Jour. of the KGS, Vol. 18, No. 3. June 2002, pp. 13~21

Effect of Moisture on Tensile Strength in Sand

모래의 인장강도에 미치는 함수비의 영향

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요 지

0.5% ~ 4.0%의 함수비를 가진 습윤모래의 인장강도 변화를 조사하기 위하여 개발된 인장 시험기를 이용한 일련의 실험을 수행하였다. 이러한 실험을 통하여 함수비, 상대밀도, 세립자 함유량 및 Precompression 수준에 따라 모래의 인장강도는 변화하는 것으로 조사되었다. 함수비와 세립자 함유량이 증가함에 따라 인장강도는 증가하는 것으로 나타났다. 특히, 상대밀도가 증가함에 따라 인장강도의 증가 경향은 더욱 분명하게 나타났다. 그러나, 인장강도에 대한 상대밀도와 세립자의 효과는 실질적으로는 함수비에 따라 결정됨을 알 수 있었다. 낮은 함수비 ($w < 0.5\%$) 에서 모래의 인장강도에 미치는 상대밀도와 세립자의 영향은 감소하는 것으로 나타났다. 또한, 인장강도에 미치는 Precompression 효과도 실질적으로는 함수비에 의해 결정되며, Precompression의 크기와 기간의 영향은 상대적으로 적게 나타났다.

Abstract

An extensive tension experiment was carried out to examine the variation of tensile strength in moist sand having moisture contents in the range of $0.5\% < w < 4.0\%$ with newly developed direct tension apparatus. It was observed that tensile strength of sand varied as functions of moisture content, relative density, presence of fines, and level of precompression. Tensile strength increases with increasing moisture content and fines, and this trend is more noticeable at increasing relative densities. However, the influences of relative density and fines on the tensile strength are substantially dependent on the water content. These effects are reduced at low moisture levels ($w < 0.5\%$). The precompression effects also depend on the water content but less on the duration and level of the precompression.

Keywords : Moist sand, Moisture effect, Precompression, Relative density, Tensile strength

1. Introduction

In geotechnical engineering practice, it is generally assumed that sandy soils exhibit only shear strength and insignificant or no tensile strength and cohesion. This is generally true for dry or fully saturated and drained sandy soils subjected to confinement stress levels observed at normal geotechnical engineering operating ranges, where sand displays insignificant cohesion except in very dense states, and it is for these conditions (dry or saturated) that most laboratory data exist. In view of these considerations, investigations of the tensile behavior of sand have not received much attention. However, in the field, perfectly dry sandy soils seldom

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occur, and moist near-surface deposits are frequently located above the water table and exist in an unsaturated rather than fully saturated state. It is exactly these unsaturated soils that comprise the vast majority of normal construction environments, and thus these factors should be of special concern. Field experience shows that within the unsaturated zone, an excavated surface in fine-grained sandy soils can be sustained for some period of time, and some slopes may remain stable for extended time periods due to capillary forces (Kim et al., 1992; Hong et al., 1993). Both observations indicate small but significant non-zero values for tensile strength and cohesion in unsaturated sands, especially at overall low stress levels.

Thus, it is apparent that capillary forces exist in unsaturated sandy soils and lead to apparent cohesion or adherence between the grains, and that this phenomenon has an impact on real-world soil behavior. This is in contrast to the common Mohr-Coulomb strength assumption and means that we may be ignoring significant aspects of soil behavior when we assume that tensile strength and apparent cohesion in relatively clean sands are equal to zero (Fig. 1). Despite this effect on soil behavior, variations in the magnitudes of the tensile strength and cohesion due to changes in moisture content, its relationship to relative density, presence of fines, and level of precompression are not well known.

This paper describes experiments on tensile strength of moist sandy soil as functions of relative density, fines content, and precompression level and discusses influence of these functions on tensile strength. Experiments on apparent cohesion of moist sandy soil and a method for predicting the tensile strength and apparent cohesion of this soil will be described in another publication.

