Research Review Report on Effect of Moisture Content on Shear Strength of Soil

Maurya Suresh Seopal and Palani A Kumar

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RESEARCH REVIEW REPORT ON EFFECT OF MOISTURE CONTENT ON SHEAR STRENGTH OF SOIL

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By

Shri Maurya Suresh Seopal, Scientist 'D'
Shri Palani kumar A., Scientict 'B'

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Central Soil and Materials Research Station
Olof Palme Marg, Hauz Khas
New Delhi – 110016

ABSTRACT:

Water in soil acts both as a lubricant and as a binding agent among the soil particulate materials, thereby influencing the structural stability and strength of soil. Literature studies in this report show the necessity of taking moisture conditions into account, when processing stability analysis, in order to achieve reliable and safe construction. Shear strength of soils is highly affected by moisture conditions, especially if the soil contains clay materials. Usually the laboratory specimen, which are used to determine shear strength of the soil are prepared at water content and dry density same as in the field conditions, without respect to the fact, that the conditions in the future might not remain the same.

Shear strength of soil is characterized by cohesion (*c*) and friction angle (ϕ). These two parameters mentioned primarily, define the soil maximum ability to resist shear stress under defined load. It is understood that cohesion mobilises at the beginning of stress conditions and reaches maximum values around the plastic limit, i.e. at the beginning of structural collapse. Cohesion decreases at water content heading towards the liquid limit (w_L) and increases towards the shrinkage limit (w_s). Cohesion usually does not increase with increasing stress, except for clayey soils, where the increase in stress causes increase in molecular binds. Friction increases with increase in normal load. Reduction of water content in clayey soils results in higher friction angle, due to the fact, that clay particles group into aggregates, hence shear strength, are expected to exert higher Factor of Safety (FOS), when these parameters are used for evaluation of the slope stability.

Presented study aims to upgrade the knowledge of relationship between moisture conditions (i.e. water content) and parameters of shear strength of soil. The test conditions and shear parameters should be chosen to represent the field conditions as closely as possible. The choice between the effective stress analysis using the effective stress parameters c' and ϕ' and total stress analysis using the apparent parameters c and ϕ depends upon the condition whether the pore water pressure can be estimated or not. In case the pore water pressure cannot be accurately estimated or measured, the total stress analysis is more convenient. However, it gives little indication of the real factor of safety. There may be uncertainty, whether the analysis would give error on the side of safety or on the unsafe side. If the pore water pressure can be estimated or measured, the effective stress analysis should be done, as it is more rational. It is based on well established, unique functional relationship between the shear strength and the effective stress on the failure plane at failure (i.e., $\tau' = c' + (\sigma - u) \tan \phi'$).

Keywords: Moisture Content, Shear Strength, Soil, Cohesion, effective stress

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RESEARCH REVIEW REPORT ON EFFECT OF MOISTURE CONTENT ON SHEAR STRENGTH OF SOIL

1. INTRODUCTION

Soil is a highly complex material. It differs from conventional structural materials, such as steel and concrete. Steel is a manufactured material, the properties of which are accurately controlled. The properties of concrete are also controlled to some extent during its preparation. Soil is a natural material which has been subjected to vagaries of nature, without any control. Consequently, soil is a highly heterogeneous and unpredictable material. The properties of soil changes not only from one place to the other but also at the place with its depth. The properties also changes with the change in the environment, loading and drainage conditions. The properties of the soil depend not only on its type but also on the conditions under which it exists. The engineering properties of soils depend upon a number of factors and it is not possible to characterize them by two or three parameters. Elaborate testing is required to determine the characteristics of the soil before design can be done.

The top of earth crust is filled with soil. Because of huge quantities of soil involved, it is the primary construction material for earth retaining structures, embankment dams and all foundation structures resting on the soil. Shear strength is the principal engineering property which controls the stability of a soil mass under loads. It governs the bearing capacity of soils, the stability of slopes, the earth pressure against retaining structures and many other problems in soil mechanics. All problems in soil engineering are related in one way or the other with the shear strength of the soil. Hence, study of the shear strength of soil is very important for stability of the structure.

1.1. SHEAR STRENGTH

Shear strength is an important strength property of soil, which helps designer to design any geotechnical structures. The shear strength is an internal resisting force to arrest movement of the soil particles. The shear stress is developed both by applied load and overlying soil load. The shear strength of the soil is its maximum resistance to shear stresses just before the failure. The shear stresses develop when the soil is subjected to compression. Thus the shear failure of a soil mass occurs when the shear stresses induced due to the applied compressive loads exceed the shear strength of the soil. Soil derives its shearing strength from the following components:

1. Structural resistance to displacement due to interlocking of particles,

2. Frictional resistance to translocation between the individual soil particles at their contact points and
3. Cohesion or adhesion between the surface of the soil particles

Granular soils of sands may derive their shear strength from the first two sources, while cohesive soils or clays exhibit the third sources alone for their shearing strength. Most natural soil deposits are partly cohesive and partly granular and as such, may fall into combination of all the three strength categories.

The soil resist external load by its shear resistance in terms of cohesion '*c*' (cementing or bonding between particles) and angle of internal friction 'ϕ' (interlocking of particles). The shear strength can be evaluated in terms of total stress and effective stress. In consolidated drained test, effective stress result is obtained because during shearing pore water is released. Whereas in consolidated un-drained test with measurement of pore water pressure the drainage valve is closed during shear and pore water pressure is noted, in which total and effective strength parameters can be obtained.

The shear strength is influenced by soil density, mineralogy, grain size, shape of particle, moisture content and drainage condition. If the density of sample is more, the shear strength also increases. The presence of montmorillonite minerals in soil particles, increases cohesive force '*c*'. When clay is dominant in soil mass, the maximum shear strength is taken by cohesive force '*c*' and when sand is dominant in soil mass, then the maximum shear strength is taken by angle of internal friction 'ϕ'. The test results may vary and depends largely on the moisture content and drainage condition. Therefore, adopting or simulating the field drainage condition in laboratory can yield better results

1.2. STRESS-STRAIN

The stresses induced in soil due to applied loads depend upon its stress-strain characteristic. The stress-strain behavior of soils is extremely complex and it depends upon a large number of factors, such as drainage condition, water content, void ratio, rate of loading, the load level and the stress path. Strain is an important parameter measured to understand the stiffness characteristics of soil structure. Stress-strain graph obtained from triaxial compression test is widely being used to measure the shear strength of soil. However, simplifying assumptions are generally made in the analysis to obtain stresses. It is generally assumed that the soil mass is homogeneous and isotropic. The stress-strain relationship is assumed to be linear. The theory of elasticity is used to determine the stresses in the soil mass.

During shearing of soil samples in a triaxial test the deviator stress-strain graph may vary depending on the type of soil. Sandstone/cemented soil follows brittle failure and shear stress attains a peak value at a small strain, thereafter follows strain softening and reaches residual state. In case of loose or normally consolidated soil, the shear stress increases gradually and finally attain a residual strength. However, when the specimen is compacted more, strain hardening occurs at an early strain and shearing resistance of the soil increases upto the maximum resistance i.e., peak shear strength. In compacted soil after attaining the peak shear strength, specimen losses its dense state and follows strain softening behavior to reach at residual state. Figure 1 shows the deviator stress-strain curve for different soil.

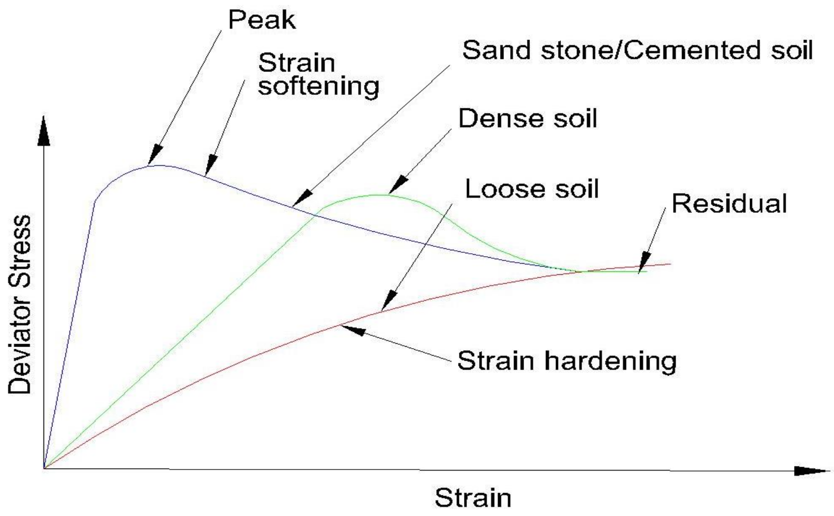

Fig. 1. Deviator stress- strain curve for different soil

1.3. MOHR-COULOMB FAILURE ENVELOPE

A number of theories have been propounded for explaining the shear strength of soil i.e., Hvorslev theory, Bishop and Henkel theory etc. However, the theory is generally used only for research purposes. For practical use in engineering problems, the Mohr-Coulomb theory is commonly used.

Mohr-Coulomb failure theory is valuable function in analysis of the shear strength of soil. According to Mohr, the failure is caused by a critical combination of the normal and shear stress. Figure 1 shows the Mohr's graphical representation of stresses when a soil element is subjected to principal stresses (σ_1 and σ_3).

