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新しく開発した引張り試験装置による粘性土の引張り強度について

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Tensile Strength of Soil Measured Using Newly Developed Tensile Strength Apparatus

By Surendra B. TAMRAKAR*, Yasuo TOYOSAWA** and Kazuya ITOH**

***Abstract*:** Recently, many soil-slopes get failed during the excavation or trimming process of slopes. In case of circular slope failure, it is generally thought that the failure is occurred due to shearing of soil layers. In such case, shearing surfaces are also seen at the failure sites. But in some failure excavation sites, such types of shearing surfaces are not seen. Instead soil layers seem to be detached from each other. The cause of such failure could be due to the development of tensile cracks. Also, many earth dams, embankments, pavements, etc. are failed due to the development of tensile cracks. In addition, location of the development of ice lens in freezing soils is also related with tensile strength. In order to understand the development of tensile crack, it is necessary to know the exact value of tensile strength that the particular soil consists of. Several methods of tensile testing of soils have been used in the past. But up to now, due to limitations of the existing test methods, the earlier tests were focused on to the more brittle and elastic materials (stiff, compacted and cement mixed soils) which have higher tensile strengths rather than for ductile (soft, saturated and clayey soils) materials which have lower tensile strength.

This paper describes a newly developed tensile strength measuring apparatus which could be used for measuring the tensile strength of saturated, compacted and soft soils. At first, the tensile strength measurement procedure using this apparatus is explained which is very simple and quick. Then, two types of tensile molds are described and results obtained using them are compared. Statically compacted soils ; Kanto loam, clay-sand mixture, clay-silt mixture and CFP silt-sand mixture, and one dimensionally consolidated NSF-clay are used as test samples. Unconfined compression test and suction test are also performed for Kanto loam to get their relationship with tensile strength.

1) Maximum strengths for Kanto loam are obtained around 50～60% of water content for all the samples prepared at three different dry densities (ρ_d = 0.66, 0.68 and 0.7 g/cm^3). In the dry side (water content lower than 60%), strengths are reduced with the decrease in water content whereas in the wet side (water content higher than 60%), strengths are decreased with the increase in water content. Difference in the strengths due to change in dry density at dry side is lower than that at wet side.

2) For compacted Kanto loam, it is found that the average ratio of unconfined compression strength (q_u) to tensile strength (q_t) is around 12.5. But it varies differently with water content at dry and wet sides.

3) The effect of the amount of finer particles and their size on tensile strength are also observed

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by changing the proportions in the mixtures in clay-silt, clay-sand and sand-silt. It could be observed that with the increase in the amount of finer particles, tensile strength increases. But with the increase in the size of finer particles, there is a reduction in tensile strength.

4) In case of pre-consolidated saturated NSF clay, tensile and unconfined compression tests are performed. Saturated NSF clay samples are prepared under the pre-consolidation stresses of 100, 200 and 300kPa. The ratio of strength (q_u/q_t) obtained for this saturated NSF clay is around 6.

Keywords; strength, tensile crack, test equipment, compacted soil, Kanto loam, NSF clay

1. Introduction

In order to understand the development of tensile cracks which leads to the failure of slopes, earth dams, embankments, pavements and ice lens development process during the freezing of soils, it is necessary to know the exact value of tensile strength that the particular soil exhibits. The development of a simple and appropriate method for the determination of tensile strength in the laboratory is necessary. In the past, tensile strength of soils has been generally neglected. Because the tensile strength of the soils, especially soft and saturated ones, is considered to be zero or relatively very small in comparison to compressive strength. Furthermore it is difficult to measure the tensile strength directly in the laboratory. Several methods of tensile testing of soils, such as uniaxial direct tensile test , a simple splitting test and unconfined penetration test, flexure (beam) test, indirect Brazilian test, hollow cylinder tests, etc., have been used in the past[1)~8)]. But up to now, due to the limitations in those test methods, the earlier tests were only focused on to the more brittle and elastic materials (stiff, compacted and cement mixed soils) having higher tensile strength rather than for ductile materials (soft, saturated and clayey soils) having lower tensile strength. Few researches have been made to measure the tensile strength of soils having lower tensile values[9)~11)]. But those are mostly applicable to unsaturated soils rather than saturated soft soils.

In this paper, a new simple testing apparatus which can be easily used for both compacted and saturated soft to medium soils is described and the testing method is explained. Compacted soil specimen can be directly prepared within the mold of the apparatus itself. Also, by transferring the saturated soil specimen prepared in the special consolidation mold to the tensile mold of this apparatus, one can easily measure the tensile strength of saturated soft soils. Test results on compacted and saturated soils shows that they are reproducible, and reliable. Effect of water content, dry density and the proportions and size of fine particles mixed in the soil are examined.

