In real-time terramechanics case, vehicles move on soil as particulate matter, thus a reason behind cancelling this part of the curve tendency and not considering it when accounting the curve tendency. The Figures 4.19 and 4.20 in the dissertation show the physical behaviour of the two tested silty clay textures.

3. Mohr-Coulomb principle for finding the soil shear strength and its parameters

The soil response to an exerted load differs from a texture to another. The soil shear strength is directly affected by its cohesion and the internal friction angle under a normal stress. This chapter illustrates the shear strength values of different soil textures at different moisture contents obtained using the direct shear test. The shear strength values of three soil textures were obtained (from the textures used above in the colour measurement section) using the geo-civil engineering method, parameters determined by drawing the Mohr-Coulomb line, but in undrained condition (higher shearing speed), the case that complies with a terramechanics study case.

Having the curve's tendency equation of each soil shear strength value (cohesion, internal friction, and shear strength) as function of moisture content prepared, will serve in knowing the safety limit of the tested soil at a moisture value, that beyond it the soil fails.

3.1 Shear strength measurement (direct shear test) with textures used

The shear strength values (shear cohesion, internal friction, and shear strength) of three soil textures, Table 3.1, were obtained at different moisture contents. The soils tested in this section were also tested (but other samples) for finding their colour reflectance (chapter 2).

Table 3.1. Soil textures used for the shear strength measurements.

Soil texture	Sand (%)	Silt (%)	Clay (%)
Loam sand	90.50	3.20	6.30
Sand	95.68	2.12	2.21
Silty clay	3.34	52.05	44.61

For ending up with convincing cohesion and internal friction results using the Mohr-Coulomb line, there is standardized method to rely on, thus ending with realistic results.

The ASTM (American society for testing and materials) direct shear test method (ASTM D3080/D3080M-23) is a standard method for finding the soil strength parameters. This method deals with a soil as a drained material, thus shearing the soil at very low shearing rate (less than 1 mm/min). This method requires carrying out the measurement in a professional way, thus demanding experienced persons in this test from geotechnical or civil engineering fields (relying on references in the measurement) (ASTM, 2023).

The soil will be tested at 9 mm/min shearing speed (maximum speed in the machine), the case that might lead to unconvincing cohesion and internal friction angle results.

Finding the shear strength parameters using the Mohr-Coulomb line at a speed higher than the drained condition speed, might lead to unaccepted results (such as negative cohesion, or low cohesion relative to the soil physically recognized cohesion). Based on the empirical work carried out using the direct shear test, a conclusion was deduced, and is that before applying the masses that will be used for drawing the Mohr-Coulomb line, the soil samples (each) should be subjected to a mass that is higher than the maximum mass that will be used in drawing the Mohr-Coulomb line. In the below measurements, 30, 40, 50, and 60 kg (95.86, 127.81, 159.77, 191.72 kPa) masses will be used for drawing the Mohr-Coulomb line, thus 70 kg (223.68 kPa) was chosen as a preloading mass to compact the soil before applying each of the four masses.

In each of the sections below (3.2, 3.3, 3.4), each for a soil texture, the procedure followed for measuring the shear strength values of the tested texture is presented. The sections embed shear strength results with analysis.

The direct shear test machine used (ELE 26-2112/01), Figure 3.1, is connected to a computer, and through a software, the applied shear stress and the resulting shearing displacement are recorded relying on the sensors installed on the machine (shear force and displacement sensors).

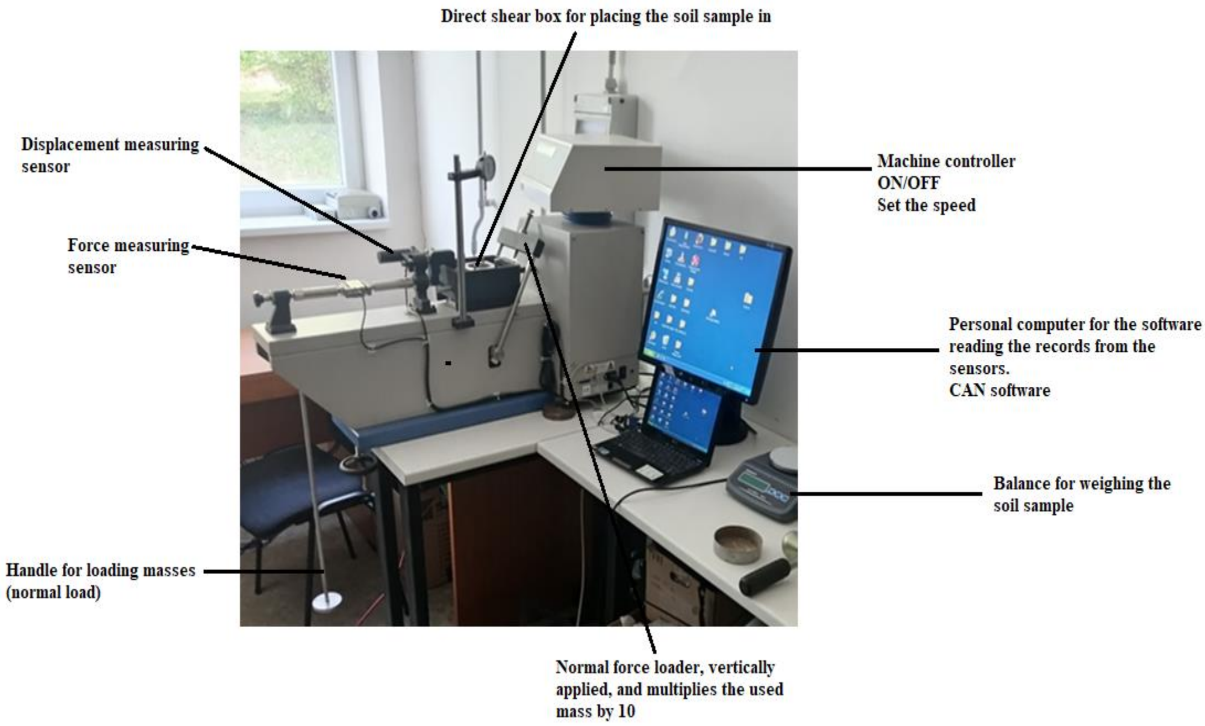


Fig. 3.1. Direct shear test (ELE 26-2112/01).

3.2 Loam sand soil shear strength (with parameters) measuring procedure

In measurements on loam sand soil samples at different moisture contents, the cohesion and the internal friction angle were obtained relying on the Mohr-Coulomb line. Even though the shear strength can be obtained under a consolidation stress at a shearing speed (relatively higher speed), but when it comes to using shear strength results (under different normal stresses) for drawing the Mohr-Coulomb line, wrong (unrealistic) strength parameters might be obtained. Based on empirical work and with many trials, convincing results were obtained, achieved by consolidating the soil in direct shear box for few seconds using a mass that is higher than the maximum load (stress) used for fitting the Mohr-Coulomb line, thus making the loose soil with an OCR value above 1. The soil was consolidated with a high mass, maximum mass to be used in the measurement is 60 kg, thus a 70 kg was used for initial consolidation. The cohesion is built up under the 70 kg, and is of a value close to the cohesion that is built up under the lower masses (used for Mohr-Coulomb linearity).

The initial status of the soil per each measurement was fixed by fixing its soil mass and marking its initial height in the shear box (initial volume is fixed before applying the initial 70 kg mass). For each shear measurement carried out on a sample (at a moisture content), the soil mass and its initial thickness were fixed in the direct shear box to 110 g and 2.38 cm, thus soil of initial density 1.46 g/cm^3; density before normal consolidation. The 70 kg mass is applied for few seconds, and then replaced by the shearing mass, applied during shearing the soil (each, 30, 40, 50 and 60 kg). The obtained results of the cohesion and the internal friction angle, both have ended up with logical tendency as function of moisture content. For the tested soil, the internal friction angle is decreasing with the increase in the moisture content, while the cohesion is increasing with moistening. Figures 3.2, 3.3 and 3.4 show the shear strength values as function of moisture content. Measurements were carried out on the tested soil at moisture contents 1.05, 3.07, 6.91, 9.02 and 12.52 % mc.