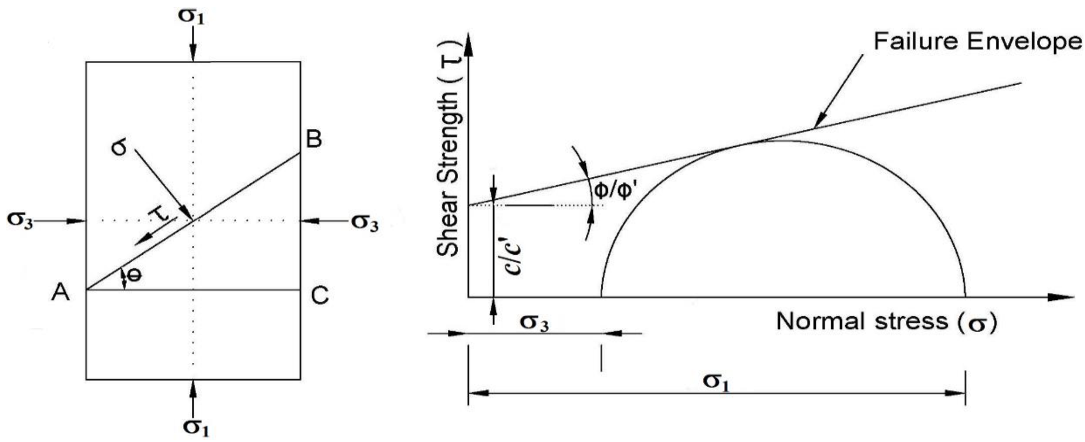

Fig. 2. Mohr's graphical representation of stresses

Mohr-Coulomb failure envelope is represented by a straight line. It represents shearing resistance of soil linearly related with 'σ'. Here 'c', equals to the intercept on τ-axis and 'ϕ' is the angle which the envelope makes with the σ-axis.

$$\text{Total shear strength, } \tau = c + \sigma \tan \phi$$

Parameter 'c' and 'ϕ' depends upon the number of factor such as water content, drainage conditions and conditions of testing. Actual stresses which control the shear strength of a saturated soil (i.e. when degree of saturation is 100 %) are effective stresses and not the total stresses. Thus above equation is modified as Mohr-Coloumb equation for the shear strength of soil as.

$$\text{Effective shear strength, } \tau' = c' + \sigma' \tan \phi'$$

Where,

c/c' = Cohesion for total and effective stress

ϕ/ϕ' = Angle of internal friction for total and effective stress

σ_3 = Minor principle stress

σ_1 = Major principle stress

1.4. DIFFERENT TYPES OF TESTS AND DRAINAGE CONDITION

The following tests are used to measure the shear strength of a soil

a. Direct Shear Test
b. Tri-axial Compression Test
c. Unconfined Compression Test
d. Shear Vane Test

The Shear test must be conducted under appropriate drainage conditions that simulate the actual field problem. Shear test consist of two stages:

i. Consolidation Stage: In this stage, normal stress (or confining pressure) is applied to the specimen and it is allowed to consolidate.
ii. Shear Stage: In this stage, shear stress (or deviator stress) is applied to the specimen to shear it

The drainage condition of the test depends upon the hydraulic performance of the soil on the field conditions. The cohesionless or course grained soil are permeable in nature and freely drainage during loading. For such materials consolidated-drained test is suitable to stimulate the field condition, whereas cohesive or fine grained soils are impermeable in nature and there is chance of pore water pressure to develop during loading. Hence consolidated-undrained test is suitable to stimulate the field condition. Unconsolidated undrained test is suitable for finding the shear strength of soil during construction and end of construction of embankment.

Depending upon the drainage conditions, there are three types of testing conditions:

1. **Unconsolidated-Undrained Test (UU Test)**

   In UU test the sample is packed at in-situ moisture content and is kept constant. Specimen is sheared immediately after applying the desired confining pressure. Drainage is not permitted during consolidation and shearing stages. The shear strength which obtained from this test is total shear strength. This test is applicable to impervious foundation layer in which the consolidation rate is slow as compared to the fill placement. In case where the foundation soil exits in unsaturated state but is likely to get saturated during construction, due to creation of partial pool or due to any other reason, it is desirable to saturate the samples prior to triaxial shear testing so as to simulate the site conditions to obtain realistic results.

2. **Consolidated-Undrained Test with measurement of pore water pressure (CU Test)**

   In CU test, the specimen is allowed to consolidate at the desired confining pressure and drainage is permitted to allow volume change in the specimen. After completion of consolidation, shearing is conducted with closing of drainage valves. During shearing, pore water pressure is noted which helps to derive the total and effective shear strength. The test results are used to design the embankment dam during sudden drawdown of impervious zones and impervious foundation layers that have consolidated fully by the time the reservoir came into operation. The results may also be used in analysis of upstream side slope for partial pool condition and downstream side slopes for steady seepage.

3. **Consolidated-Drained Test (CD Test)**

   During this test condition, the drainage is permitted in both the stages. The specimen is allowed to consolidate in the first stage. When the consolidation is completed, it is sheared at a very low rate to ensure that fully drained condition exists and the excess pore water is zero. Hence the effective strength parameter is calculated from this test. The results are suitable for freely draining soil in which pore pressure do not develop.

1.5. MOISTURE CONTENT

Moisture content of a soil is an important parameter that controls its behavior. It is defined as the ratio of the mass of water to the mass of solids. The water content of the fine-grained soils, such as silts and clays, is generally more than that of the coarse grained soils, such as gravels and sands. The water content of some of the fine-grained soils may be even more than 100 %, which indicates that more than 50 % of the total mass is that of water. The characteristics of a soil, especially a fine-grained soil, change to a marked degree with a variation of its water content.

The term soil moisture is used to denote the part of the sub-surface water which occupies the void in soil above the ground water table. Under certain conditions soil moisture or water in soil is not stationary but is capable of moving through the soil. The movement of water in the soil affects the properties and behavior of the soil. Construction operation and performance of completed construction could be influenced by soil water. Ground water frequently encountered during construction operations may change the soil strength properties.

Consistency of the fine-grained soil may also be looked upon as the degree of firmness of a soil and often directly related to strength. It is conventionally described as soft, medium stiff or hard. This is applicable specifically to clay soils and is generally related to the water content. Consistency is that property of a material which is manifested by its resistance to flow. In remoulded state, the consistency of a clay soil varies with the water content, which tends to destroy the cohesion exhibited by the particles of such soil. As the water content is reduced from the stage of almost a suspension, the soil passes through various states of consistency. Atterberg a Swedish soil Scientist, in 1911, distinguished the following stages of consistency as liquid, plastic, semi-solid and solid state. The water contents at which the soil changes from one state to the other are known as consistency limit i.e., Liquid limit, Plastic limit and Shrinkage limit. The moisture content plays a major role in describing the strength property of soil. A soil containing high water content is in a liquid state and offers no shearing resistance. It has no shear deformation and, therefore the shear strength is equal to zero. As the water content is reduced, the soil becomes stiffer and starts developing resistance to shear deformation.

2. OBJECTIVE OF THE STUDY

Shear strength is the principal engineering property which controls the stability of a soil mass under loads. The shear strength of soil helps to design the foundation of all the civil engineering structures, stability of slopes, earth retaining walls, embankments, man-made excavation etc. All the problems of soil engineering are related in one way or the other with shear strength of the soil. In field saturation level of soil may vary and depends upon climatic condition, drainage condition, porosity, density of particle etc., which may affect the shear strength of soils. If the volume of air is relatively small, the soil may get saturated itself under stresses. If the air content is very large, the soil remains unsaturated and undergoes large volume changes even in undrained conditions. However, an actual soil deposit in the field may not remain unsaturated if it has an access to water. The shear strength parameters i.e., cohesion 'c' and angle of internal friction 'ϕ' largely depends upon moisture content and drainage conditions. Therefore, it is important to understand the relationship of varying water content and shear strength parameters of soil in partially saturated to saturated soils. In the present study, the effect of moisture content on shear strength parameters i.e., cohesion 'c' and angle of internal friction 'ϕ' of soil is studied.

3. LITERATURE REVIEW

3.1. Effect of soil moisture in the analysis of undrained shear strength of compacted clayey soil, Rohit Ghosh (2013).

Rohit Ghosh (2013) studied the effect of moisture content of undrained shear strength of compacted clayey soil by vane shear test. Shear strength curve drawn for different compaction effort showed exponential decrease in the shear strength with gradual rise in water content.

An experimental study was undertaken to study the principles of soil compaction and establish a relation between the undrained shear strength of compacted clay and its moisture content. Compaction of soil is an important prerequisite for the construction of man-made structures like bridges, roads, dams, embankments etc. In the present study fine grained saturated clay finer than 2×10^{-6} m were used for all purposes. An important property of cohesive soils is that compaction increases their shear strength and compressibility. The shear strength of clay is the maximum shear stress it can sustain. If the soil is sheared without changing the water content its strength remains the same. During the study the optimum moisture content was analyzed from the compaction curve. Finally, the shear strength curve was drawn for different compaction efforts which clearly showed an exponential decrease in the shear strength of clayey soil with gradual increase in the water content. Factors other than the change in water content and compaction energy were not considered

Procedure

For compacting the clayey soil, Standard Proctor Compaction Tests were used. The clay was mixed with sufficient amount of water to reach saturation point. The degree of saturation of compacted soil was found to be 100 % through back calculation from the measured value of bulk unit weight, water content and specific gravity as, Sr = (w.G/e) × 100%.

The undrained shear strength of clayey soil is determined by the Laboratory and Field Vane Shear Tests as per IS: 2720. This test is prescribed in ASTM D4648/ D4648 M-10. It provides a rapid determination of shear strength on undisturbed or remolded or reconstituted soils. This test method covers the miniature vane test in very soft to stiff saturated fine-grained clayey soils. This test is performed on clay compacted with 5, 10 and 15 blows in three layers. The torque is measured using a spring which controls the degree of rotation of the metallic dial. Essentially, the torque is dependent on the degree of rotation of the spring and varies with it. The shear strength of the soil is a function of the torque generated at failure. It is given by: $T = \tau \times K$

Here, T is the torque in N-m (Lambe and Whitman, 1979), τ is the undrained shear strength at failure in Pa and K is the vane blade constant in m^3. From experiments, it is found that K= {11 D2H(1+D/3H)} / (2 × 106)} in SI system, where D and H are the diameter and height of the vane respectively.