2. Testing Apparatus

Tensile test apparatus (**Fig.1**, **Photo. 1** and **Photo. 2**) consists of a two halves box ; a fixed box and movable one, resting on a horizontal platform. Inside this box, a newly developed tensile mold is placed. This tensile mold consists of two separate " C" structures whose inner shape is

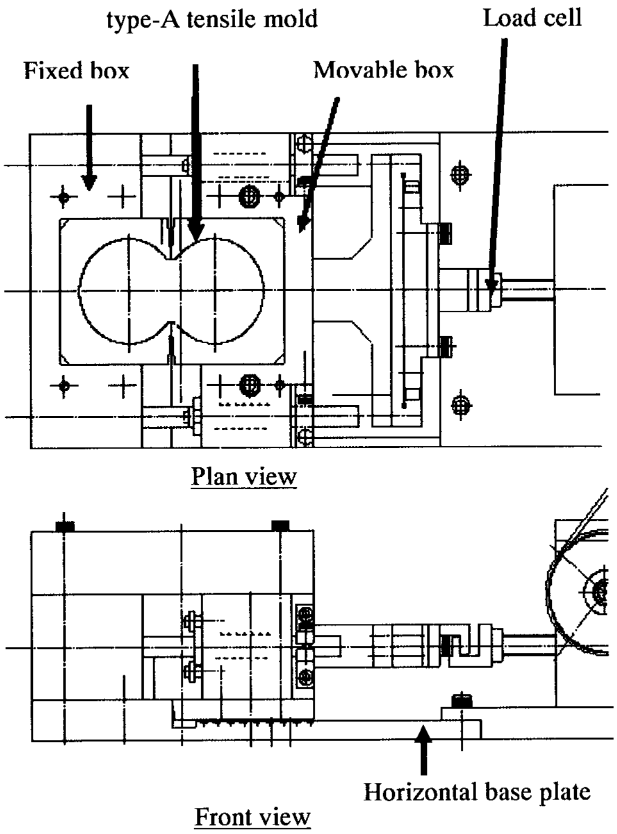

Fig. 1　Outline of tensile apparatus with type-A mold.

almost circular except at the portion where these two halves join. This mold holds the specimen and its two halves are screwed to the apparatus box. One box of the apparatus is fixed to the horizontal platform while the other box can move freely on the horizontal platform.

To reduce the friction between the movable box and platform, linear sliding rollers are placed below the movable box and above the platform. The movable box is pulled away in a horizontal direction until the soil specimen fails in tension as indicated by tensile crack appearing at the middle of the specimen where the two halves of the mold are attached. The load cell placed between the movable box and motor axis measures the tensile load. The tensile strength is obtained by dividing the tensile load by the area of the tensile crack perpendicular to horizontal pulling.

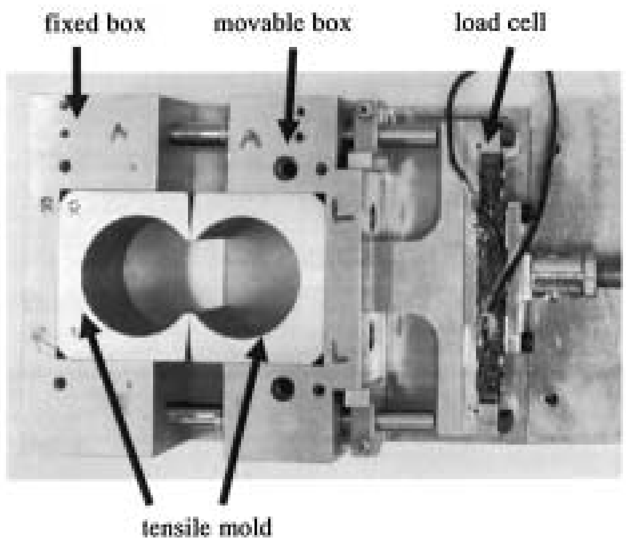

Photo. 1 Tensile apparatus with tensile mold (type-A).

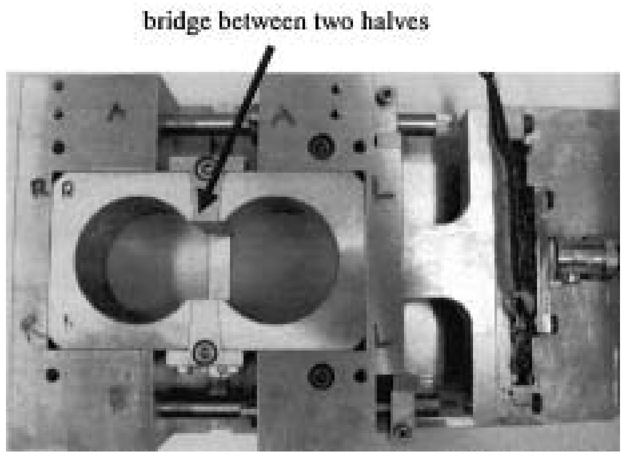

Photo. 2 Tensile apparatus with tensile mold (type-B).

To see the effect of stress concentration at the most constricted part of the specimen during the pulling, two types of tensile molds having different structures are used. These molds can be easily changed as they are connected to the main apparatus by the screws only. In the first type (type-A, **Photo. 1**, **Fig. 1**), there is no bridging structure between the two halves whereas in the second type (type-B, **Photo. 2**), bridging structures are placed in between the two halves (1 cm in thickness). The total surface area of type-A mold is 38.51cm^2 (total volume = 192.53 cm^3) and that of type-B mold is 41.51 cm^2 (total volume = 207.53 cm^3). The minimum width for both types of mold is 3 cm and depth is 5 cm.

The apparatus box along with the mold and platform can be completely separated from the motor for preparing the specimen before the test. Compacted soil specimen is prepared within this mold by direct static compression whereas saturated specimen is prepared by direct transfer of consolidated specimen prepared in a consolidation mold. Once the specimen is ready within the mold for the test, then it is connected to motor shaft. A load cell is attached between the motor shaft and the movable apparatus box. The rate of deformation is maintained at 0.35 mm/min.

Unconfined compression tests are performed in a standard unconfined compression test unit and constant strain rate is maintained. The height of the specimen is 10 cm and diameter is 5 cm. Specimen is allowed to fail at a constant displacement rate of 0.1 mm/min. Suction test is performed using a simple suction testing apparatus[12].