3.2.1 Loam sand soil shear strength (with parameters) results

Results recorded by the sensors installed on the machine are imported to the computer. For simplifying reaching the maximum force recorded by the sensor when shearing the soil, which based on it the shear strength can be calculated, the shear force-displacement curves of the tested samples (different moisture contents) were drawn (in dissertation, curves, 5.2, 5.7, 5.11).

In order to understand what is happening to the shear strength with the increase in the moisture content, the peak force was converted to shear strength (divided by area) and plotted as function of moisture content, considering the 30 kg consolidation mass (taking one mass as an example). New measurement was carried out on the soil when dry under 30 kg (with 70 kg applied initially), so that all plotted results will be consistent (under 30 kg). Figure 3.2 shows the shear strength results as function of moisture content. Same initial condition in this plot, and is that the soil experienced a compaction load 70 kg (for few seconds), before setting the 30 kg applied load (shearing load). The soil was tested at the following moisture contents, 1.05, 3.07, 6.91, 9.02 and 12.52 % mc.

Note: with having the soil dry, for drawing the Coulomb line, higher masses were used while shearing, also higher mass for the initial consolidation, check the dissertation for more details (check each soil texture case).

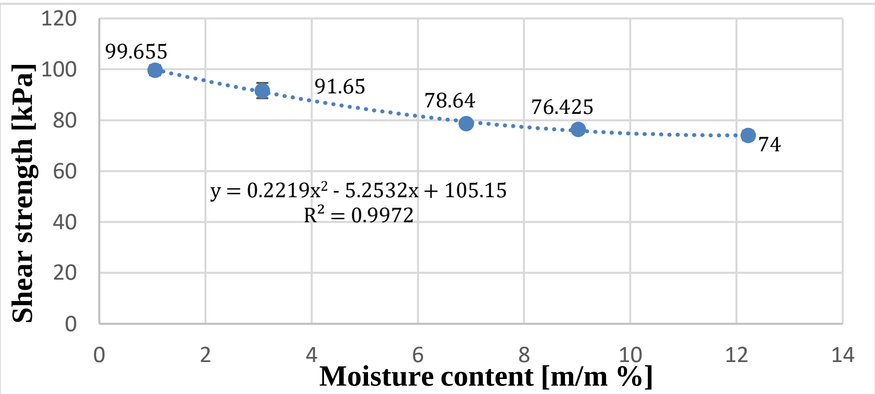


Fig. 3.2. Loam sand soil shear strength as function of moisture content (70 kg/223.68 kPa initially applied load/stress, and 30 kg/95.86 kPa is used with shearing).

The shear cohesion and the internal friction angle results of the tested soil are shown in Figures 3.3 and 3.4, plotted as function of moisture content.

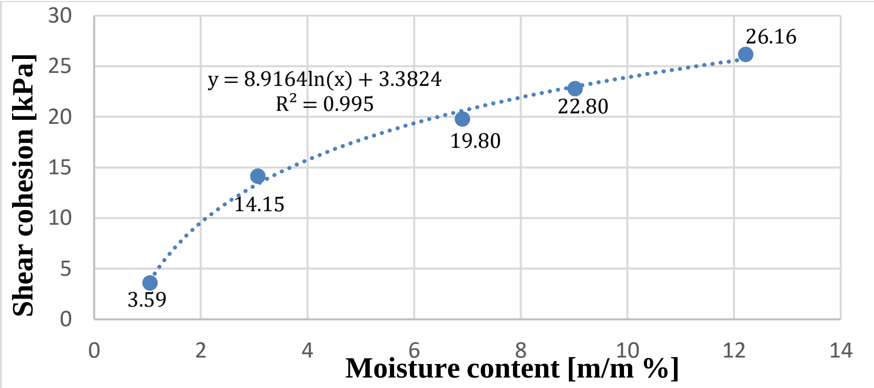


Fig. 3.3. Loam sand soil shear cohesion as function of moisture content.

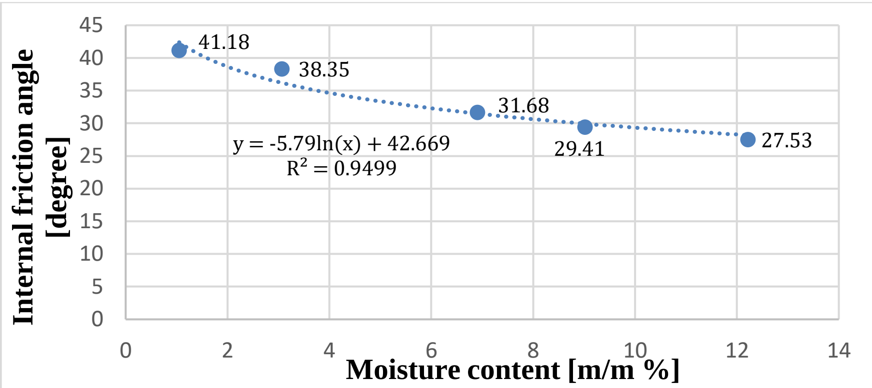


Fig. 3.4. Loam sand soil internal friction angle as function of moisture content.

3.2.2 Discussion on the loam sand soil shear strength (with parameters) results

In Figure 3.2, the shear strength under 30 kg mass as function of moisture content, the curve shows that with the increase in the moisture content, the shear strength is decreasing. The shear strength is weakening with the increase in the moisture content.

For the shear strength parameters, with the increase in the moisture content, the shear cohesion is increasing reaching a peak at the maximum moisture value reached. This result complies with how the soil is changing physically with the increase in the moisture. Initially the soil is dry and sieved with approximately neglected cohesion value (particles' dismantled), physically with moistening the soil it is showing cohesive behaviour, the case that complies with the numerical cohesive results (the increasing tendency).

For the internal friction angle, the angle is decreasing with the increase in the moisture content, these results comply with the physical behaviour of the soil. Having the soil dry, the particles are of weak bonding, besides that the particles are not hydrated. The unhydrated particles will increase the friction when the particles' surfaces contact each other, also the weak bonding will lead to the movement of the particles in excessive way compared to when bonded, the case that will lead to the particles interlocking each other. With moistening, particles get hydrated, thus decreasing the contact friction, also particles bond to each other leading to decreasing its movement.

In the tested loam sand soil and sand soil (section 3.3) textures, the maximum reached moisture content is around 12 % moisture content, considering that till this moisture content, the soil is still holding a strength to resist the shearing, since at high moisture values the soil becomes of weak strength (entering the weak stage beyond a critical moisture content that depends on the texture). Beyond a critical moisture content, the water starts acting as a lubricant weakening the friction term, in addition to that the water film breaks the bonding between the particles. When it comes to vehicle mobility study case, the range till 12 % (in the loam sand and sand soil measurements) moisture content is considerable range for studying the strength values. In the silty clay soil (section 3.4), the moisture range is wider due to the strong cohesion of the soil, and the reached value in the measurements is around 17 % mc.

3.3 Sand soil shear strength (with parameters) measuring procedure

The tested soil is of sand type, of mechanical composition (2.21 % clay, 2.12 % silt, 95.68 % sand). The shear strength values were obtained at different moisture contents. Starting with the soil at ambient conditions, the moisture is due to the surrounding humidity, and by adding water, the soil was moistened. For each shear measurement carried out on a sample (at a moisture content), the soil mass and its initial thickness were fixed in the direct shear box (110 g and 2.38 cm, thus of initial density 1.46 g/cm^3; density before normal consolidation).

After placing a sample in the box, the soil was compacted by initial compaction load (mass used 70 kg, but not on dry samples) for few seconds, and then the required measuring load was applied (removal of 70 kg and applying the normal load required during shearing). The masses used for changing the consolidation stresses are 30, 40, 50 and 60 kg (for Mohr-Coulomb line).

3.3.1 Sand soil shear strength (with parameters) results

Figure 3.5 shows the shear strength results. Initially the soil experienced a compaction load 70 kg (also when dry, just here, for unifying the conditions of this diagram) before setting the 30 kg load (applied while shearing). The soil was tested at the following moisture contents, 0.54, 3.11, 6.33, 9.72, and 12.53 %.