Results

The optimum moisture content was found to be around 16 % from the compaction curve. The maximum dry density recorded was 17.53 g/cc (Table 1 and Figure 3). From the Atterberg's test the results of liquid limit and plastic limit are found to be 84 % and 46 % respectively.

Table 1. Proctor compaction test results

Weight of mould + soil (kg)	Weight of empty mould (kg)	Weight of wet soil (kg)	Density of soil (g/cc)	Moisture content (%)	Dry density (g/cc)
6.364	4.625	1.739	17.39	9	15.955
6.488	4.625	1.863	18.63	12	16.63393
6.613	4.625	1.988	19.88	14	17.4386
6.659	4.625	2.034	20.34	16	17.53448
6.626	4.625	2.001	20.01	18	16.95763
6.611	4.625	1.986	19.86	20	16.55
6.578	4.625	1.953	19.53	22	16.0082
6.522	4.625	1.897	18.97	24	15.05556

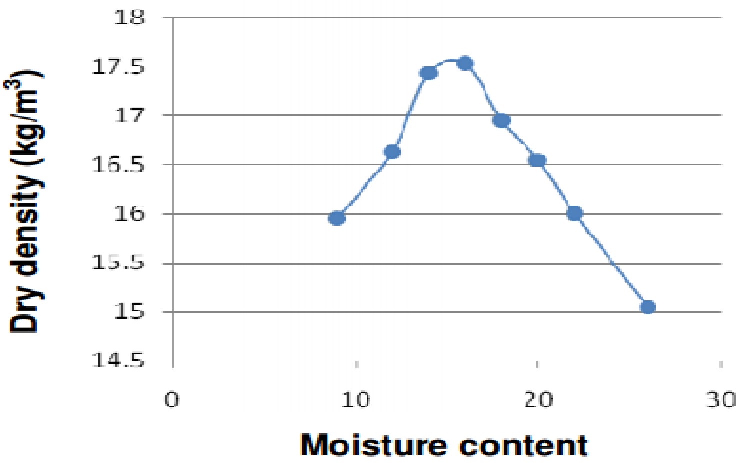

Fig. 3. Dry density and moisture content compaction curve

For the field test the undrained shear strength is calculated for both the undisturbed and remolded state and results are presented in Table 2. First, the vane is pushed into the soil. The torque is applied at the top of the torque rod to rotate the vane at a uniform speed. The plot is drawn with the undrained shear strength (kN/m^2) along Y-axis and moisture content along X-axis (Figure 4). The shear strength curve is also plotted with the moisture content (%) along X-axis and the undrained shear strength (kN/m^2) along Y-axis for 5 blows, 10 blows and 15 blows as shown in Figure 5. The blue line is for 5 blows, red line for 10 blows and green line for 15 blows. The three curves clearly indicate an exponential decrease in the shear strength of compacted clayey soil with gradual increase in moisture content.

Table 2. Undisturbed and Remoulded field shear strength

Depth (m)	Moisture content (%)	Undrained shear strength (kN/m^2)
1.0	20.44	48.914
2.0	28.18	44.784
3.0	34.52	57.932
4.0	37.86	32.119
5.0	39.12	21.659
6.0	42.52	24.406
7.0	45.40	18.847
8.0	49.22	18.754

Depth (m)	Moisture content (%)	Undrained shear strength (kN/m^2)
1.0	20.44	26.876
2.0	28.18	21.225
3.0	34.52	22.542
4.0	37.86	14.870
5.0	39.12	5.114
6.0	42.52	5.790
7.0	45.40	5.215
8.0	49.22	5.208

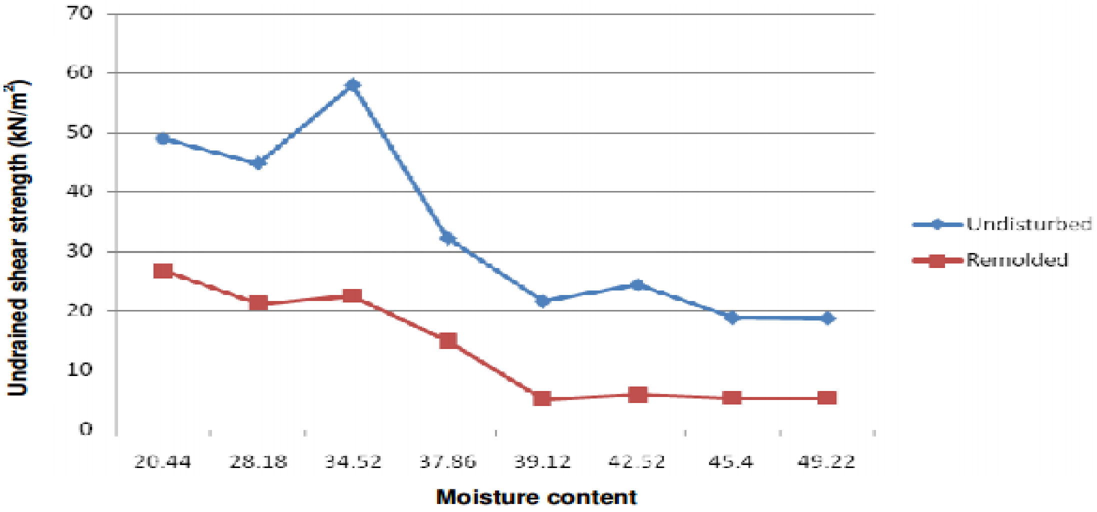

Fig. 4. Relation between undrained shear strength and moisture content

Discussion

The undrained shear strength of soil is a function of its moisture content and mineralogical properties. It is seen that the Laboratory Vane Shear Test shows steeper decrease in the undrained shear strength than the Field Test. This could be partly attributed to the fact that due to the absence of any overburden pressure the sample in the lab exhibits the maximum shear strength at a moisture content which is close to the Optimum Moisture Content. It will be slightly more than the one obtained from the Proctor

Compaction Test because of different compaction energy. It is found that the Lab Shear Test values are significantly higher than the Field Shear Test values for the same moisture content and hence correction has to be applied for checking the safety against shear failure during foundation design.

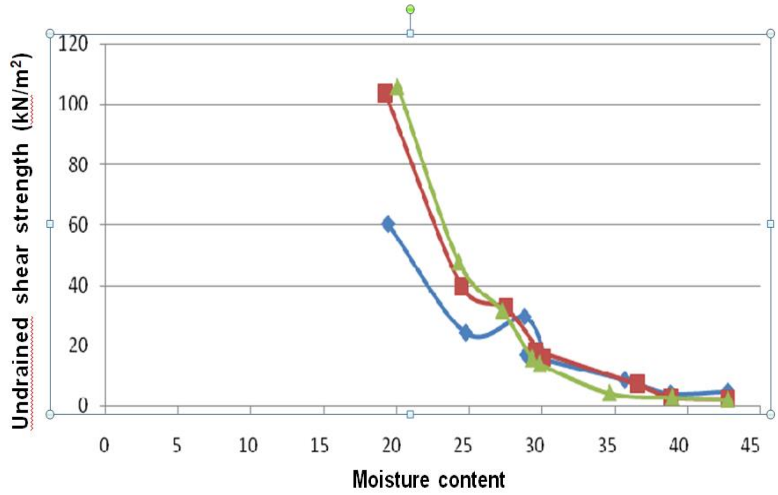

Fig. 5. Relation between undrained shear strength and moisture content for different blows

3.2. Effect of different moisture content and triaxial test methods on shear strength characteristics of loess, Yong Wang et al (2019).

Yong Wang et al (2019) conducted triaxial test of loess soil under different drainage condition (CD and CU test). Soil samples were taken from a typical section in Yuci County, which is located in Northwest China. In the field, a suitable excavation site was selected, and a 5 meter deep exploration well was used to extract soil samples 5-meter below the ground. The soil samples were cut into cylindrical shape with a diameter of 10 cm and a height of 20 cm, and then wrapped in a moisture-retaining film and transported to the laboratory. The basic physical and mechanical properties of samples are presented in Table 3. In order to investigate the effect of moisture content on shear deformation of loess, four groups of soil samples with different water content were set up, which were 15%, 18%, 20% and saturated soil respectively. Considering that the loess in engineering construction is mostly disturbed soil, all the soil sample was crushed and screened by 5mm. Then the water content was determined according to the test plan. The sample was prepared into a cylindrical sample with a diameter of 61.8 mm and a height of 120 mm by means of a mould. The difference in moisture content of the same group of samples shall not exceed 1%, and the difference in density shall not exceed 0.01%; otherwise, the soil sample should be made a new, as shown in Table 3.

Table 3. Basic physical properties of undisturbed and remolded loess

Sample State	Dry density	Natural density	Moisture content	void ratio	Plasticity limit	Liquid limit	Plasticity index	Saturation
Undisturbed	$1.36 g/cm^3$	$1.58 g/cm^3$	13.4%	1.08	16.9%	27.5%	10.6	28%

Sample State	m (%)	Gs (g/cm^3)	ρ_d (g/cm^3)	e	ω_P (%)	ω_L (%)
Remolded loess	15	2.70	1.34	1.01	16.8	27.2
	18	2.70	1.36	0.99	16.9	27.5
	20	2.70	1.36	0.99	16.9	27.5
	Saturated (32)	2.70	1.35	1.00	16.7	26.8

Methodology

Two types of drainage conditions, namely consolidated drained (CD) shear and consolidated undrained(CU) shear, were adopted to explore the influence of test conditions on the shear characteristics of loess. At the same time, four confining pressure grades were set, which were respectively 50kPa, 100kPa, 200kPa, and 300kPa (Table 4). The test was composed of two stages: consolidation and drainage. The consolidation time was set to 4 hours. When the pore water pressure dissipated more than 95%, the consolidation was considered stability and the next shear test can be carried out. The shear rate was set to 0.08mm/min. When the deviation stress peaked, it was considered that the sample has been destroyed. If there was no peak value, the shear can stop when the axial strain reached 18%. After consolidated undrained shear test, about 15 grams of soil were selected from the upper and lower parts of the sample to determine its moisture content.