3. Materials, Specimen Preparation and Installation

3.1 Materials

Index properties of materials used in this research are shown in **Table1**. Soil particles passing through the 2mm sieve are used for Kanto loam.

To examine the effect of the amount and the

Table. 1 Index properties

materials	ρ_s	w_L	w_P	ρ_{dmax}	ρ_{dmin}
	g/cm^3	(%)	(%)	g/cm^3	g/cm^3
Kanto loam	2.65	143.5	74.6		
NSF-clay	2.78	55.1	30.6		
silt (CFP-100)	2.66			1.59	1.17
Toyoura sand	2.64			1.65	1.34

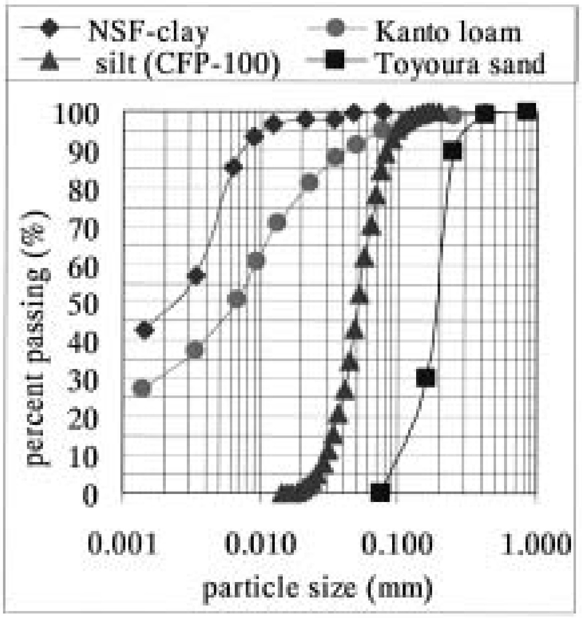

Fig. 2　Grain size distribution curves for diffferent materials.

size of soil particles, three types of mixtures were prepared ; (a) clay-silt, (b) clay-sand and (c) silt-sand. Here, clay means NSF clay and silt means CFP-100 silt[13]. This CFP-100 silt is prepared by crushing silica sand. Sand used is standard Toyoura sand. NSF clay, silt (CFP-100) and Toyoura sand are commercially available. Grain size distribution curve for each material is also shown in **Fig. 2**. For saturated sample, NSF clay is used.

3.2 Specimen Preparation and Testing Procedure

Type-A and type-B molds are first assembled as shown in **Photo. 1** and **Photo. 2**. Type-A is simpler and easier to handle. To prevent the free movement of the movable part of the apparatus box before testing, the movable box is screwed to the horizontal plate of the apparatus. Also, to reduce the friction between the specimen and the inner wall of the tensile mold, a thin film of grease is applied all over its inner surfaces.

Compacted specimens are prepared by thoroughly mixing the materials with prerequisite distilled water and then kept in a plastic bag and sealed for a week so that water is uniformly distributed within the material. Then, the specimens are prepared by directly and statically compressing the prerequisite amount of water mixed material within the tensile mold of this new apparatus, using bellofram cylinder water content maintained for Kanto loam is varied from 30 to 100%. Compacted Kanto loam specimens are prepared at three dry densities (ρ_d) ; 0.66, 0.68 and 0.70 g/cm^3. In the case of clay-silt mixtures, they are mixed in the following proportions by weight ; 25 : 75, 40 : 60, 50 : 50, 60 : 40, 75 : 25 and for clay-sand they are mixed in following proportions ; 30 : 70, 35 : 65, 40 : 60, 45 : 55, 50 : 50, 55 : 45, 60 : 40, 65 : 35 and 70 : 30. Similarly, for silt-sand mixtures, they are mixed in the following proportions ; 00 : 100, 20 : 80, 40 : 60, 50 : 50, 60 : 40, 70 : 30, 80 : 20 and 100 : 00. Water content, (w) for all the mixtures is maintained around 10%. Dry densities for clay-silt, clay-sand and silt-sand mixtures, are maintained at 1.5, 1.5 and 1.4 g/cm^3, respectively.

Pre-consolidated saturated NSF clay specimen is prepared by thoroughly mixing NSF clay powder with distilled water using a mixer until it changes to slurry. The amount of water mixed is two times

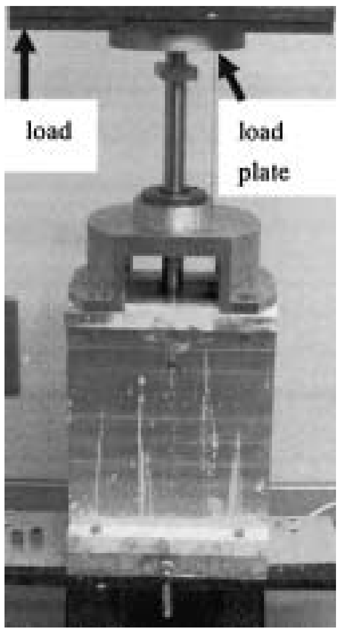

Photo. 3　Consolidation mold for saturated soil.

the liquid limit of NSF clay. After the slurry was poured into the consolidation mold (**Photo. 3**), two days de-airing was done by keeping the consolidation mold within a big cell under vacuum. The cross-section of the consolidation mold is similar to that of the type-A tensile mold. At the bottom of this mold, there is a detachable plate with porous stone whereas on the top, there is a piston shaft which has many small holes on it. Drainage is allowed via these two parts during consolidation. One dimensional consolidation is done by putting the loads on the loading plate (see **Photo. 3**). Consolidation stresses applied to the slurry are 100, 200 and 300kPa.