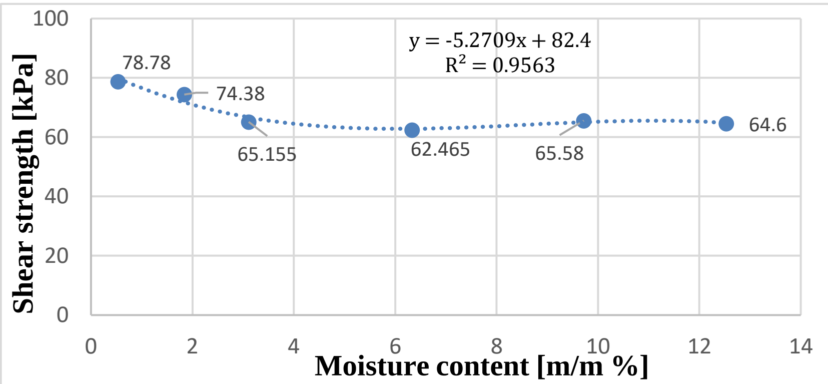
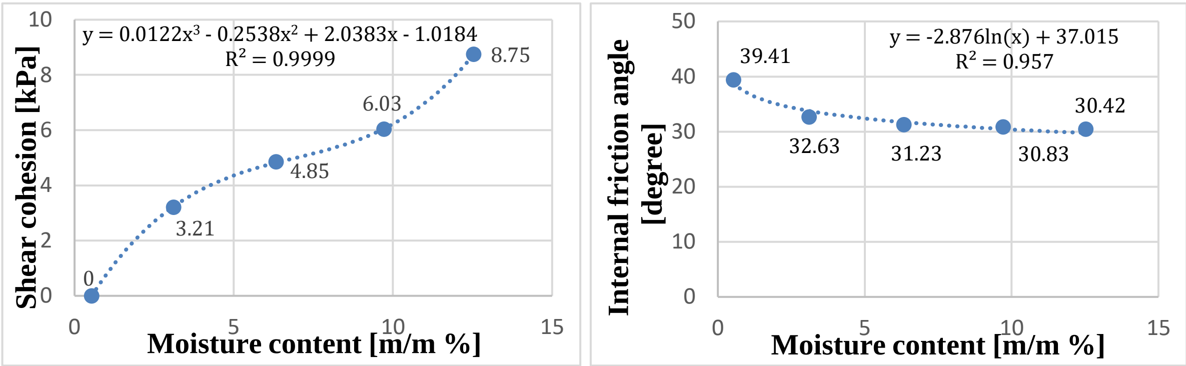


Fig. 3.5. Shear strength of the tested sand soil as function of moisture content (70 kg/223.68 kPa initially applied load/stress, and 30 kg/95.86 kPa is used with shearing); shear strength at 1.84 % is included in the figure.

The equation in the figure belongs to the decay in the shear strength (moisture content, 0.54 % to 3.11 %), since the beyond shear strength is approximately constant.

In the work below (Figure, 3.6), the cohesion at 0.54 % mc is considered approximately equal to zero. Having the soil dry at 0.54 %, and considering the cohesion is of null value, also knowing that the shear strength under the 30 kg (95.86 kPa) consolidation stress is 78.78 kPa (Figure 3.5), the internal friction angle can be calculated from the Mohr-Coulomb linear equation. Using the Mohr-Coulomb equation to calculate the internal friction angle, the resulting friction value is 39.41 degree. The sand soil is a frictional soil, thus shows its maximum friction behaviour when dry compared to when moistened. Comparing the friction results at different moisture values, having the soil dry (0.54 %) shows that the friction is at its maximum value (39.41 degree).



(a) (b)

Fig. 3.6. (a) Sand soil shear cohesion as function of moisture content, (b) internal friction angle as function of moisture content.

3.3.2 Discussion on the sand soil shear strength (with parameters) results

With the increase in the moisture content from 0.54 % to 3.11 % mc, the shear strength of the soil decreased from its maximum value, 78.78 kPa, having the soil dry, to a value around 65 kPa. Beyond the moisture content 3.11 %, the shear strength remains of a value around 65 kPa.

In this measurement even though the cohesion results are close, the cohesion (Figure 3.6) was considered in a tendency that occurs on most of the soil types, which is the increase in the cohesion with the increase in the moisture content. The cohesion is increasing from approximately 3.21 to 8.75 kPa, while the internal friction angle decreases from 32.63 to 30.42 degree (Figure 3.6). The slight increase in the cohesion and decrease in the internal friction angle reflect that the results are approximately equal, since not having a recognized change.

The cohesion and the friction angle results comply with the shear strength tendency of the tested soil as function of moisture content under 30 kg consolidation load (Figure 3.5). The stability in the shear strength beyond 3.11 % mc, which is around 65 kPa, is because of the stability in the shear cohesion and the internal friction angle, except for the dry soil, where there is no cohesion and the friction is maximum.

3.4 Silty clay soil shear strength (with parameters) measuring procedure

The strong cohesive bonding resulting with increasing the moisture must lead to decreasing the friction between the particles, since the strong bonding will limit the movement of the particles. The shear strength values were obtained at different moisture contents, starting with the soil of moisture content due to the surrounding humidity. For each shear measurement carried out on a sample (at a moisture content), the soil mass and its initial thickness were fixed in the direct shear box (90 g and 2.88 cm, thus of initial density 0.99 g/cm^3; density before normal consolidation).

After placing a sample in the box, the soil was compacted by initial normal load (mass used 70 kg) for few seconds, and then the required measuring load was applied (removal of the 70 kg, and applying the normal load required during shearing).

3.4.1 Silty clay soil shear strength (with parameters) results

Figure 3.7 shows the shear strength results under applied consolidation load (from 30 kg). Initially the soil experienced a 70 kg compaction load for few seconds before setting the 30 kg shearing normal load (same on the dry soil, just for this measurement - the shear strength and not the parameters - to compare the results at unified conditions). The soil was tested at the following moisture contents, 4.19, 7.19, 10.07, 14.46, and 17.72 %.

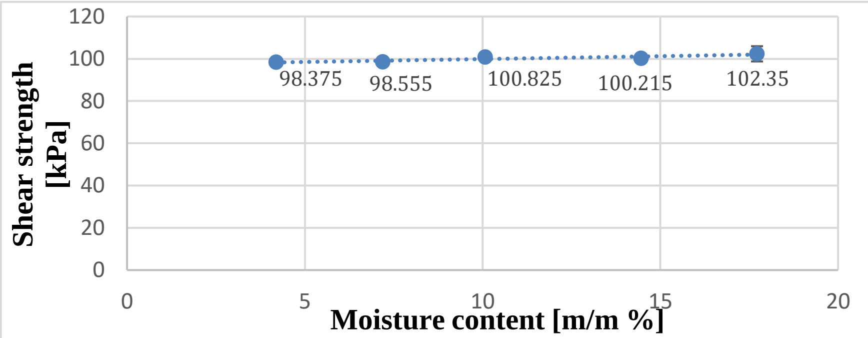


Fig. 3.7. Shear strength as function of moisture content (70 kg/223.68 kPa initially applied load/stress, and 30 kg/95.86 kPa is used with shearing).

In Figure 3.7, under 30 kg applied mass, and at the same shearing speed, the shear strength remains approximately unchanged with the increase in the moisture content. Even though the results show a slight increase in the shear strength, but can be considered approximately constant. The constancy in the shear strength is resulting from the compensation between the shear cohesion and the internal friction angle with moistening. The Mohr-Coulomb equation embeds both, the shear cohesion and the internal friction angle (under normal stress). The two strength parameters, despite one of them is increasing and the other is decreasing, they are changing in a rhythm that keeps the shear strength constant with the increase in the moisture.