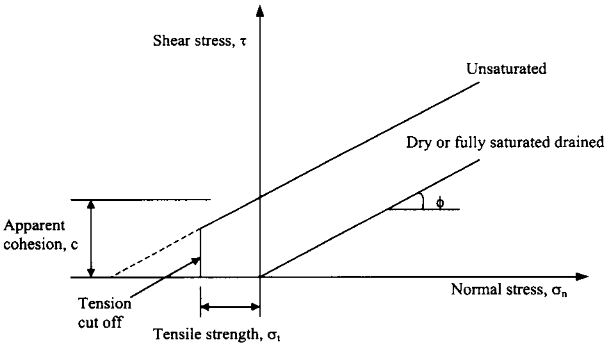


Fig. 1. Idealized shear strength envelopes of sandy soils

2. Capillary Forces

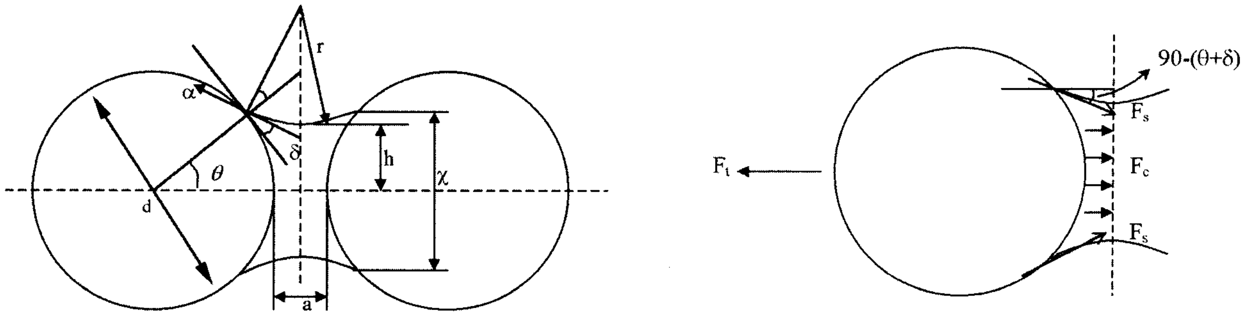
Capillary forces induced by interstitial water can substantially control the properties and behavior of an assembly of solid particles. Even at low moisture contents, small amount of water forms water-bridges at contact points, and as the water content increases these bridges become larger and more developed. This results in capillary bonding between particles, giving rise to both cohesion and tensile strength. Capillary bonding generally leads to two force components at low water content levels : 1) the surface tension force acting along the water-particle contact line, and 2) the force due to the difference in the pressures outside and inside the bridge acting on the cross sectional area. The surface tension tends to force the particles together, whereas the force due to the pressure difference can only contribute to particle adhesion if there is a net pressure deficiency within the bridge. Due to the presence of water-bridges between the particles, these two forces act together as a bonding force. Let us consider a water-bridge existing between two particles of diameter, *d*, and separated by a distance, *a*, as shown in Fig. 2 (a). The first attractive force, F_s, is due to the surface tension of the liquid and is given in dimensionless form as

$$\frac{F_s}{\alpha d} = \pi \sin\theta \sin(\theta + \delta) \tag{1}$$

where θ is the filling angle, and α and δ are the surface tension and contact angle, respectively (Schubert, 1984; Pierrat and Caram, 1997). The second force, F_c, is due to the difference in the bridge pressure acting on the cross sectional area:

$$\frac{F_c}{\alpha d} = \pi\left(\frac{\sin\theta}{2}\right)^2\left(\frac{1}{r^*} - \frac{1}{h^*}\right)$$

$$h^* = \frac{h}{d} = \frac{\sin\theta}{2} + \frac{r}{d}[\sin(\theta+\delta) - 1]$$