Once the consolidation is over, the bottom porous plate and filter paper are detached from the consolidation mold. Then the mold with the consolidated specimen is placed over the tensile mold. Centering of mold is done by guiding support screws which are attached to the fixed portion of the tensile mold. By pushing the shaft of the consolidation mold slowly, the consolidated specimen is allowed to be inserted into the tensile mold. Once the full depth (5 cm) insertion is completed, then it is separated from the tensile mold by using a wire saw which is also used for final trimming of the upper surface of the specimen after the insertion into the tensile mold.

In the case of tensile test specimen, materials are kept within the tensile test mold whereas specimens for unconfined compression and suction tests, materials are kept within the splitting mold. Water content and dry density of the specimens are the same for all the tests. Dimension of tensile test specimen is the same as that of tensile mold whereas the height and diameter of the unconfined compression test specimen are 10cm and 5 cm, respectively. Similarly, the thickness and the diameter of the suction test specimen are 2 cm and 5 cm, respectively. Unconfined compression test is done at a constant displacement rate of 0.1 mm/min. Suction tests are only done for Kanto loam soil with dry density of 0.70 g/cm^3. The air entry value (AEV) of the ceramic disk used in the suction test is 240 kPa.

3.3 Testing Procedure

After the completion of compaction in the case of compacted specimens or after the insertion of the consolidated specimen into the tensile mold, the load cell is set up towards the pulling side of the mold box. Finally, the screws which were earlier fixed to prevent the movement of movable box of the apparatus are un-screwed. In the case of type-B mold, extra bridging structures have to be removed carefully. For this, lots of attention has to be paid. Hence, from the simplicity of the testing procedure, type-A mold is better than type-B mold. Test results with tensile pulling rate of 0.17, 0.35 and 0.86 mm/min are done and compared. But the difference in the values of tensile strength obtained is very small, displacement rate 0.35 mm/min showing the minimum value. Hence, all the tests are carried out with the displacement rate of 0.35 mm/min.

4. Results and Discussions

Test results of tensile tests carried out on type-A and type-B molds for clay-sand mixture (ρ_d = 1.44 g/cm^3 and w = 10%) are shown in **Fig. 3**.

Both types of molds gave almost the same peak strength and showed the similar stress-displacement behavior. As the testing procedure with type-B is complex in comparison to type-A,

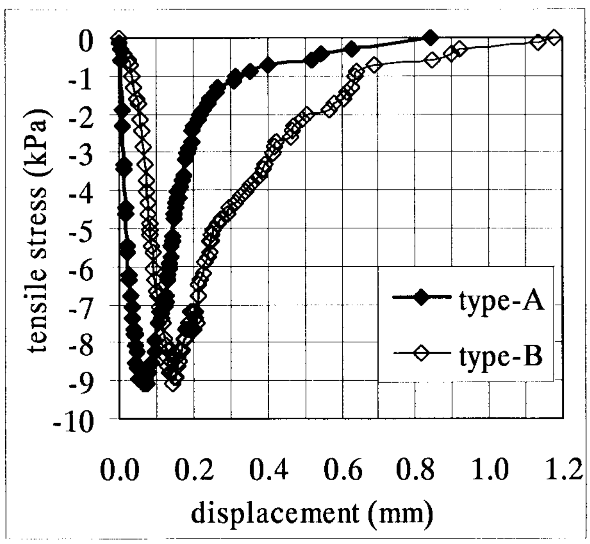

Fig. 3 Results from type-A and type-B molds (clay-sand mixtures : ρ_d = 1.44 g/cm^3, w = 10%)

it is therefore suggested to use type-A mold. From now on, test results obtained using the type-A mold are only explained.

Tensile cracks developed during the compacted and saturated tensile tests for different specimens are shown in **Photo. 4**. The clear separation of specimen into two parts could be seen in all the tests. Tensile crack surfaces are also smooth showing the clear detachment from each other as those are generally seen at slope failure sites where slopes are failed due to tensile cracks. Macroscopically, detaching surfaces (failure planes) are smooth and it shows that there is an even distribution of tensile force along the failure surfaces. But if the tensile failure surfaces are studied microscopically, there is little variation on the surface which is due to the difference in the distribution of soil particle size.

The plots of tensile stress versus displacement for compacted Kanto loam are shown in **Fig. 4**. Good and clear stress-displacement curves can be seen with the maximum tensile stress, q_t (tensile strength) developing within the range of 0.05 to 0.1 mm displacement. Here, the maximum tensile strength is the maximum tensile stress necessary to break the most of the soil particle bonds. Thus, tensile stress keeps on reducing even after reaching the maximum value. Some researchers have also mentioned about the similar trend of decrease in tensile stress after the maximum value[11), 14)]. On the top surface of the specimen, tensile crack development could be seen during the test. In case of compacted specimens, cracks are developed throughout the surface almost at the same time. While in the saturated specimens, crack is at first seen at the outer side and it continuously protrude inward till whole the surface is separated.