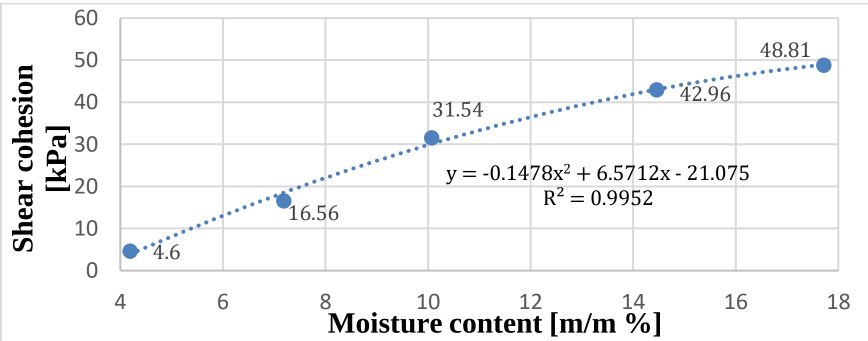


Fig. 3.8. Shear cohesion as function of moisture content.

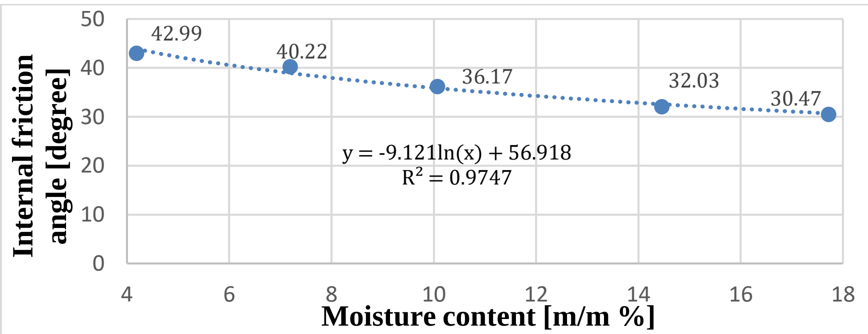


Fig. 3.9. Internal friction angle as function of moisture content.

3.4.2 Discussion on the silty clay soil shear strength (with parameters) results

Figure (3.8) shows the shear cohesion results as function of moisture content. With the increase in the moisture content, the shear cohesion increases, applicable till the maximum reached moisture content (at high moisture contents the soil becomes a paste like material). The shear cohesion tendency complies with the change in the physical behaviour of the soil and with its identity (the clay texture).

For the internal friction angle (Figure 3.9), with the increase in the moisture content, the friction angle decreases, applicable till reaching the maximum considered moisture content. The tendency complies with the physical behaviour of the soil, since the increase in the cohesion limits the interparticles' friction, due to the strong polarity bonding.

Upon having any moisture content provided as input to any of the equations mentioned in the figures (shear cohesion and friction angle), this leads to predicting the parameters at the moisture content used. Using both parameters with the normal stress, the shear strength can be predicted.

4. Soil properties obtained from the colour reflectance

4.1 Shear strength determined from the colour reflectance

As mentioned in the introduction, linking the mechanical properties of the soil to its colour facilitates knowing the infield mechanical properties of the soil from its colour. This work was achieved through laboratory work, and the results should be validated by field measurements.

Having the equation of the curve fitting the colour reflectance points at 700 nm (section 2, Figurs 2.3-2.7), will help in finding the moisture content of the soil upon substituting the reflectance value in it (new record at 700 nm); thus, the moisture content is obtained.

With the equation of the curve passing through the plotted shear cohesion points as function of moisture content, the shear cohesion can be calculated at the moisture content (predicted from the reflectance). By using the equation of the internal friction angle curve fitting the plotted points, the internal friction angle is obtained at the predicted moisture content. The same process is applicable on the shear strength plotted as function of moisture content (under a normal consolidation stress). Figure 4.1 presents the flowchart of the correlation process/methodology.

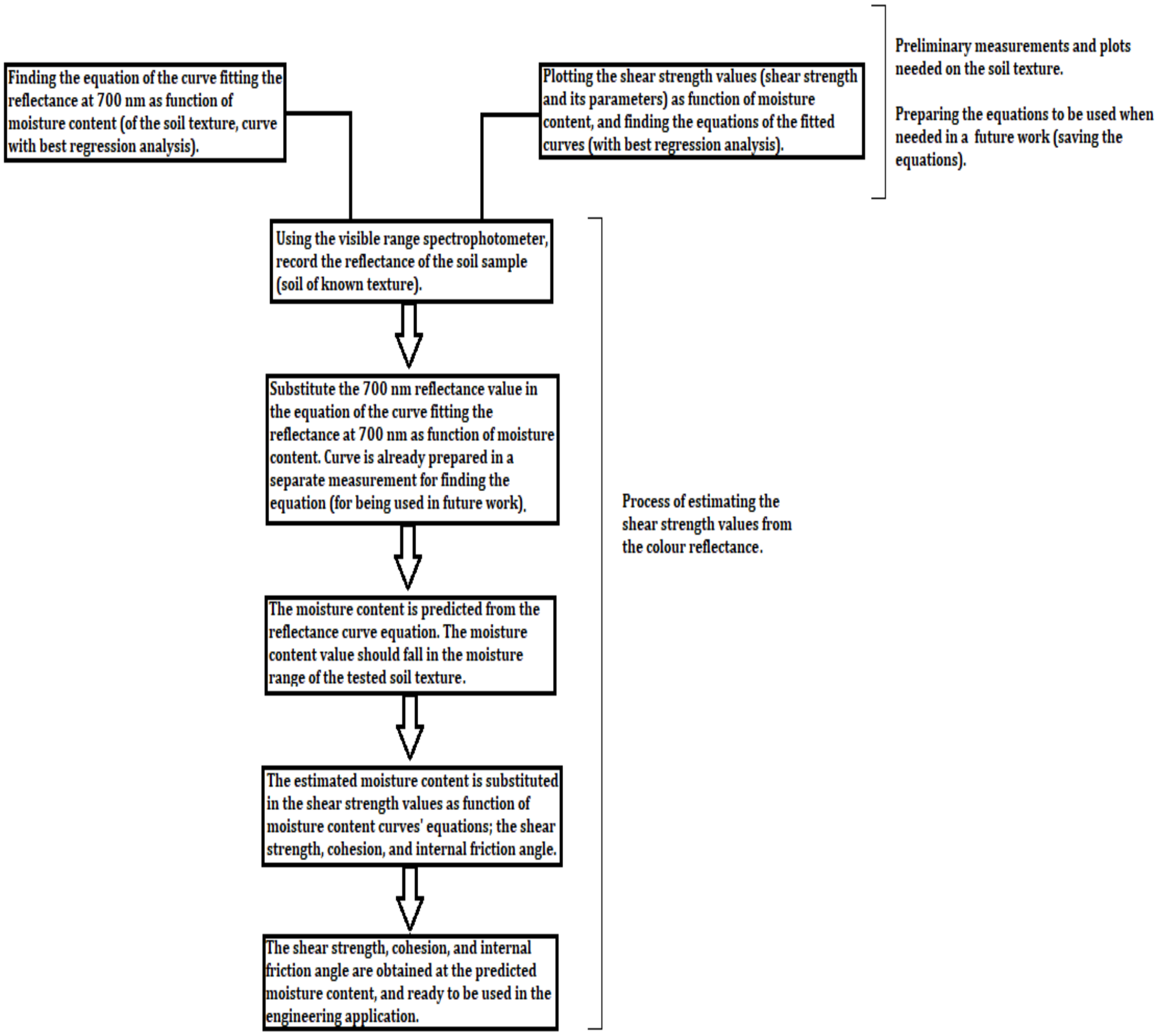


Fig. 4.1. Flowchart showing the process followed for predicting the shear strength values from the colour reflectance.

An example is given on one of the tested soils regarding finding the shear strength and the parameters from the reflectance. Considering the loam sand soil for this example, for input colour reflectance y=10.24 (record of another prepared sample), and relying on the curve equation (section 2.2, Figure 2.5), the estimated moisture value is 5.07 % mc (check the reflectance-moisture validity section in the dissertation for more details, section 4.6). The 5.07 % mc is substituted in the loam sand soil shear strength curves' equations (subsection 3.2.1, Figures 3.2, 3.3 and 3.4).

The strength equations of the loam sand are the following equations, under the condition that the soil is tested as loose soil.