Table 4. Triaxial test methodology adopted

Specimen type	Moisture content	Test condition	Confining pressure (kPa)
Loess	15%	CD	50,100,200,300
		CU	
	18%	CD	50,100,200,300
		CU	
	20%	CD	50,100,200,300
		CU	
	saturated	CD	50,100,200,300
		CU	

Results and discussion

Fig. 6 presents the results of CD test and CU test on loess samples. It indicates that shear strength is highly depended on moisture content and confining pressure, when the strain reaches about 5%, the stress-strain curve appears inflection point, and then changes slightly. This inflection point is also defined as the yield point, which decreases significantly with moisture content ranges from 15% to saturation. For the case of σ3=50kPa and σ3=100kPa, the stress-strain curve shows strain softening. While the stress-strain curve shows strain hardening under the condition of σ3=200kPa and σ3=300kPa during both the CU and CD test method. The cohesion of loess is very large when the water content is lower than the plastic limit no matter which method is adopted, while the value decreases significantly when the water content exceeds the plastic limit, as illustrated in Fig. 7. The friction angle shows relative stable during the course of changing of moisture content. The inflection point of stress-strain curve of CU method is always higher than that of CD method (Fig. 6), and the shear strength parameters of loess obtained by CU method are always larger than that of CD method (Fig. 7). It is suggested that the measured strength parameters are equivalent to the total stress strength under the condition of consolidation and undrained (CU), because the moisture content is not excluded during shearing, there will be a certain excess pore water pressure in the specimens. However, there is no excess pore water pressure in the samples under consolidation drainage (CD) test, and the measured strength can be regarded as an effective shear strength index.

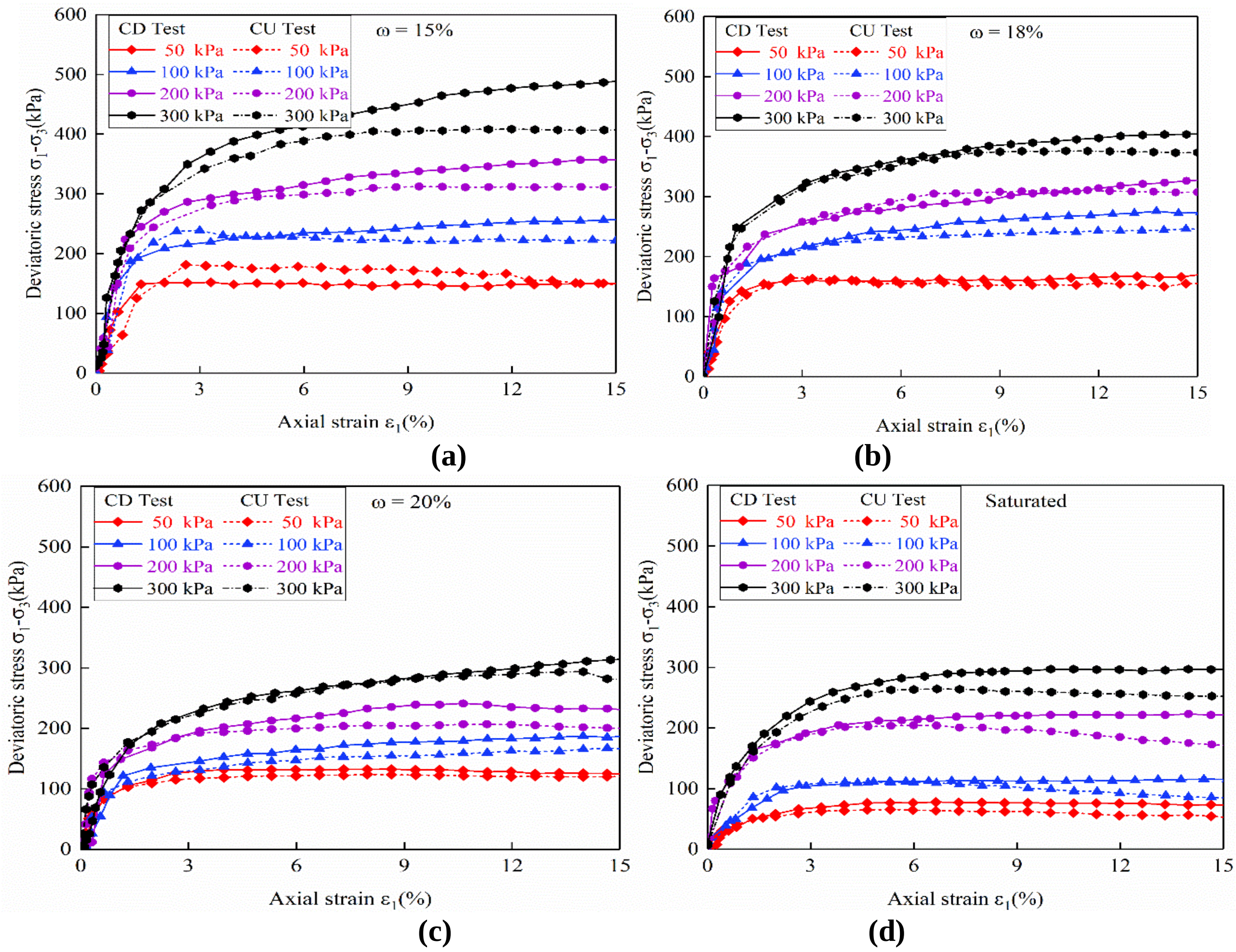

Fig. 6. Deviatoric stress versus axial strain for the loess samples with the moisture content of (a) 15%, (b) 18%, (c) 20% and (d) saturated

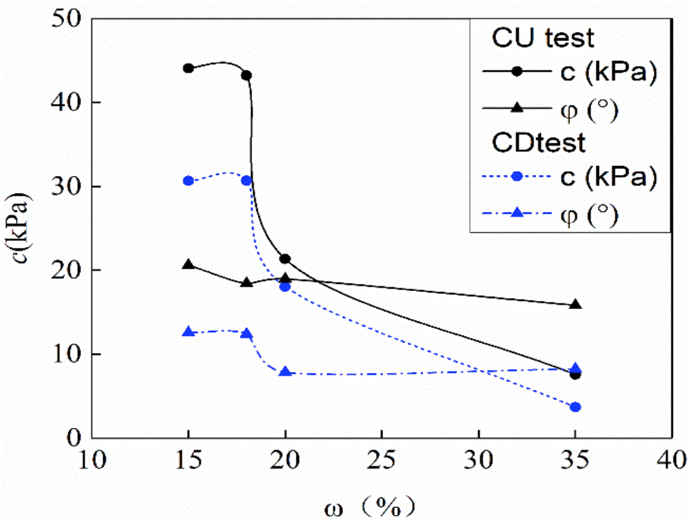

Fig. 7. Shear strength of loess specimens under CU test and CD test

Secant modulus E_{50} of loess specimens is also derived from triaxial test, including CD test and CU test, so that the value can be employed to investigate the influence of moisture content and confining pressure on shear strength of loess. Fig. 8 shows the relationship between modulus and confining pressure of triaxial test. It is noteworthy that moisture content has significant effect on the E_{50}, for the specimens with moisture content of 15% and 18%, the secant modulus increased obviously under both CU test and CD test, while the secant modulus changed slightly with moisture content of 20% and saturated condition. The variation of E_{sec} for samples with moisture content of 20% shows a constant increase as the rising of confining pressure during the CD test, while the value of firstly decreased and then keep a rising trend. The plot in Fig. 8 indicate that for the specimens at moisture content ＜20%, the modulus and confining pressure show an approximate linear relationship, when the moisture content of the sample increases. For saturated samples, the modulus hardly changes with the increase of confining pressure, shows a relatively stable trend.

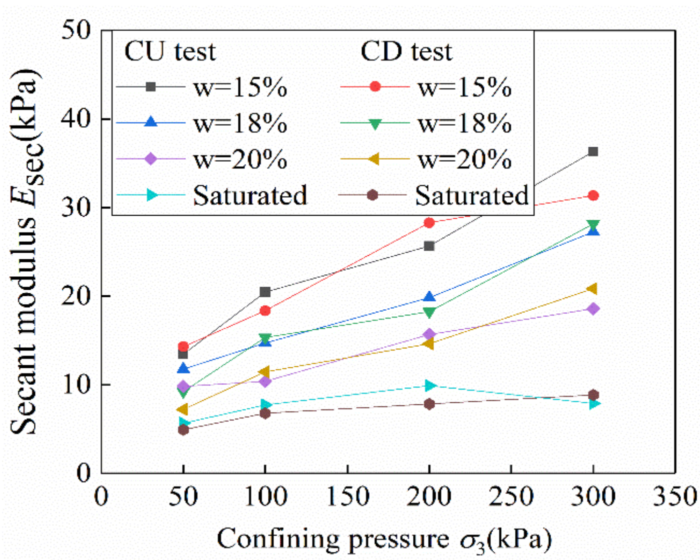

Fig. 8. Secant modulus loess specimens with different moisture content under CU test and CD test

Conclusion

This paper compared shear characteristics of loess by triaxial test under different drainage conditions, namely consolidate drained (CD) test and consolidated undrained (CU) test. The data of these two types of test were employed to investigate the effect of moisture content and test methods on loess shear strength. The following conclusions can be drawn based on the results obtained:

(1) Moisture content and confining pressure are the main factors controlling the shear strength of loess. With the increase of moisture content, the stress-strain curve of loess shows obvious strain softening behaviour. The cohesion and decrease slightly with the increase of moisture content, when it is lower than the plastic limit, while when the water content exceeds the plastic limit, the cohesion decreases significantly. The internal friction angle did not decrease significantly with the change of water content.