(a) Water-bridge bonding two spherical particles (From Pierrat and Caram, 1997)

(b) One-dimensional free-body diagram of bonding forces

Fig. 2

$$r^* = \frac{r}{d} = \frac{(1-\cos\theta) + \left(\frac{a}{d}\right)}{2\cos(\theta+\delta)} \qquad (2)$$

where $h^*(=h/d)$ and $r^*(=r/d)$ are dimensionless radii of curvature of the water-bridge, and a/d is a dimensionless separation distance. Expressions for h and r are derived assuming that both radii of curvature are arcs of circles. The exact shape of the water (liquid) surface is defined by the Laplace-Young equation and h and r must be determined numerically. However, Heady and Cahn (1970) compared the rigorous solution to one based on a circle approximation and showed that the error was very small. The total dimensionless bonding force is the sum of the two components as functions of the contact and filling angles (δ and θ) and dimensionless separation distance (a/d).

$$\frac{F_t}{ad} = \pi \sin\theta \left[\sin(\theta+\delta) + \frac{\sin\theta}{4}\left(\frac{1}{r^*} - \frac{1}{h^*}\right)\right] \qquad (3)$$

A simple one-dimensional free-body diagram illustrating bonding forces is shown in Fig. 2 (b). When contacting particles with a water-bridge are pulling at each other by an external force, the bonding force, F_s, acts along the water-particle contact line ($=\pi\chi$) with an angle of $\sin(\theta+\delta)$ and the force, F_c, acts on the cross sectional area ($=\pi\chi^2/4$) of the water-bridge. These forces act together as the total bonding force against the external force until the water-bridge eventually breaks apart.

3. Experiments

This section briefly describes the experiments performed in the direct tension apparatus. The testing apparatus, material properties, specimen preparation, experimental procedure are described in more detail in another publication (Kim, 2001; Kim, 2002).

3.1 Apparatus

A tension apparatus was developed and is shown in Fig. 3. The specimen container (17.8 x 17.8 x 17.8 cm) was split in two equal halves. Inside the container, four triangular wedges were attached in order to facilitate contact between the specimen and container as tension is developed across the plane of separation. Wedges having larger angles than the dilatancy angle of the material were selected to reduce movement of the soil particles relative to the container, when the specimen was split into two halves, and to achieve a uniform stress distribution on the plane of separation. The dilatancy angle of F-75 Ottawa sand is about 17° for confining pressures in the range of 11.2 to 68.9 kPa (Batiste, 1998; Sture et al, 1998). Thus, wedges having angles of 20° were selected to kinematically constrain the sand near the wall during the motion. Sandpaper was attached to the sides of the wedges to provide a no-slip condition between the sides of the wedges and the soil. This main device rests on a support table equipped with two pulleys, which connect thin wires to two gravity loading containers.