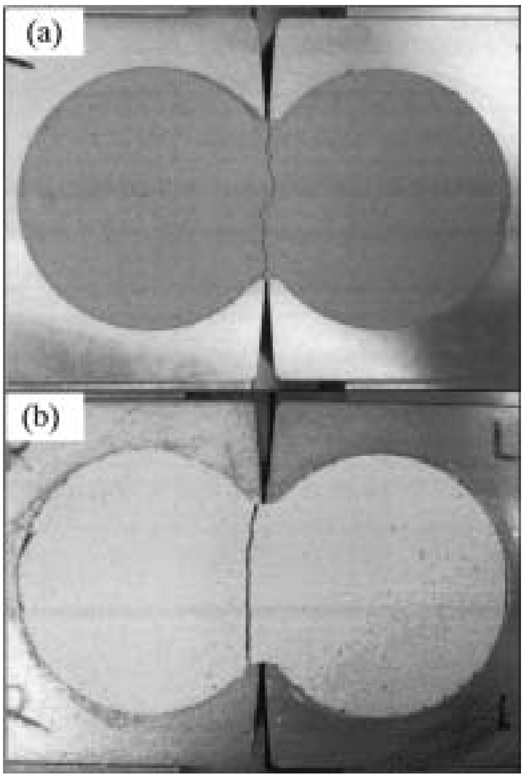

Photo. 4 Tensile cracks produced during the tests; (a)compacted Kanto loam (w=40%, ρ_d=0.7g/cm^3), (b)saturated clay (200kPa).

Fig. 5 shows the results of Kanto loam tests at different water content with repetition. Although, there are some differences in the maximum tensile strength for the repeated water content, it can be said that reproducible results can be obtained with this new apparatus. Relationship between q_t, ρ_d and w for Kanto loam are shown in **Fig. 6**. Three distinct curves are seen for three different dry densities. But all the curves show similar trends giving maximum tensile strength around 60% of water content. Tensile strength decreases along both sides of this maximum value.

Comparing the three curves, it can be said that with the increase in dry density, tensile strength

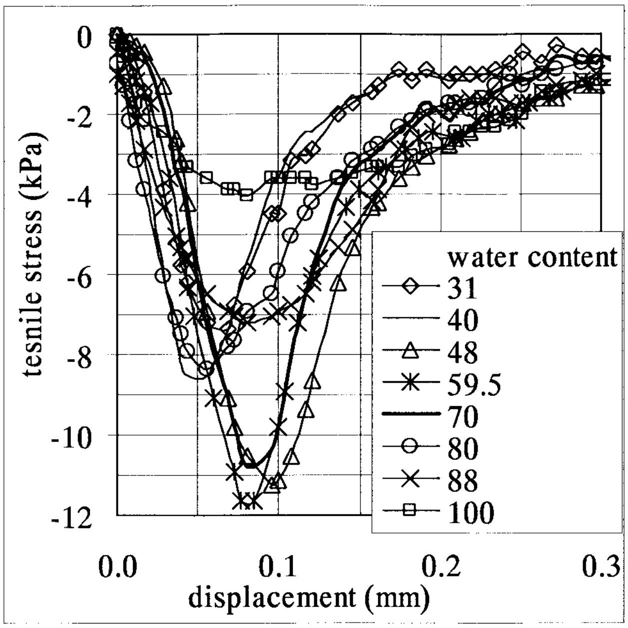

Fig. 4 Stress-displacement curves (for compacted Kanto loam, ρ_d=0.66g/cm^3).

also increases. But the difference in the tensile strength values with the change in dry density at two sides of maximum tensile strength is different, showing larger difference at the dry sides (lower than 60% water content) and smaller difference at wet sides (higher than 60% water content). At nearly saturated condition, tensile strength values are almost same. Therefore, it could be said that with the increase in dry density tensile strength also increases, but the ratio of increment depends upon the amount of water content.

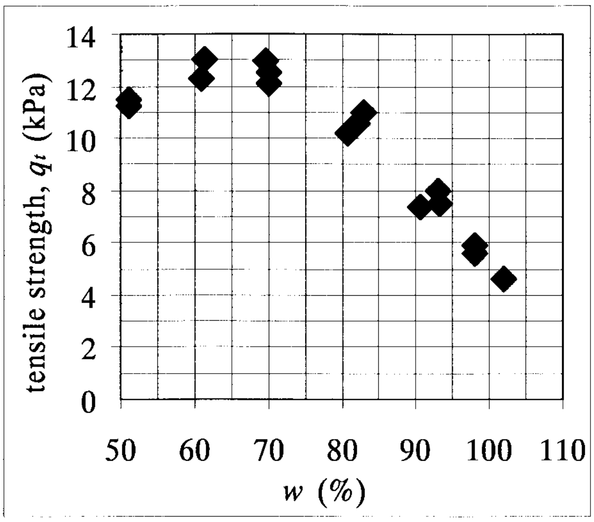

Fig. 5 Reproducibility of tests (for Kanto loam).

Unconfined compression test results performed for compacted Kanto loam are shown in **Fig. 7**. Here, the maximum q_u is seen around 50% of water content. The trend of curves is almost similar to that for tensile tests results shown in **Fig. 6**.

Relationship between q_u and q_t is shown in **Fig. 8**. In plotting the direct relationship between these strengths, their ratio varies from 10.64, 13.1 and 12.69 depending upon the dry densities equal to 0.66, 0.68 and 0.70 g/cm^3, respectively. Taking the average, it can be said that q_u is 12.5 times larger than q_t in case of Kanto loam. Krishnayya et al. have also showed this ratio in the range of 12 to 32 for Mica Till[6].

In **Fig. 9**, it can be observed that the slope of this ratio is different at dry and wet sides. With the increase in water content, this ratio increases at dry sides and decreases at wet sides. But the decreasing ratio of q_u/q_t at wet side is much less, showing the average value of 10. Hence, it is necessary to consider the water content if the q_t value is to be estimated from the calculated q_u.