The shear strength equation (under 30 kg mass) as function of moisture content (Figure 3.2) is:

$$Y_1 = 0.2219x^2 - 5.2532x + 105.15 \tag{4.1}$$

The shear cohesion equation as function of moisture content (Figure 3.3) is:

$$Y_2 = 8.9164\ln(x) + 3.3824 \tag{4.2}$$

The internal friction angle equation as function of moisture content (Figure 3.4) is:

$$Y_3 = -5.79\ln(x) + 42.669 \tag{4.3}$$

Solving for the input moisture value (5.07 %, estimated from colour),

$Y_1 =$ 84.22 kPa , $Y_2 =$17.85 kPa , $Y_3 =$ 33.26 degree.

The above work clarifies the correlation process between the colour reflectance and the shear strength values of a soil texture. The same process is applicable on other textures, following the same steps.

In the dissertation, a measurement (section 6.2) was carried out for checking the validity of estimating the moisture content from the reflectance curve (at 700 nm) in field. In addition to that, a section (6.3) is mentioned showing the ability of using the colour reflectance in identifying the soil texture.

5. Soil shear strength parameters from mechanics perspective

5.1 Influence of density on the shear strength in translational shearing mechanism

The shear strength was measured at different densities using the direct shear test (same speed, 9 mm/min), the work that ended up with clarifying the linearity in the Mohr-Coulomb failure criterion.

Table 5.1. Shear strength of loam sand soil at different densities, of 4.38 % mc, measured using the direct shear test.

Loam sand soil at moisture content 4.38 %		
Density [g/cm^3]	**Shear strength [kPa] (30 kg is the applied mass while shearing)**	**Shear strength results - sample standard deviation**
1.49 (using 30 kg)	79.28	3.36
1.59 (using 70 kg)	88.18	1.73
1.64 (using 90 kg)	85.40	0.64

Table 5.2. Shear strength of loam sand soil at different densities, of 11.51 % mc, measured using the direct shear test.

Loam sand soil at moisture content 11.51 %		
Density [g/cm^3]	**Shear strength [kPa] (30 kg is the applied mass while shearing)**	**Shear strength results - sample standard deviation**
1.73 (using 30 kg)	62.69	1.00
1.77 (using 70 kg)	64.01	4.33
1.81 (using 90 kg)	62.69	2.12

The results in the two tables (5.1 and 5.2) show that with the increase in the density and under the same applied normal stress while shearing (from 30 kg), the shear strength is approximately the same. Thus, under these loads that are applied initially to compact the soil there is no change in the cohesion built up, cohesion is approximately the same in the three density cases, and the actual factor that has influence on the translational shearing strength of the soil is the friction part which is due to the applied normal stress (σ). This work complies with Mohr-Coulomb linear equation. The linearity of the Coulomb line is applicable in a normal stress range (dependent on the stresses used for drawing the Coulomb line), beyond a certain level (normal stress), the linearity will not be applicable due to the change in the built up cohesion.

5.2 New method for measuring the shear strength (mechanics method)

This method relies on two measurements for finding the shear strength, one for the cohesion, where shearing is carried out without normal load, and another which is based on a new design for finding the friction angle, thus obtaining the friction term in the shear strength.

A new suggested idea for measuring the friction coefficient was tried, yielding accepted shear strength results compared to measured results (validated). The target behind the suggested idea is to achieve the shearing on a thin soil layer, thus shearing against friction without cohesion.

The following work was done using the direct shear test machine, but with a small change in the shearing sample design. Two teflon cylinders were used with double face tape on each, a face is glued on a teflon side, and on the other side, soil (at a moisture content) is placed. When shearing the soil it will shear over each other, with no cohesion built up (might be of a very small value, explained in the dissertation text), and in addition to that, a light mass is applied while shearing (5 kg used, and not heavy mass, to avoid the building up of pore pressure cohesion). The steps followed for preparing the shearing soil sample are shown in Figure 5.1.

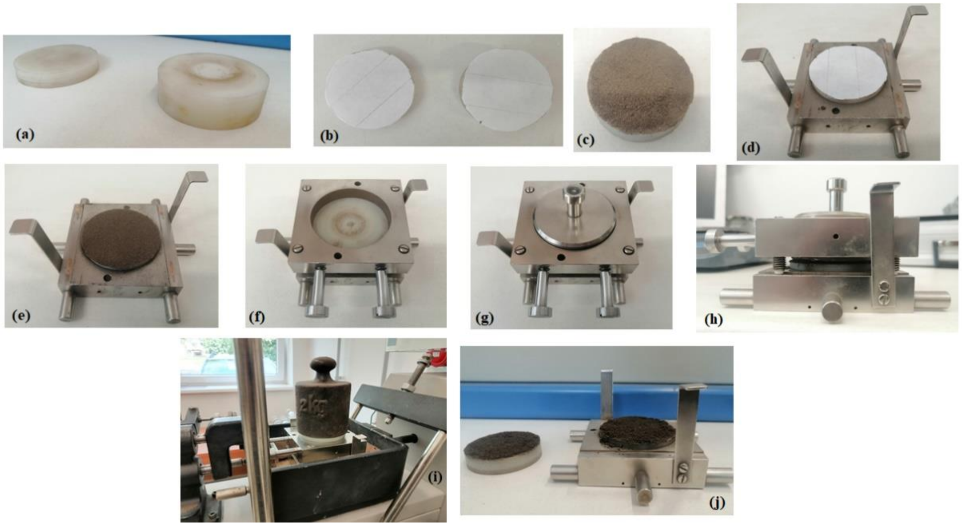


Fig. 5.1. (a, b) show the prepared teflon cylinders, with double face tape used on them, (c) shows the soil sticking on the other face of the tape, this sample is prepared for the upper frame, (d, e) lower frame teflon with soil prepared on it, (f, g, h) frame assembled, shearing zone seen in h, (i) Box installed in the shear machine with normal load applied - all masses applied are considered (with the teflon piece mass), (j) soil of high moisture content on the tape face.

5.2.1 Results obtained using the mechanics method

The soil was tested under two light masses (1 kg and 2 kg) at different moisture contents, except for the high moisture value reached, where a 200 g mass was also used. The internal friction angle is independent of the normal load applied, and the aim behind using a light mass is to avoid building up of cohesion between the particles, thus running the friction measurement at the particles' level without any disturbances on the measured friction force value. The loam sand soil is used; friction coefficients obtained at the different moisture contents are shown in Table 5.3.

Table 5.3. Friction coefficients of the tested soil at different moisture contents (112 g teflon piece mass added to the applied mass).

Moisture content [m/m %]	0.62	3.23	6.07	9.64	12.07
Friction coefficient under 1.112 kg	0.89	0.67	0.62	0.67	0.65
Friction coefficient under 2.112 kg	0.86	0.64	0.56	0.69	0.76

In Table 5.3, at the moisture contents, 0.62, 3.23, and 6.07 % mc, the friction coefficient results show an approximation in the results under the two masses. The tendency shows a decrease with the increase in the moisture at the first three moisture contents. At 9.64 % mc and 12.07 % mc, the friction coefficients show an increase in the friction value.

Logically the friction should decrease with the increase in the moisture content, but these two results contradict the logical tendency. The reason behind that might be due to cohesion building up in the soil under the masses used (even if very small cohesion value), the case that is leading to the force being recorded embedding this very small cohesive value, thus yielding a higher force at this stage. At high moisture contents, the plasticity of the soil increases. For the 9.64 % mc, preparing another sample (soil on the tape), and following the same procedure for measuring the friction, but now applying and then removing the masses (upper teflon with soil layer is kept, is of light mass), so just measuring the built up cohesive force. For the 9.64 % mc, the cohesive force values built under the used masses are, c = 6.56 N [2.08 kPa] under 1.112 kg [3.55 kPa] and c = 7.03 N [2.23 kPa] under 2.112 kg [6.74 kPa].

Having the cohesion force obtained at the 9.64 % mc, also knowing the friction obtained, the cohesion and the frame forces should be deducted from the measured friction force, this will lead to the precise friction force of the soil. Dealing with the results (at high moisture contents) in the mentioned way, ended with the friction coefficients under the two used masses (1.112 kg and 2.112 kg / 3.55 kPa and 6.74 kPa). The obtained friction coefficients are μ=0.50 (under 1.112 kg) and μ=0.57 (under 2.112 kg). The two results are convincing and fall in the friction change tendency with increasing the moisture content.