(2) The stress-strain curves obtained from consolidated drainage (CD) test and consolidated undrained (CU) test show similar characteristics. Similar changes in shear strength parameters of loess under two different test methods. However, strength parameters (i.e. c and φ) obtained from consolidated undrained test are larger than consolidated drained test.

(3) Moisture content and confining pressure has a great influence on secant modulus, and there is an approximate linear relationship between them. When the water content is less than 20%, the secant modulus increases significantly with the increase of confining pressure, while the secant modulus changes slightly at the moisture content of saturated condition.

3.3. Effects of Clay and Moisture Content on Direct Shear Tests for Clay-Sand Mixtures, Muawla A. Dafalla (2012).

Muawla A. Dafalla (2012) studied the effect of different proportions of clay content to sand with moisture content using direct shear test. The cohesion of the mixture was found to increase consistently with the increase of clay content. Increase in moisture content was found to cause a drop in both cohesion and angle of internal friction.

Artificial clay-sand mixtures were considered by design geotechnical and environmental engineers for use as hydraulic barriers. Adding clay to the sand helps in achieving low hydraulic conductivity. The term Bentonite Enhanced Sand (BES) was used by many researchers instead of clay sand mixtures. As implied by the name the material is dominantly granular, and the amount of added clay is not large enough to classify the paste as anything other than sand. However, there is a stage at which the paste starts behaving as pure clay when the sand grains are pushed apart, and clay dominates the engineering properties of the mix.

This research work considers adding clays to sand at proportions of 5% to 15% and increasing water content in respective clay groups. Result obtained for various proportions of clay and water content are presented in Table 5. Increase in shear strength was reported for the increase of clay content for all normal stresses tested (0.5, 1.0, and 1.5 g/cc).

Table 5. Direct shear test results

Sample no.	Clay (%)	Dry density (g/cm^3)	Moisture content (%)	Cohesion C, kg/cm^2	Angle of friction (degrees)
DS-1	5	1.73	15	0.120	40.7
DS-2	5	1.73	17.5	0.080	40.3
DS-3	5	1.73	20	0.053	39.6
DS-4	10	1.77	15	0.150	39.4
DS-5	10	1.77	17.5	0.120	39.0
DS-6	10	1.77	20	0.090	38.6
DS-7	15	1.80	15	0.260	41.0
DS-8	15	1.80	17.5	0.150	40.0
DS-9	15	1.80	20	0.040	38.3
DS-10	0	1.63	7.0	0.000	43.0
DS-11	0	1.63	10.0	0.010	41.0
DS-12	0	1.63	13.0	0.090	38.6
DS-13	100	1.20	30.0	1.140	38.7
DS-14	100	1.20	35.0	0.900	35.8
DS-15	100	1.20	40.0	0.610	33.4

Very moist clay-sand mixture showed steep drop in both cohesion and angle of internal friction when the clay content is high as shown in Figure 9. Increase in moisture content of clay caused the cohesion to drop for 5% and 10 % of clay sand mixtures at a nearly similar rate, but the 20 % clay mixture showed a very steep drop. Similarly, the angle of internal friction, rate of drop increased for the 20 % moisture content.

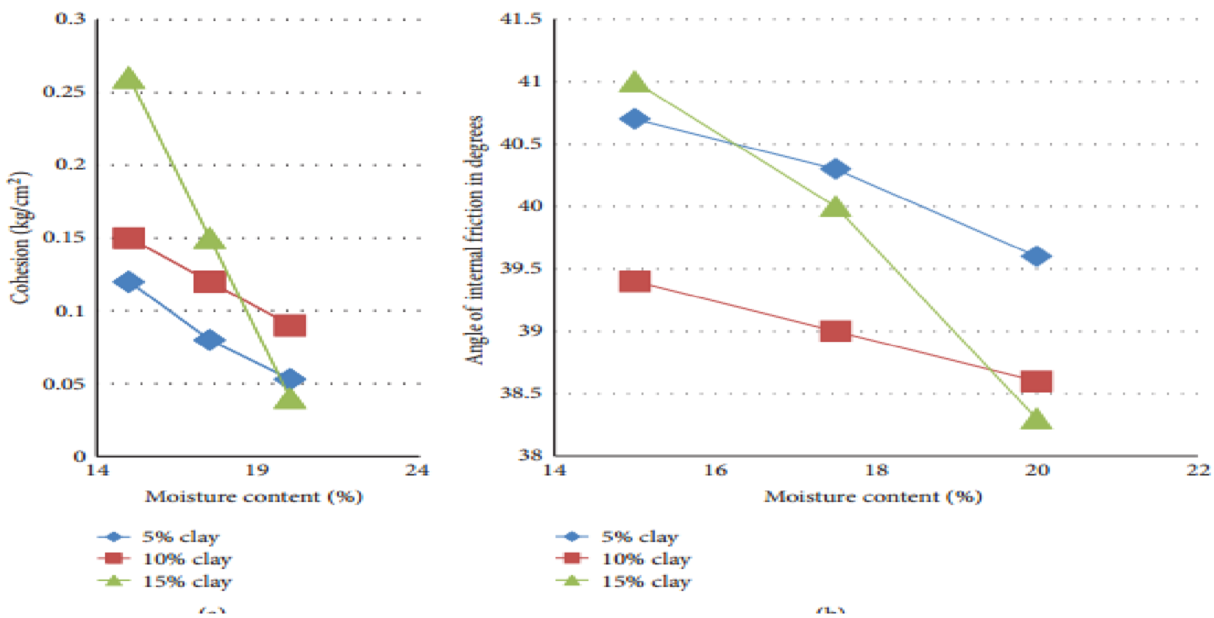

Fig. 9. Influence of moisture content on friction angle and cohesion

Increase in clay can help in the increase of cohesion for 5% and 10% of clay. There will be a limit for clay content beyond which the cohesion can drop due to high water content. The angle of internal friction has shown to give a minimum value for 10 % clay content while it slides to less than 38 degrees for a clay-sand mixture of 20 % moisture content (Figure 10).

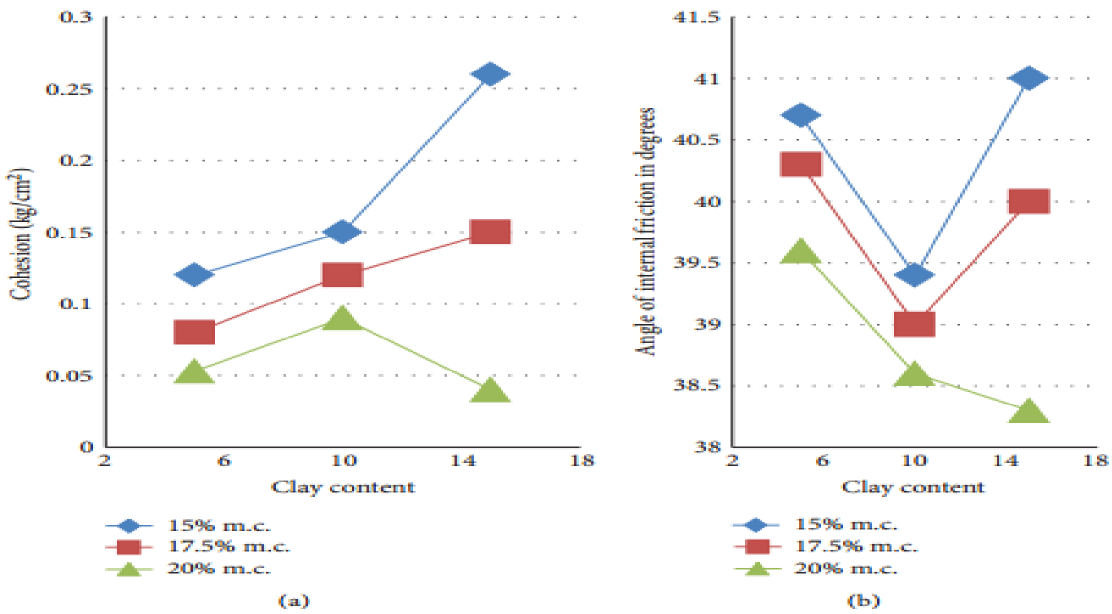

Fig. 10. Influence of clay content on friction angle and cohesion

3.4. Laboratory Study on Shear Strength of Loess Joint, Y. Luo et al (2014).

Y. Luo et al. (2014) conducted direct shear test on loess soil and studied the relationship between shear strength and moisture content. Laboratory experiments were carried out both on undisturbed samples and remolded loess joint samples. Undisturbed soil samples were obtained from the northern suburb of Xi'an, China. The samples made are cubical in shape and the size of each line is more than 10 cm. They were carefully cut down from the soil stratum and bound with rubber belt in order to keep its structure intact. Dry density (ρ_d) of the undisturbed loess is 1.31 g/cm^3, void ratio *(e)* is 1.07, liquid limit (w_l) is 17.6 %, and plastic index (I_p) is 12.1. Remolded soil samples were made with soil obtained from the same soil stratum. The soil was crushed first and then compacted by using compactor. Soil was put into the compaction barrel in 3 times. It was compacted with same energy every time after adding new soil. The samples were a cylinder. The height is 11.6 cm, and the diameter is 10.2 mm. In laboratory, both the undisturbed soil samples and remolded soil samples are further cut to the certain size for direct shear test use by cutting ring. To study the impact of dry density and water content on shear strength of loess joint, soil samples of different dry densities and water content were prepared. Since soil samples of different densities cannot be obtained from the same area, only the impact of the changes in water content is taken for undisturbed soil. Remolded soil samples of different densities and water contents were prepared as well to study the impact on shear strength of loess joint

Direct shear apparatus was adopted in the experiment. Loess with developed joint usually contains little water. Water content of soil samples in the experiment was low as well. In the experiment, direct shear apparatus was slightly modified. The porous stone was removed. The purpose was to increase the thickness of soil samples so as to avoid experiment errors caused by thin samples.