To see the effect of initial suction on tensile strength of compacted Kanto loam, simple suction

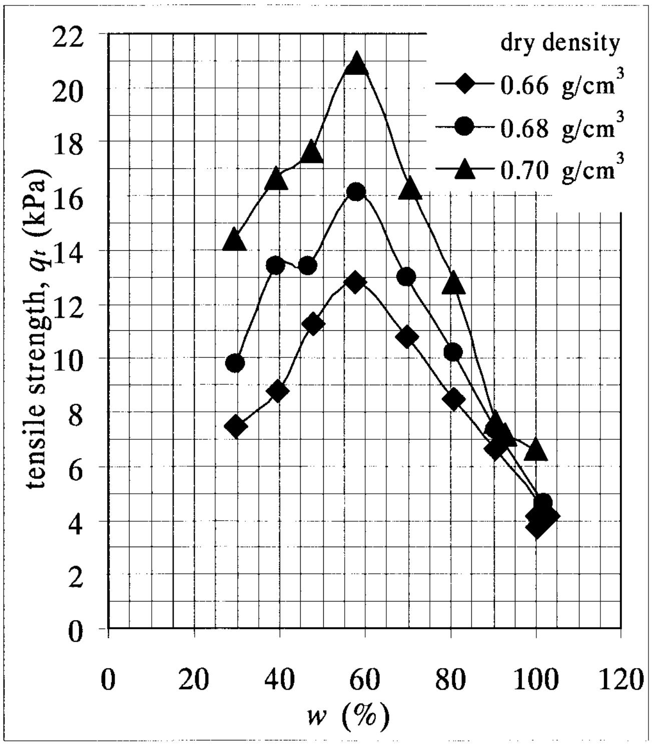

Fig. 6 Relationship between q_t, w and ρ_d (for compacted Kanto loam).

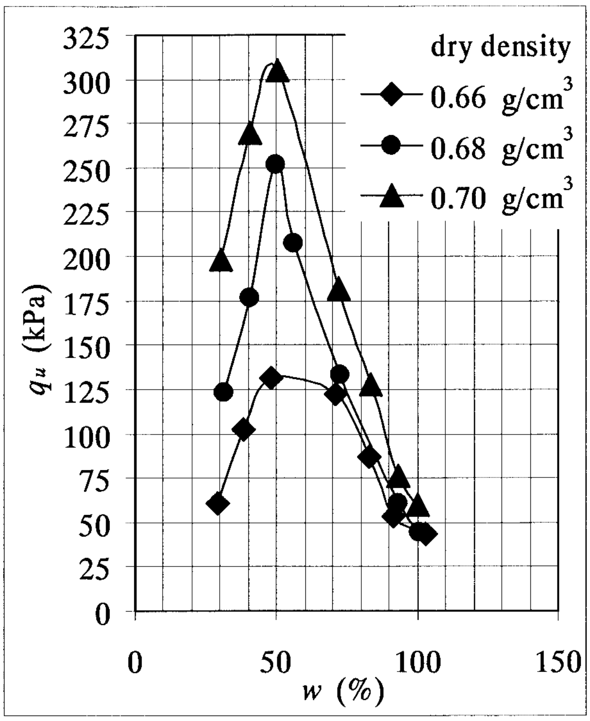

Fig. 7 Relationship between q_u, w and ρ_d (for compacted Kanto loam).

tests are conducted and their results are shown in **Fig.10**. It is to be noted that the suctions measured here are the suctions at the beginning of tensile testing. So, it is not necessarily the suctions when tensile failure occurred. Suction tests

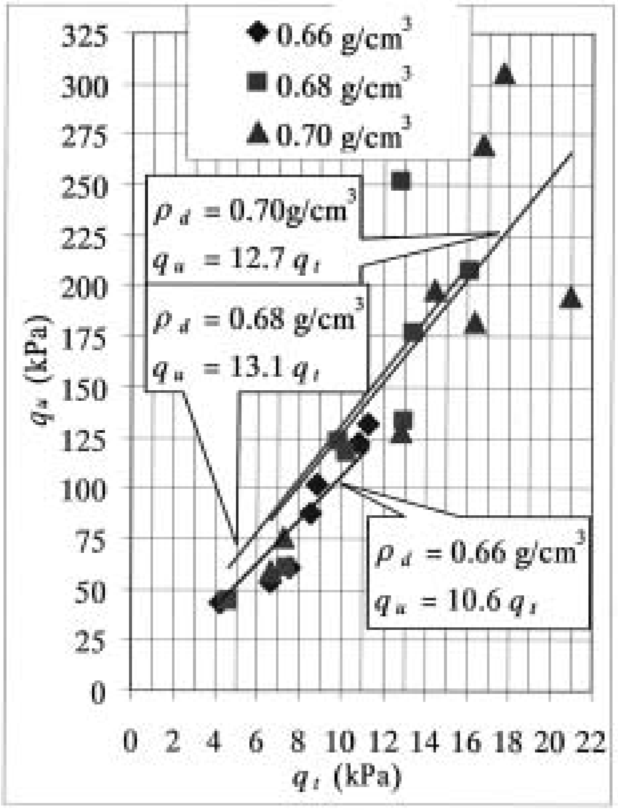

Fig. 8　　Relationship between q_u and q_t (for compacted Kanto loam).