For decreasing the error in the measurement, the same work principle was followed for the 12.07 % mc, but this time the mentioned masses were not used (1 and 2 kg), and tried with a very low mass (200 g), considering that this will not build a recognized cohesion. The mass was applied on the teflon piece, and 2 records were taken, one for the cohesion (remove the mass then shear), and the second for the friction (embedding the light cohesion). Having the 2 values, then deducting the cohesion and the frame forces from the measured friction value, will yield the actual friction force. Under the 200 g mass (lighter upper teflon piece used, 47 grams, both summing 247g / 0.789 kPa), the obtained friction coefficient is 0.47. Table 5.4 shows the friction coefficient with the internal friction angle of the tested soil at the different moisture contents.

Table 5.4. The friction coefficient and internal friction angle of the tested loam sand soil at the different moisture contents.

Moisture content [m/m %]	0.62	3.23	6.07	9.64	12.07
Friction coefficient (average results in table 5.3)	0.87	0.65	0.59	0.53	0.47
Internal friction angle [degree]	41.18	33.22	30.54	28.14	25.17

Table 5.4 shows that with the increase in the moisture content, the internal friction decreases. It is important to mention that the friction coefficient (even if having the soil dry) should be of a value less than one, this makes the measuring work sensitive.

5.2.2 Validity of the obtained friction results

The obtained friction results were validated under 5 kg (sum 5.112 kg / 16.33 kPa) normal mass applied while shearing. For the cohesive force measurement, place the soil (at a moisture content) in the shear box, then apply 200 kg (623.45 kPa) mass (chosen mass for the cohesion), after that remove the mass and run the machine. The maximum force is recorded by the sensor (the cohesive force).

The shearing force was measured in a new measurement (new sample, same speed) under 5 kg. A 5 kg was applied during shearing, and a 200 kg mass was initially used for building up the cohesion. Table 5.5 shows the cohesion and both, the measured and the calculated shear strength, results are after deducting the 4.6 N force (the frame force).

Table 5.5. Shows the validity of the obtained friction angle results (at moisture contents close to the friction angle results moisture contents).

Moisture content [m/m %]	0.62	3.20	6.40	9.64	12.53
Cohesion [kPa] (under 200 kg)	2.45	10.14	8.80	4.56	5.24
Cohesion results - sample standard deviation	0.15	0.24	0.08	0.45	0.20
Measured shear strength [kPa] (one record considered)	22.04	20.24	16.45	15.25	14.46
Calculated shear strength [kPa] (Mohr-Coulomb equation, using the cohesion and the friction angle)	16.18	20.91	17.76	12.54	12.89
% Relative [relative to the highest value, measured and calculated]	73.41	96.79	92.62	82.22	89.14

5.3 Comparing the obtained results (from the mechanics method) to the Mohr-Coulomb line results

The shear cohesion in Figure 3.3 (chapter 3) shows an increasing tendency with the increase in the moisture content, but the results do not comply with the ones obtained in Table 5.6. The word shear cohesion in translational shearing should be the force that is resisting the shearing process, resulting from the cohesive bonding, thus it should be the value that is resulting from the resistance without the friction term. The additional cohesion recognized in Figure 3.3 results compared to Table 5.6 (at each moisture content) might be due to additional cohesion that is built up with shearing (from the plasticity of the soil, also under normal stress, because when the soil is dry the results are approximate). Further investigation is required on the difference in the results as it is not an aim behind the project. Since the shear vane test does not require a normal load while measuring the soil shear strength, so the friction term is eliminated from the Mohr-Coulomb equation, thus the cohesion should be approximately equal to the shear strength. The cohesion to be used in translational shearing is supposed to be of a value close to the shear strength obtained by the shear vane.

Table 5.6. Tested loam sand soil shear cohesion (using the direct shear test machine with no consolidation stress).

Moisture content [m/m %]	1.05	3.12	6.75	9.00	12.07
Shear cohesion [kPa] (frame force included)	4.50	6.23	7.11	7.73	5.80
Cohesion results - sample standard deviation	0.14	0.02	0.06	0.02	0.21

The friction angle results shown in Figure 3.4 (chapter 3, loam sand) approximately comply with the friction angle results obtained using the above method (see results in Table 5.4).

6. Conclusion on the research

The main target behind the research has been achieved, which is relating the shear strength of the soil to its colour reflectance. This target was reached and checked on five different soil textures. As a preliminary step for relating the shear strength to the colour reflectance, it is to predict the moisture content from the colour reflectance of the soil.

For each soil texture, relying on the colour reflectance records captured by the spectrophotometer and dealing with them empirically and mathematically, it has appeared that plotting the reflectance records at 700 nm as function of moisture content is ending with a curve that is of reliable equation to be used in predicting the moisture content from the colour reflectance. This reached finding was validated through laboratory work by using new samples' reflectance records, also was checked infield. Predicting the soil moisture content from its colour reflectance might be helpful in different fields such as, terramechanics, agriculture, civil and geotechnics. The tendency of the change in the colour reflectance as function of moisture content is dependent on the soil type, as sand or silty clay, which is specified by its texture. In a chapter, it is mentioned the ability of determining the soil texture of a sample from the colour reflectance record (at 700 nm) when having the soil dry (0 % mc, dried), and is achieved by saving the record in a properties database to return back to it as an identity of the soil.

Using the direct shear test machine, the shear strength results of three different soil textures were found in undrained condition (higher speed compared to the standardized method shear speed, the speed used in civil and geotechnical engineering). The shear strength parameters obtained, shear cohesion and internal friction angle, show convincing curves changing tendencies as function of moisture content in the three tested textures. In each tested texture, the change in the shear strength results as function of moisture content comply with how the soil is physically changing with moistening. Having the moisture content estimated from the colour reflectance, it can be substituted in a shear strength value equation (shear strength, shear cohesion, or internal friction angle) as function of moisture content for ending with the required shear strength value, also applicable infield, but under the condition that the physical status of the soil infield is similar to the tested in the laboratory (loose soil in this project).

The linearity of the Mohr-Coulomb failure was clarified based on empirical work, and it is that the Mohr-Coulomb line (the linear equation) is applicable in a normal stress range (range relative to normal stresses used for finding the shear strength parameters), due to the influence that might result from the normal stress (initially before shearing) on the cohesion.

Dealing with soil from mechanics perspective for finding its shear strength parameters at a shearing speed that might be helpful in terramechanics study case, was given in a chapter. This method splits the shear strength to two terms, the shear cohesion and the friction, with finding each of the them in a separate measurement at the required speed.

Finally, as the main target is achieved, and is determining the shear strength or it parameters from the colour reflectance, this step will serve in saving time, cost, and effort. When it comes to finding the moisture content or the required shear strength value infield, this work will be performed using a remote sensor, thus no strength machines or instruments, or a moisture analyzer to be used infield. In vehicle mobility study science, with this reached target, a step is leaped for enhancing the mobility of a vehicle on soil terrains, thus at least taking the no-go decision to avoid having the vehicle getting stuck infield incase of not adjusting the tractive element contact patch area or its driving torque.

7. New scientific findings

As the main target behind the research work is to relate the soil shear strength values to its colour, new important scientific results were reached during dealing with the project, and the most important scientific findings are *(5 scientific findings)*:

7.1- The reflectance at 700 nm is used for predicting the moisture content from the colour.

Determining the correlation between the spectrophotometric colour reflectance records and the moisture content of the soil. Plotting the reflectance colour records at the **wavelength 700 nm as function of moisture content**, the equation of the curve fitting the plotted points with the best regression analysis is a reliable equation to estimate the moisture content from the colour reflectance of the soil.

I obtained the connection that relates the colour to the moisture content of the soil as a preliminary step for connecting the colour to the shear strength *(scientific finding 7.4)*. Based on my measurements, I state reaching the ability of estimating (predicting) the moisture content from the colour in a visually homogenous soil (no impurities and vegetation). I measured the colour using a visible range spectrophotometer (measures in the visible spectrum). Five different soil textures were tested.