Test Result

Experimental data are shown in Table 6. Figure 11 shows the change law of internal friction angle of loess joint with the change of water content. The hollow points represent the remolded soil samples; the solid points represent the undisturbed soil samples. Different point's shapes represent different dry density. Figure 11 reveals that the change between internal friction angle and water content takes on the form of parabola with a peak value. No matter the density is high or low, and either the soil is undisturbed sample or remolded one. It is similar to the compaction curve of soil. When water content reaches a certain value, internal friction angle is the largest. While water content is lower than the certain value, internal friction angle increases with the increase of water content. If water content is higher than the certain value, internal friction angle decreases with the increase in water content. This value ofwater content is called the "limit water content". The internal friction angle corresponded to the limit water content is the largest one.

Table 6. Data of direct shear test for Remolded and Undisturbed soil

Remolded soil								Undisturbed soil	
$\rho_d = 1.40\ g/cm^3$		$\rho_d = 1.60\ g/cm^3$		$\rho_d = 1.70\ g/cm^3$		$\rho_d = 1.80\ g/cm^3$		$\rho_d = 1.31\ g/cm^3$	
w (%)	φ_j (°)	w (%)	φ_j (°)	w (%)	φ_j (°)	w (%)	φ_j (°)	w (%)	φ_j (°)
1.5	31.7	1.7	33.6	1.9	33.4	2.0	35.5	3.1	25.6
3.3	34.3	3.4	34.8	3.1	34.5	3.0	36.1	4.9	27.4
5.0	36.1	5.0	37.1	5.5	37.3	4.5	37.5	6.4	29.0
6.6	37.0	7.3	38.3	8.7	38.8	5.8	38.6	8.6	31.8
8.0	37.5	8.4	38.4	12.1	37.1	8.2	39.0	10.3	32.8
9.4	37.7	10.9	38.2	12.6	36.6	9.2	38.8	12.0	33.7
10.9	37.4	12.2	37.5	14.6	34.1	10.7	38.4	13.8	33.6
12.7	36.6	13.0	36.9	14.8	33.9	12.7	37.6	15.1	32.8
14.2	35.2	15.7	33.8	16.8	25.8	14.8	35.2	17.1	31.3
15.8	33.3							18.8	29.5
17.3	31.0							20.9	25.5

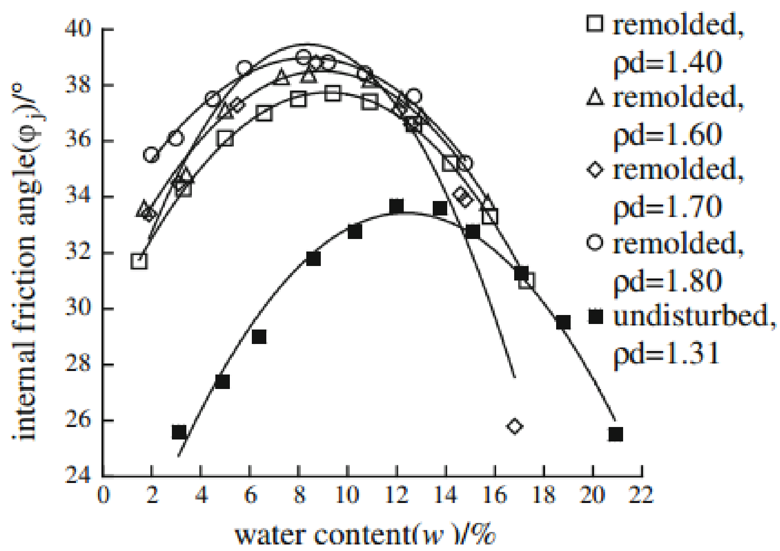

Fig. 11. Relationships between internal friction angle (ϕj) and water content (w)

Internal friction angle of loess joint also has something to do with the change in dry density. But Figure 11 displays that it does not change greatly with different dry density. On the condition that water content is the same, the change of internal friction angle caused by the change of dry density from 1.4 to 1.8 g/cm^3 is not remarkable. After a comparison between the test result of undisturbed soil samples and remolded soil samples, we can discover that there is a big difference on the internal friction angles of loess joint. The limit water content between undisturbed and remolded soil samples is quite different. The limit water content of undisturbed soil samples is the highest of all the other remolded soil samples.

Table 7. Limited water content and friction angle

Soil type	Dry density (g/cm^3)	The peak fric tion angle (°)	Limit water content (%)
Remolded soil	1.80	39.0	8.4
Remolded soil	1.70	38.7	8.6
Remolded soil	1.60	38.5	8.9
Remolded soil	1.40	37.7	9.2
Undisturbed soil	1.31	33.4	12.4

From Table 7, we can discover that the maximum internal friction angle of loess joint declines with the decline of dry density. While the limit water content increases with the decline of dry density. But remolded joint soil samples' limit water content and maximum internal friction angle change insignificantly with the change in dry density. They are greatly different from those of undisturbed joint soil samples. The impact on internal friction angle by water content is greater than that by dry density.

In nature, the change in dry density of loess is small, but water content changes remarkably because of rain or evaporation. Therefore, the change is mainly caused by water content

Discussions

In order to study how the internal friction angle of joint changes with the matrix suction, the soil–water characteristic curve (SWCC) of the tested soil is also given in Figure 12. The experiment was carried out by null-type pressure plate apparatus. The two values, internal friction angle and matrix suction, both change with water content. Their tendencies are described in Figure 13 for comparison.

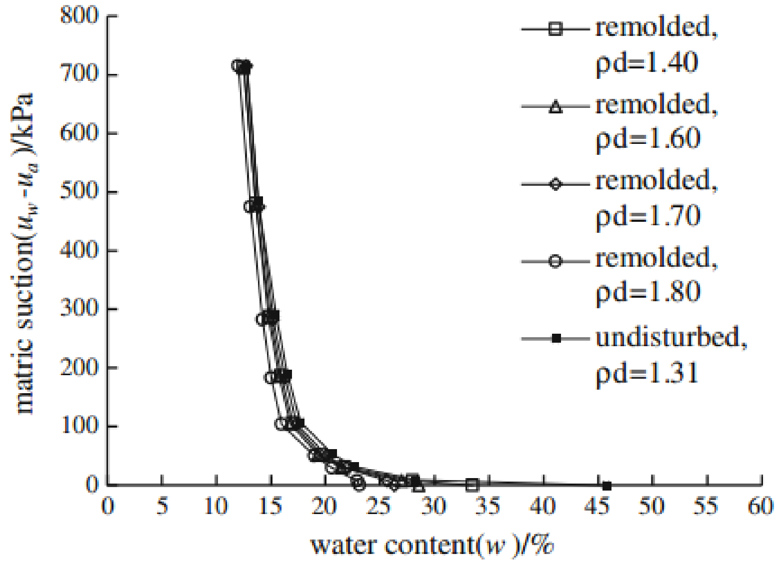

Fig. 12. Soil–water characteristic curve of tested loess

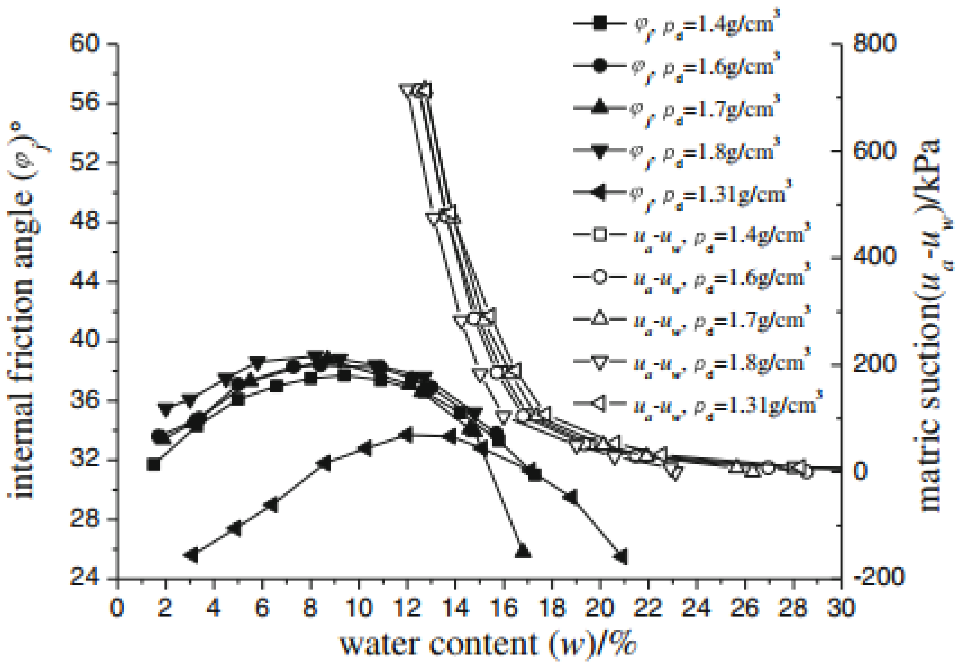

Fig. 13. Internal friction angle and matrix suction change with water content

In the field of unsaturated soil research, it is generally concluded that matrix suction declines (characteristic curve of soil and water) with the increase in water content. Shear strength declines with the increase in water content too. Experiment results and above analysis show that the conclusion is only applicable to soil with high water content. If soil contains little water, the conclusion does not apply. When there are only strong attached water and internal weak attached water in soil samples, surface tension of effective force exerted on soil particles does not exist or is very small. Only with the gradual increase in external weak attached water and free water, the effect of surface tension starts to appear. Therefore, shear strength starts to increase. So, there is a limit water content. When water content is higher than the value, the current understanding of characteristic curve of soil and water is suitable. That is matrix suction declines with the increase in water content. But when water content is lower than the limit value, the understanding is unsuitable. That is matrix suction increases with the increase of water content. When the limit water content is equal to the content of attached water in soil requires further research and discussion.