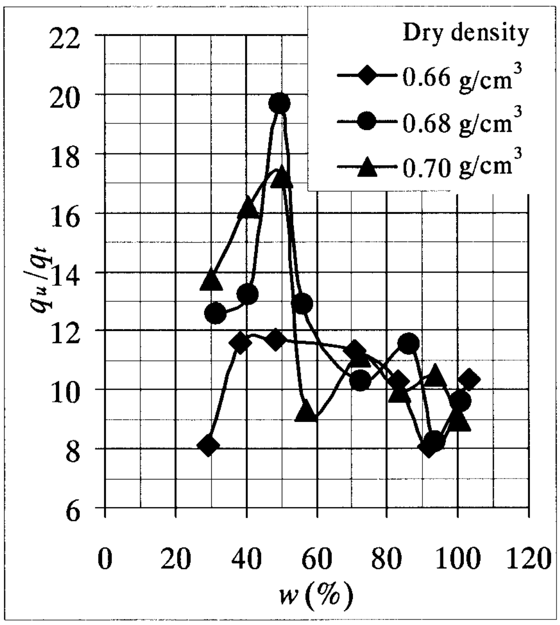

Fig. 9　　Relationship between q_u/q_t and $w\%$ (for compacted Kanto loam).

are carried out by applying the back air pressure[12]. **Fig.10** shows the difference in the values of suction and q_t at the same initial water content. This indicates that the q_t value measured does not fully represent the initial suction of the specimen. Only some effect of suction is included in the q_t. Relationship between the tensile strength and suction is also shown by Tang et al.[2]. Their results also showed that the measured suction is not equal to tensile strength. Instead, tensile strength values are much lower than the suction measured.

The effects of amount and size of finer particles in the tensile strength are shown in **Fig.11** and **Fig.12**. Here, finer particles mean the clay in the clay-silt and clay-sand mixtures and silt in the silt-sand mixture. tensile test results of the mixtures ; clay-silt, clay-sand and silt-sand are shown. All the curves show similar trend of increment in q_t and q_u with the increase in the amount of finer particles ; i.e. the ratio of clay in the clay-silt and clay-sand mixtures and silt in silt-sand mixture. This implies that with the increase in the finer particles, both q_t and q_u increase.

Comparing the strength of mixtures compacted at $\rho_d = 1.5\,g/cm^3$ for clay-silt and clay-sand mixtures, it is seen that the strengths (q_t and q_u) of clay-silt mixture is higher than the strength of clay-

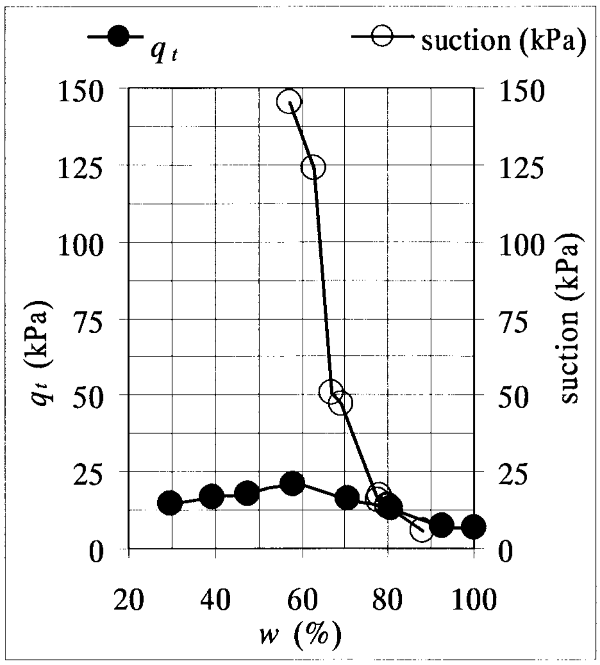

Fig. 10　　Relationship between suction, $w\%$ and q_t for Kanto loam ($\rho_d = 0.7\,g/cm^3$).

sand mixture. Here, clay-silt mixture shows the highest strength and silt-sand mixture shows the lowest strength. Since the size of clay particles is smaller than the size of silt and sand particles, it can be said that the size of fine particles affects tensile strength ; the larger the size of the fine particles, the smaller the tensile strength becomes. This might have occurred as there is a direct relationship between contact points of soil particles and strength of soils. Soils having more fine particles increase the contact surfaces between the particles which then increases the strength.

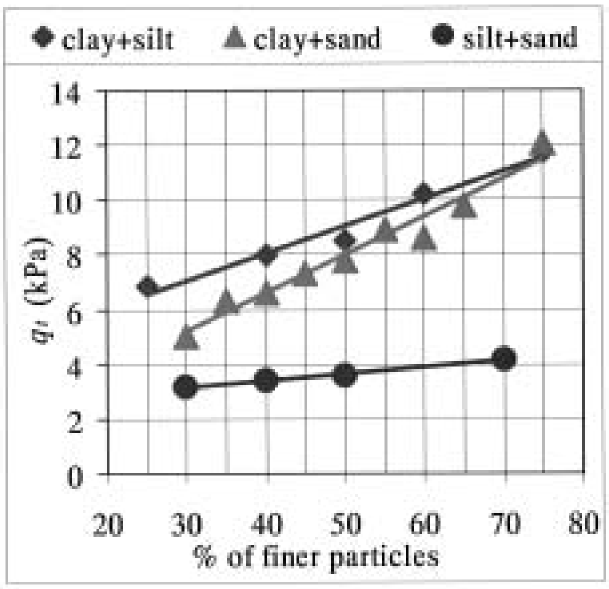

Fig. 11 Tensile strength of compacted mixtures.