Dealing with the records taken by the spectrophotometer mathematically and empirically by plotting different reflectance parameters at different moisture contents, I was able to reach the reliable curve (for each tested soil) that relates the colour to the moisture content, which based on it the moisture content is estimated.

Each soil has its initial colour when dry, and has its colour (reflectance) change behaviour (colour change tendency) with moistening. The amount of moisture a soil holds from humidity (when dry) differs from a type (specified by texture) to another, that is why the starting soil moisture content differs in the measurements, also the soil moisture content at saturation level (approximately maximum moisture content reached in each colour measurement) is affected by the type (curves below; findings in 7.2).

7.2- The reflectance-moisture content curve tendency changes with the change in the soil texture (type).

a- Colour-moisture curve tendency in loam sand soil (the tendency is showing stability in the reflectance beyond a moisture value).

By relating the colour to the moisture content, I figured out that the soil texture (mainly the type which is based on texture) plays an important role in the colour-moisture curve tendency, this can be recognized in the tested soils, and among them the loam sand soil. Figure 7.1 shows the curve tendency of the tested loam sand soil.

In the loam sand soil, the tendency of the curve has shown a decrease in the reflectance (on average) with the increase in the moisture content, and this is applicable till a certain moisture range (around 6 % moisture content), and beyond this range the reflectance becomes constant. The tendency is shown in Figure 7.1. For resulting with the best curve fitting of the best regression analysis, the constancy part was removed and the equation of the curve in the first moisture range was taken into account as the reliable equation for estimating the moisture content from the colour reflectance.

I have reached out that in the first moisture range the colour reflectance is decreasing with the increase in the moisture content (on average) due to the darkening in the soil colour, but beyond approximately 6 % moisture content, the results become constant (visually stable colour).

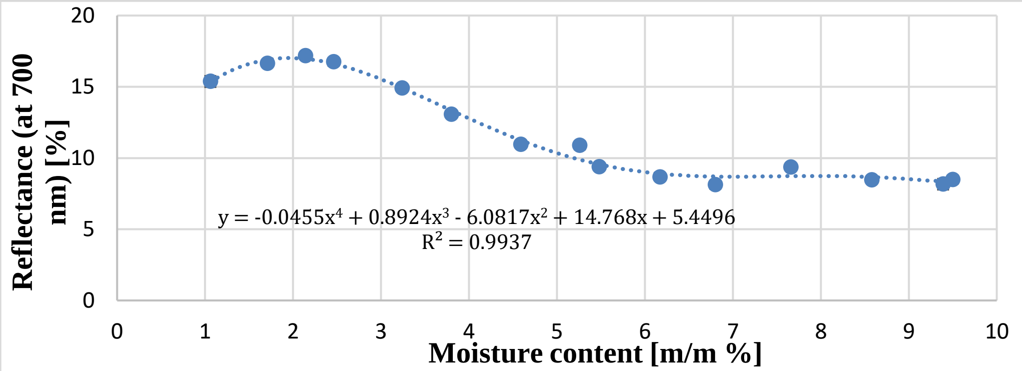


Fig. 7.1. Colour reflectance (at 700 nm) as function of moisture content, loam sand soil (90.50 % sand, 3.20 % silt, 6.30 % clay), the equation is of the curve in the range 1.06 to 6.80 %.

The equation (of the curve in the range 1.06 to 6.80 %, Figure 7.1) was validated resulting in moisture values close to the moisture content obtained by the gravimetric measurement (moisture analyzer).

b- Colour-moisture curve tendency in silty clayey soils (the tendency is showing an increase in the reflectance at high moisture content).

Two of the investigated textures are silty clayey soils (embedding high amount of clay and silt in the texture), and based on the colour obtained results a new finding was reached out.

I have found that in silty clay soils (based on the tested textures), at high moisture content, the reflectance shows a slight increase, and that can be seen in Figure 7.2. Another silty clay soil texture was tested, its tendency is in chapter 2 (of similar curve tendency).

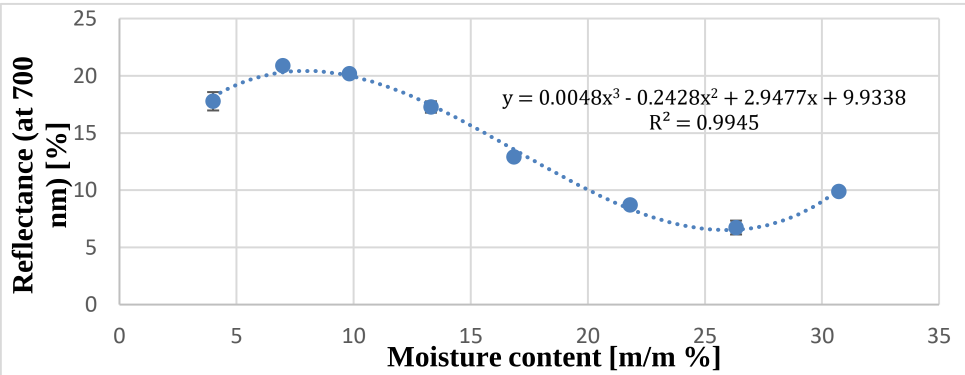


Fig. 7.2. Colour reflectance (at 700 nm) as function of moisture content, silty clay soil (3.34 % sand, 52.05 % silt, 44.61 % clay).

The presence of silt and clay, mostly clay, will lead to the particles bonding each other forming one face at high moisture content, the case that prevents (or decrease its ability) the spectrophotometric sent light wave from entering the particles' level and getting scattered and absorbed (maybe small portion), leading to increasing the reflectance. At high moisture contents (beyond the minimum point) the colour visually reaches stable level (pictures in the dissertation), and what dominates the reflectance of the sent light wave is the physical behaviour of the material (paste like material, which is not applicable in terramechanics), which becomes of high cohesion at the particles' level.

c- Colour-moisture curve tendency in sandy soils (the tendency is decreasing in logarithmic function).

I have reached based on the colour-moisture curves tendencies of the two tested sand soils, that with the increase in the moisture content, the reflectance keeps on decreasing (logarithmic change) despite the moisture content reached (close to saturation level). Figure 7.3 below shows the colour change tendency as function of moisture content. Another sand soil texture was tested, its tendency is in chapter 2 (of similar curve tendency).

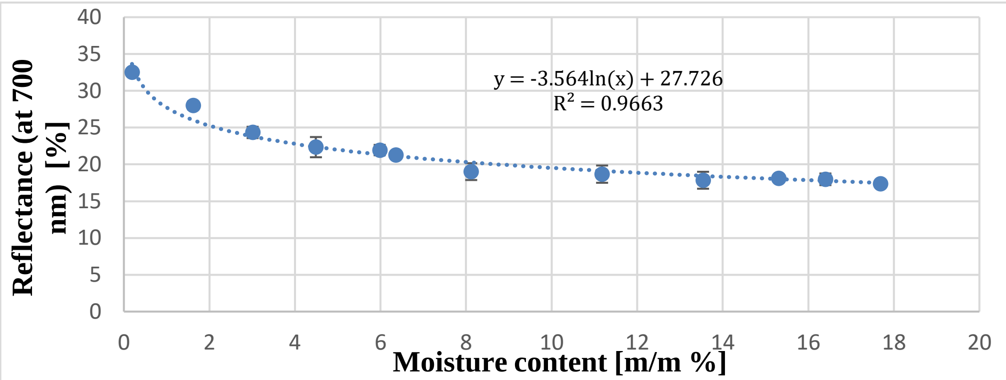


Fig. 7.3. Colour reflectance (at 700 nm) as function of moisture content, sand soil (94.53 % sand, 4.78 % silt, 0.69 % clay).

The tendencies in the two curves show that the colour of a sand texture (based on the tested soils) keeps on decreasing with moistening, meaning that the colour keeps on darkening (due to increase in absorbtivity) till reaching the moisture content close to the saturation level.