Conclusions

Through the experiment, internal friction angles of loess joint of remolded soil samples and undisturbed soil samples are obtained. It reveals that the change in internal friction angles of loess joint with water content is similar to the compaction curve of soil. When water content reaches the limit value, internal friction angle is the largest. When water content is lower than the value, internal friction angle increases with the increase in water content. When water content is higher than the value, internal friction angle decreases with the increase in water content. The water content is called the limit water content, and the corresponding internal friction angle is the largest one. Internal friction angle of loess soil has something to do with the change in water content and density. The further analysis on the basis of experiment results show that when water content is higher than the value, the current understanding of characteristic curve of soil and water is suitable. That is the matrix suction declines with the increase in water content and shear strength declines. But when water content is lower than the limit value, the understanding is unsuitable. That is the matrix suction increases with the increase in water content and shear strength increases.

3.5. The Effect of the Moisture Content on the Strength of an Alluvial Clay, Sakuro Murayama et al. (1995).

Sakuro Murayama et al. (1995) conducted large number of tests such as U-test, vane test and triaxial compression test to research the effect of the moisture content on the strength characteristic of undisturbed saturated clay. Liquid limit can be taken as a principal factor which influences the strength of clay with the moisture content. The compressive strength of fully saturated clay has a linear relationship to the moisture content on the semi-logarithmic paper, and the above linear plotting is parallel to the virgin compression line of the consolidation test.

The vane test has a considerable reliability for clayey soils, especially for soft clays whose consistency are too high to extrude specimens from sampler tubes. There is a definite relationship $q_u=2C$ between the unconfined compressive strength, q_u and the cohesive strength, C obtained from the vane test with the same specimen. Specimens used in a series of tests are fully saturated undisturbed clays obtained from the ground at the North Harbor of Osaka, by means of the thin-walled sampler of stationary piston type. This sampler has an inner diameter of 73 mm, a thickness of tube of about 1 mm, and a length of specimen of 760 mm. The results of the physical test of the clay are as follows: specific gravity = 2.64, L.L. = 80 %, P.L. = 30 %, natural water content = 76 %, void ratio=2.01, degree of saturation = 100%.

Specimens of U-test are taken with a sectional area size of 2.5 cm x 2.5 cm and height of 6 cm, and tested under the strain control condition whose loading speed is 1 % of the height per minute. Water content of the specimens are obtained by slowly decreasing with air-drying process to have the various magnitude beginning with the natural state of 76 % to about 35 %.

Vane tests are performed by a laboratory vane tester with four vanes whose height is 3.6 cm and diameter is 2.0 cm, and the rotating speed of the vane is 60° per minute. Triaxial compression tests are performed by the consolidated undrained test in the same loading manner as U-tests after 100 % consolidation under ambient pressures. The size of specimens used in this tests is divided into two kinds; one is ϕ 3.5 cm x 8.0 cm for the tests of lateral pressure less than 3 kg/cm^2, and the other is ϕ 5.0 cm X 12.0 cm for more than 3 kg/cm^2. In this tests, paper drains are used to accelerate the lateral drainage.

Relationship between the Water Content and the Strength of Clay

Figure 3 shows the linear relationship, within a range of permissible error, when the strength of the alluvial clay are plotted against their water content on a semi-logarithmic scale. In this figure, the deviator stress is adopted as the triaxial compressive strength, and compressive strength in vane tests is regarded as twice the cohesive strength *C*. Scattering points in U-tests and also in vane tests may be caused by the growth of cracks in specimens during the air-drying process. This effect is remarkable in vane tests, where there is a tendency to give lower strength than the actual one, especially when the moisture content is low. The relationship between the water content and the strength of clay from the results of these experiments can be represented as, w = B ($\log_{10}$ A— $\log_{10} p$). Where w: water content, p: compressive strength, and A, B are constants.

Besides the above relationship between the compressive strength and the moisture content, the results of standard consolidation tests and of triaxial consolidation tests are also plotted in Figure 3. The consolidation curves of these two kinds of tests coincide with each other, within the part of virgin compression lines. The straight line representing the relationship between the compressive strength and the water content is parallel to the virgin compression line of standard consolidation test, the same statement holds for triaxial consolidation tests too. From this fact, it can be shown that the constant B above is equal to the compression index, *Cc*.

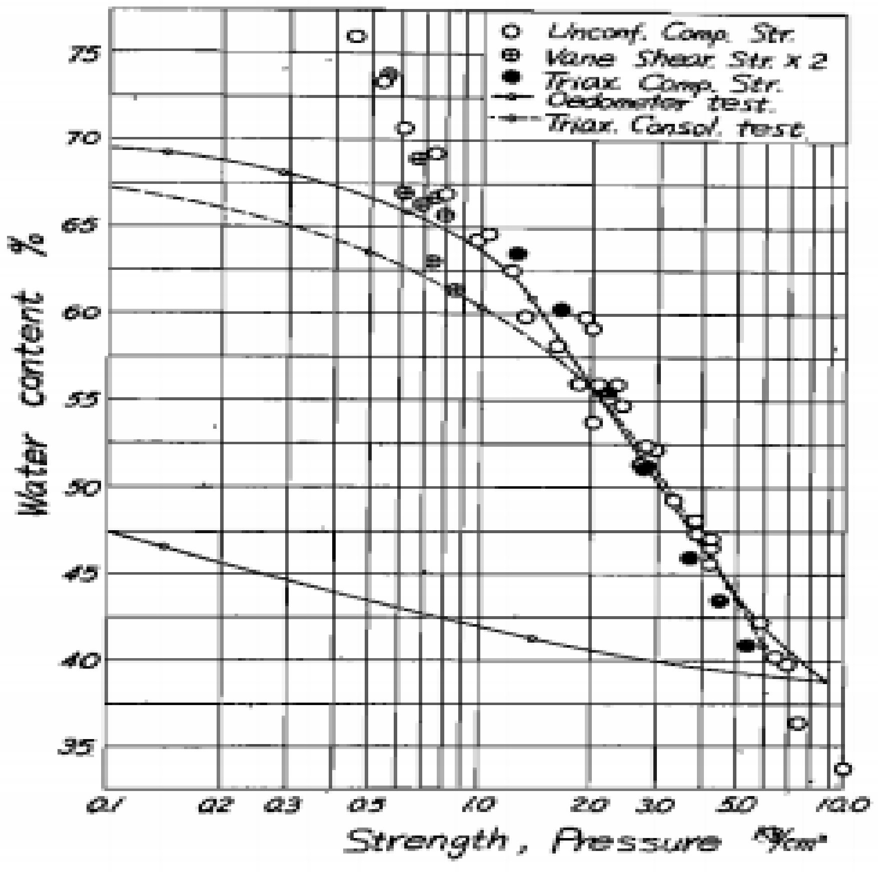

Fig.14. Consolidation curves related to pressure and water content and relationship between water content and strength.

3.6. Savanna soil water content effect on its shear strength-compaction relationship, Hossne Garcia et al (2012).

Hossne Garcia et al. (2012) studied the relationship between the shear strength and compaction of sandy loam soils under varying water content. Soil strength increased as compaction increased in the soil compaction-water characteristic curve, the optimal soil shear strength took place before the optimal compaction occurred. The effect of moistness, weakening the shear strength was greater than the effect of dry bulk density strengthening shear strength.

A random sampling, of the areas of study, were proceeded with the excavation of five test pits spaced at 30 m with an area of 100 by 80 cm. Samples were taken with the Uhland type sampler at two different sites, at three depths in five pits with five replicates per depth (2 * 3 * 5 * 5), this produced a grand total of 150 samples, 75 samples per site, which were subjected to the determination of the *in situ* bulk density and gravimetric moisture content. Uhland sample and field soil sampling, showing the pit are shown in Figure 16. A portion of the oven dried subsamples crumbled and mixed, was employed to determine the physicochemical components (Table 8) and the remainder was passed through 2 mm sieve used in the proctor compaction and shear test sufficient to meet the experimental soil needs. Proctor soil compaction test was performed by measuring the bulk density of the soil being tested at different moisture content points.

Table 8. Physical characteristics of a sandy loam soil of two different sites at two depths at Monagas State, Venezuela.

Components (%)	Horizons of two sites			
	San Jacinto, Sector Costo Arriba		Jusepin	
	0-30 cm	30-60 cm	0-30 cm	30-60 cm
Very course sand	1.03	0.37	1.77	0.50
Course sand	9.18	1.93	22.43	0.58
Medium sand	25.61	7.49	24.01	16.94
Fine sand	30.10	7.22	22.13	27.74
Very fine sand	12.60	14.06	6.33	8.39
Total sand	78.42	31.07	76.67	54.15
Silt	8.400	52.73	15.23	29.65
Clay (kaolinite)	13.151	16.2	5.2	10.2
Organic matter	1.632	0.86	0.49	0.45

Fig. 15. Uhland sample and field soil sampling, showing the pit

Results and Discussion

Figure 16 shows the shear strength and bulk density as affected by the soil water content in the Proctor compaction process of densification. The position of the maximum on the curve corresponded to the optimal bulk density. It could be observed that the optimal compaction achieved was between 9.4 and 12.2% optimal compacting water content; instead, for the shear stress it was between 6.9 and 7.7%. It may be discerned that the wetness caused the optimum compaction and shear stress in different ranges of soil consistency. It may be perceived that soil wetness influenced much over shear stress than compaction.