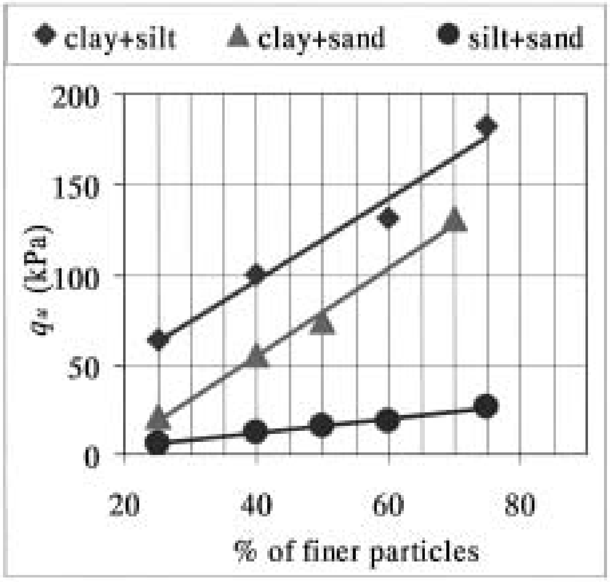

Fig. 12 Unconfined compressive strength of compacted mixtures.

According to Barzegar et al., different amount of finer particle shows different modes of particle arrangements within the soil matrix which influence the soil fabric and hence, the strength[15]. The effect of cohesion is not studied in this paper. But it might be thought that the effect of cohesion will be more prominent in saturated clayey soils rather than unsaturated compacted soils.

Relationship between the strengths and pre-consolidation stress of saturated clays is shown in **Fig.13** and **Fig.14.** With the increase in consolidation stress, both q_t and q_u strengths increase, showing their strength ratio (q_u/q_t) equal to 6. Friction between the slurry specimen and inner surface of the consolidation mold might have

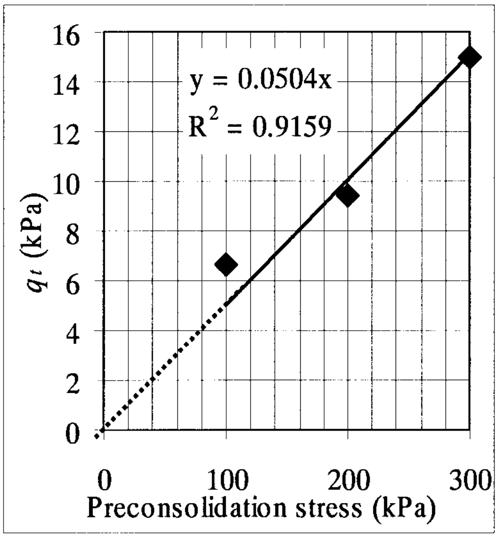

Fig. 13 Pre-consolidation stress and q_t.

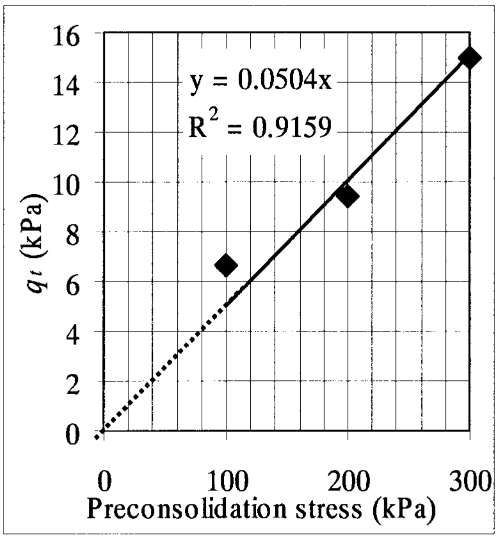

Fig. 14 Pre-consolidation stress and q_u.

affected the propagation of stress uniformly throughout the depth of the consolidation specimen. Also, some disturbances that might have occurred during the insertion of the consolidated specimen from the consolidation mold to the tensile mold of the apparatus. So, proper attention must be paid during the specimen preparation.

6. Conclusions

From the tests conducted for statically compacted Kanto loam, clay-silt mixtures, clay-sand mixtures and silt-sand mixtures ; and saturated clay, the following points can be concluded ;

1. Newly developed tensile test apparatus can be used for measuring tensile strength of both compacted and pre-consolidated clayey soils. Both type-A and type-B tensile molds give similar results. Sample preparation in the type-A mold is easy and simple.

2. Reproducibility of the test results is also verified.

Compacted Kanto loam

3. Maximum tensile strength and compressive strength are obtained around 50 to 60% of water content. With the increase in dry density, tensile strength and compressive strength also increase. The difference in the increment due to dry density is higher at the dry side than that at the wet side. At higher degree of saturation, differences become smaller.

4. The ratio of q_u and q_t is around 12.5, for Kanto loam. But there is a variation in this ratio with the water content. At the dry side, it increases with the increase in water content, while at the wet side, it remains almost constant.

5. Difference between the suction and tensile strength values becomes larger with the decrease in water content.

Compacted mixtures of clay-silt, clay-sand and silt-sand

6. From test results of mixtures, it can be said that with the increase in the amount of finer particles (clay or silt), q_t and q_u both increase.

7. Also, with the decrease in the size of the finer particles (size of clay is smaller than size of silt and sand), there is increase in the strength.

Pre-consolidated Saturated clay

8. Relationship between the tensile strength and the consolidation stress for the saturated clay show that with the increase in the consolidation pressure, there is increase in tensile strength. The ratio (q_u/q_t) obtained for pre-consolidated saturated clay specimen is around 6.

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