7.3- Determining the shear strength values of three soil types in undrained condition using the Mohr-Coulomb failure criterion, also reaching a new idea (with new design) for finding the shear strength parameters.

a- **I determined the shear strength parameters of three tested soil textures (loose soils, the physical status) using the direct shear test in undrained condition. I obtained that for finding the shear strength parameters by ending up with the Mohr-Coulomb line result (angle and intercepting the y-axis), the soil sample (each tested sample) should be of OCR >1.** Testing the soil samples with over consolidation ratio (OCR) above 1, which is the maximum effective stress that soil has experienced in the past over the current stress, is leading to realistic shear strength parameters' results at higher shearing speeds (compared to drained; 9 mm/min is used in the measurement) when loose soil is tested (my study case).

The direct shear test is geo-civil engineering test (but used in terramechanics), and for finding the shear strength parameters (cohesion and internal friction angle), this test should be carried out in drained condition (less than 1 mm/min shearing speed). The shear strength (alone and not the parameters) can be measured at any shearing speed, even if in undrained condition (higher speed), but upon plotting the shear strength results obtained under different consolidation stresses for reaching the Mohr-Coulomb line, the cohesion and the internal friction values might be unrealistic (such as negative cohesion or a high value).

The results (based on this finding) are ending up with accepted cohesion and internal friction angle curves' tendencies (plotted as function of moisture content) in the three tested soil types, knowing that finding the shear strength results at a shearing speed higher than in drained condition complies with vehicle mobility study cases (wheel/track shearing speed).

b- Since the usage of the Mohr-Coulomb line for finding the shear strength parameters is limited to testing the soil in drained condition (very low shearing speed), that case might not be too helpful in some terramechanics studies.

I ended up with a new method that based on it the shear strength parameters will be obtained from a mechanics perspective far from drawing the Mohr-Coulomb line. For shearing the soil and going over the resisting shear strength, two forces are needed (convert to stress), one for breaking the cohesion and the second for going over the friction resistance (due to the normal stress).

The new method sums the results of two measurements, one measurement results in the cohesive force (bonding) and the second in the friction resisting force.

From a mechanics side, I was able to find the cohesive bonding force by shearing a soil sample in the shear test machine (at a speed) with having no consolidation stress, the case that will cancel the friction term from the equation leading to just finding the cohesion in the soil (force over area, the cohesion in kPa). With this process the cohesion is obtained. For finding the friction term in the soil, normal stress multiplied by tangent friction angle $\boldsymbol{\sigma \cdot \tan\phi}$, the internal friction angle is needed. The friction angle at the shearing zone has to do with the friction between the contacting materials (in the soil shearing case, same soil type), and is independent of the applied stress.

I was able to end up with a design/idea for finding the friction angle, and it is by using two plastic cylinders and placing on each a double face tape. Face for sticking to the cylinder, and the second for placing a thin soil layer on (same for the second piece). The soil layers will contact each other at the shearing zone (at a speed that can be higher than the drained shearing speed), and a small mass (to avoid cohesion building up) as a normal stress (gravitational force over area) is applied during shearing the soil. The maximum recorded force is the friction resisting force that based on it and on the normal applied force the material friction angle can be obtained (friction force equalizes the friction coefficient μ multiplied by the normal force). Figure 5.1 shows the design idea and the preparation steps. Friction results obtained from this finding are similar to the results obtained from the Mohr-Coulomb line.

7.4- Relating the shear strength values of a soil texture to its colour reflectance.

I have correlated the shear strength values to the colour of the soil. **Since the colour is plotted as function of moisture content, also the shear strength results, the cohesion, internal friction angle, and the shear strength are plotted as function of moisture content, thus the moisture content is in common.**

Having the moisture estimated from the colour-moisture curve *(scientific result 7.1)*, this moisture content can be substituted in the curves' equations of the shear strength values. Plotting the results of each strength value (shear strength, cohesion, and internal friction angle) as function of moisture content, will lead to ending up with the equation of the curve fitting the plotted results (function relating the strength term to the moisture content). These curves equations are reliable to substitute the estimated moisture content in, and thus predicting the shear strength values (or a required value) at the moisture content obtained from the colour reflectance**.** Figure 4.1 (flowchart) shows the correlation process.

7.5- Explaining/Elucidating the linearity of the Mohr-Coulomb failure criterion.

Clarifying the constancy in the Mohr-Coulomb diagram cohesion, which is applicable in a normal consolidation stress range.

I determined that the consolidation stress (as initial stress on a soil) affects the soil cohesion (affecting case explained below), recognized clearly on a loose soil, thus the incapability of relating the shear strength, at a normal stress, linearly to the shear strength, at another normal stress, of the soil that is of another cohesive strength (Mohr-Coulomb linearity).

I have checked the soil translational shear strength at different densities (using the direct shear machine at same shearing speed), and I obtained that the linearity of the Mohr-Coulomb failure is applicable in a normal stress range which is dependent on the actual applied normal stress (for obtaining the shear strength under it). When it comes to relating a shear strength linearly to shear strengths obtained under different applied normal stresses (using the direct shear test) based on the cohesion and the internal friction angle, these parameters can be used to find the shear strength resulting under a mass that is of a value close the tested masses (converted to stresses, used for finding the parameters, fitting the Mohr-Coulomb line). For example, considering the mass range [30 kg to 90 kg], if finding the shear strength parameters using 40, 50, 60, 70 kg masses (stress, weight over the area, for the Mohr-Coulomb line), then the allowed mass to be used for predicting the shear strength from the parameters should fall in the mentioned range (for example under 90 kg).

The initial normal stress applied on the soil might (depends on normal stress) affect its cohesion (negative pore pressure), especially if the soil is loose (tilled), thus exceeding a certain normal stress range will lead to a recognized change in the cohesion affecting the linearity of the Mohr-Coulomb failure. Within a stress range, the cohesion change will be so small (neglected), thus not influencing the Mohr-Coulomb linearity (passing through the shear strength-normal stress plots of the close masses).

8. Summary of the research work

In chapter two, the colour reflectance results of five different soil textures were obtained using a visible range spectrophotometer, that measures in the spectrum range 400 to 700 nm. In each soil, dealing with the records taken by the spectrophotometer at different moisture contents mathematically and empirically, has led to ending up with the reliable curve that based on its equation the moisture content can be estimated. Plotting the reflectance at 700 nm as function of moisture content, the equation of the curve fitting the plots is the reliable equation to be used in predicting the moisture content. The curve's equation of each tested soil texture was validated. (more details in the dissertation)

In chapter three, the shear strength and its parameters of three soil textures were determined using the direct shear test in undrained condition. In each texture, for ending up with convincing shear strength parameters (having the soil moistened) that comply with the soil physical status, the soil was tested with an overconsolidation ratio above 1. This process was used on the three textures, and all have ended with realistic parameters' results.

In chapter four, the colour reflectance was correlated to the shear strength and its parameters. The moisture content is estimated from the colour reflectance-moisture curve (at 700 nm) by substituting a 700 nm colour reflectance record in the curve's equation. The estimated moisture content can be substituted in any shear strength value-moisture curve equation as input, thus predicting the shear strength value.

Field measurement was carried out for checking the validity of the reflectance-moisture curve equation (at 700 nm), the reliable equation, in the field. The field tested soil texture is the loam sand soil, the soil of the university's land. The field estimated moisture content results from the colour reflectance comply with the results measured using the gravimetric method (moisture analyzer). (just mentioned in a sentence, for more details check the dissertation)

The colour reflectance record at 700 nm, having the soil dry at approximately 0 % mc (dried by the moisture analyzer then taking the record), is saved in a database to be used in the future for predicting a soil texture (new field sample). The record is saved as a soil identity. (just mentioned in a sentence, for more details check the dissertation)

In chapter five, a proposed mechanics method was used for measuring the soil shear strength parameters in undrained condition, the case that will help in having the shear strength parameters at a speed higher than the speed used in the standard direct shear test method (used in geo/civil engineering). Also, the applicability of the Mohr-Coulomb linearity was clarified (applicable in a normal stress range). With having the shear strength parameters at higher speed, the shear strength can be obtained at this speed under a consolidation stress (changeable normal stress). (more details in the dissertation)

Finally, a small conclusion on the research work is given, and the new scientific findings are presented in chapter 7.

9. References

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