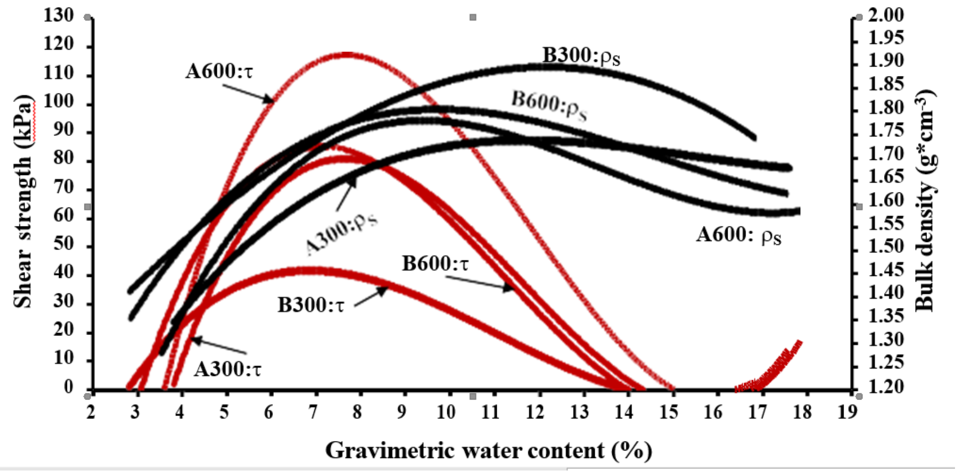

Fig. 16. The shear strength (τ) and dry bulk density (ρ_S) versus moisture content for the two sites under study, at two depths 0-300 mm and 300-600 mm

Although the increase in bulk density caused increase in the shear strength of the soil as shown in Figure 16, the soil under study was exposed to maximum shear strength below the lower limit of the friable state, and the optimum bulk density above the upper limit of the friable state close to the soil field capacity. The optimal shear strengths were far achieved from the optimal bulk densities.

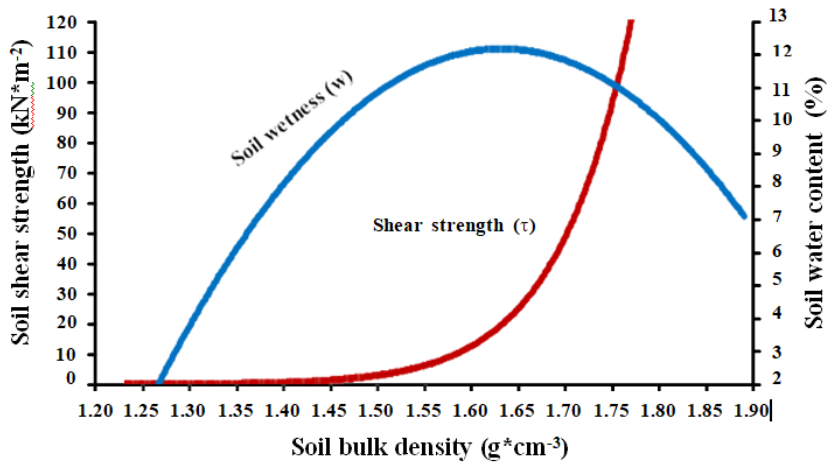

Fig. 17. General relation of the shear strength (τ) and moisture content (w) versus dry bulk density

3.7. Influence of water content on the shear strength parameters of clayey soil in relation to stability analysis of a hillside in BRNO region, Kristyna Blahova et al (2013)

Kristyna Blahova et al (2013) studied the influence of water content on the shear strength parameters of clayey soil in relation to stability analysis of a hillside in BRNO region. The soil samples used in this study were taken from surroundings of a forest road, located in a research area of the Mendel university near Brno, Czech Republic. Table 9 shows the results of Sieve analysis, Densimeter analysis, Atterberg limits and proctor standard results. The Proctor standard test according to CSN EN 13286-2 was used to determine the dry density and optimum moisture content. Soil specimen were compacted using the Proctor hammer and the optimum moisture content was identified at w = 12 %. Preparation of the specimen with direct shear mould below 9% and above 12 % was not possible, without creating extra cracks and cavities in the specimen, therefore the tested water contents had to be established dry of the optimum at w = 9 %, 10 % and 11 %.

Table.9 Phyiscal, Index and Compaction properties

Property	Value
Unit weight [kg/cm³]	1863.00
Liquid limit [%]	22.10
Plastic limit [%]	14.30
Plasticity index	7.80
Consistency index	0.90
Clay fraction [%]	37.00
Sand fraction [%]	41.00
Gravel fraction [%]	22.00
Optimum moisture content [%]	12.01
Maximum dry density [kg/cm³]	1912.00

For the purpose of this study soil specimen were compacted and the optimum moisture content was identified. After compaction soil was tested at the dry side of optimum water content at w = 9 %, 10 % and 11 %. Parameters of shear strength were also obtained and used for stability analysis with software GEOSLOPE/W 2012. According to referenced literature, it was expected for the shear strength of the soil to decrease with increasing water content but it did not happen for the case as shown in Figure 17.

Table.10 Maximum shear strength for each of the water contents

Water content	C [kPa]	ϕ [°]	τ max 50 kN	τ max 100 kN	τ max 200 kN
9 %	24,84	9,00	34,39	38,22	57,32
10 %	21,00	13,40	35,70	40,80	70,10
11 %	5,09	7,47	12,74	16,56	31,85

The results presented (Table 10 and Figure 17) are in contradiction with expected development of the values of τ_{max}. Such development was found also for values of Factor of safety (FOS) obtained from stability analyses.

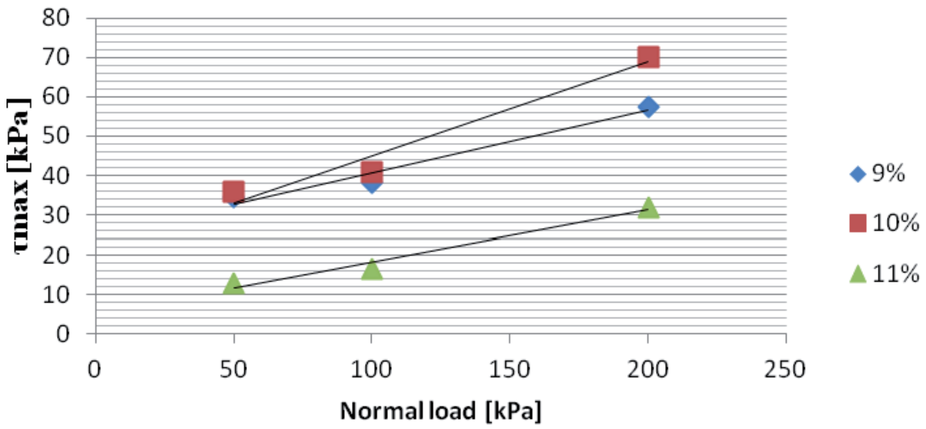

Fig. 18. Maximum shear strength at 9 %, 10 % and 11% water content

4.0 CONCLUSION

Water exerts controlling influence on most of the physical, chemical and biological processes that occur in soil. Water in soil acts both as a lubricant and as a binding agent among the soil particulate materials, thereby influencing the structural stability and strength of soil.

Shear strength of soils is highly affected by moisture conditions, especially if the soil contains clay materials. Usually the laboratory specimen, which are used to determine shear strength of the soil are prepared at water content and dry density same as in the field conditions, without respect to the fact, that the conditions in the future might not remain the same.

Shear strength of soil is characterized by cohesion (c) and friction angle (ϕ). The two parameters mentioned primarily, define the soil maximum ability to resist shear stress under defined load. It is understood that cohesion mobilises at the beginning of stress conditions and reaches maximum values around the plastic limit, i.e. at the beginning of structural collapse. Cohesion decreases at water content heading towards the liquid limit (w_L) and increases towards the shrinkage limit (w_s). Cohesion usually does not increase with increasing stress, except for clayey soils, where the increase in stress causes increase in molecular binds. Friction increases with increase in normal load. Reduction of water content in clayey soils results in higher friction angle, due to the fact, that clay particles group into aggregates, hence shear strength, are expected to exert higher Factor of Safety (FOS), when these parameters are used for evaluation of the stability of a hillside. In one of the study paper it was found that development of values of friction angle and cohesion exhibited anomalous behavior, such cases are rare and dominant by presence of concretion on the shear plan, changes in volume weight during test and limited number of specimen tested.

Literature studies show the necessity of taking moisture conditions into account, when processing stability analysis, in order to achieve reliable and safe construction.

5.0 FUTURE SCOPE FOR THE STUDY

It is concluded from the study that moisture content and drainage conditions effect the shear strength parameters i.e., cohesion and angle of internal friction. Presented study aims to upgrade the knowledge of relationship between moisture conditions (i.e. water content) and parameters of shear strength of soil. The test conditions and shear parameters should be chosen to represent the field conditions as closely as possible. The choice between the effective stress analysis using the effective stress parameters c' and ϕ' and total stress analysis using the apparent parameters c and ϕ depends upon the condition whether the pore water pressure can be estimated or not. In case the pore water pressure cannot be accurately estimated or measured, the total stress analysis is more convenient. However, it gives little indication of the real factor of safety. There may be uncertainty, whether the analysis would give error on the side of safety or on the unsafe side. If the pore water pressure can be estimated or measured, the effective stress analysis should be done, as it is more rational. It is based on well established, unique functional relationship between the shear strength and the effective stress on the failure plane at failure.

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