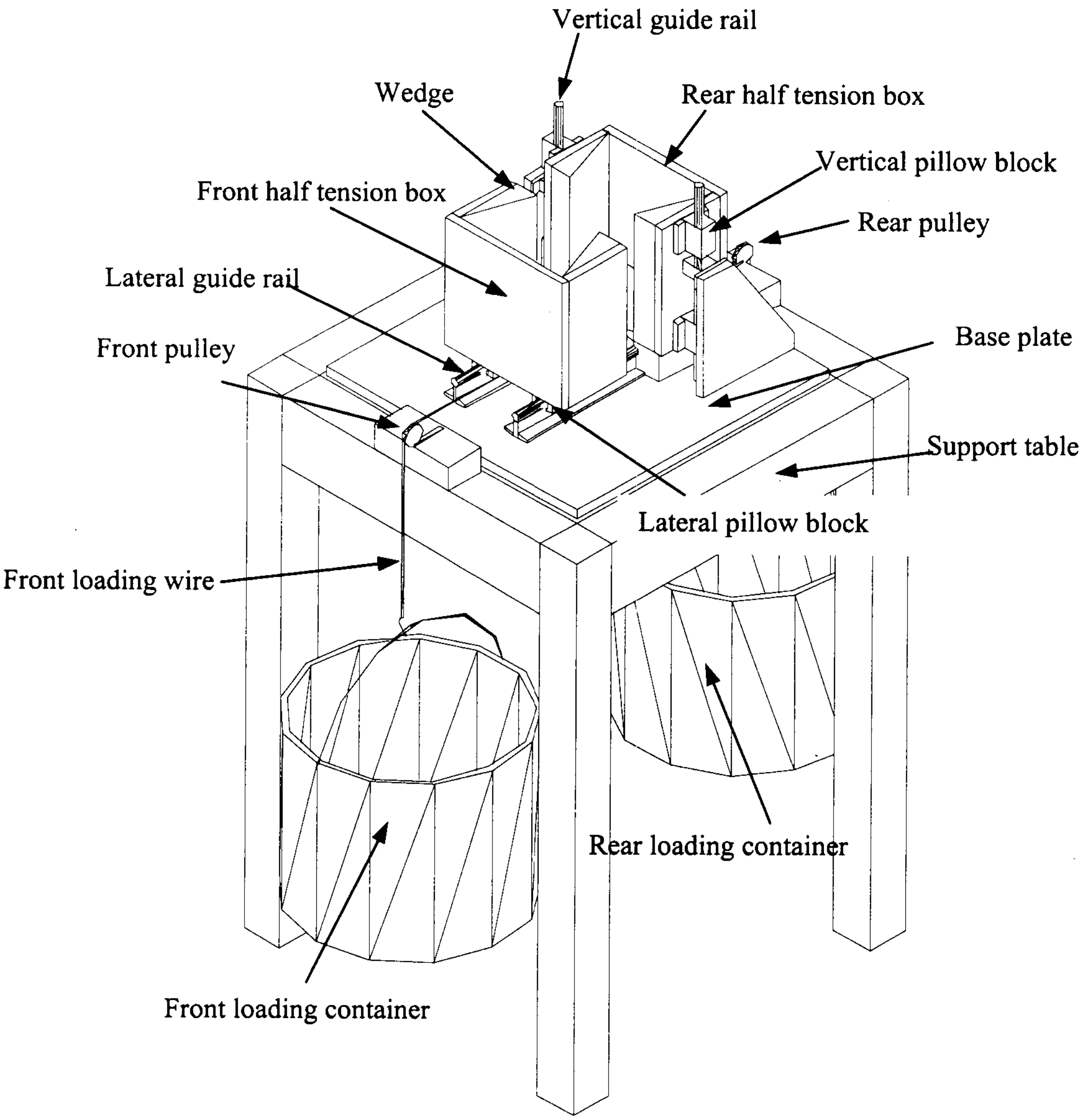


Fig. 3. Direct tension apparatus

3.2 Material Characterization

All specimens were prepared using F-75 Ottawa silica sand obtained from the Ottawa Silica Company. The material has a specific gravity of 2.65, maximum and minimum void ratios of 0.85 and 0.486, respectively. Two categories of F-75 Ottawa sand mixtures were prepared for the experiments. The first version of the sand (later referred to as F-75-C) was prepared by washing through a No. 200 sieve to remove particles smaller than 0.075 mm. After finishing a series of experiments on this sand, a second version (later referred to as F-75-F) was prepared by adding 2.0% of fines by weight. The reason for selecting a small amount of fines (2.0%) is that the inclusion of small amounts of fines, which may be produced by tumbling and abrasion of sand in the field, especially the wearing down of sharp edges, remains a concern regarding defining proper engineering properties of F-75 sand.

3.3 Specimen Preparation

The container consisting of front and rear compartments was first tightly taped to prevent the movement of the container assembly during compaction. Sand and water were then thoroughly mixed to provide a homogeneous specimen. Filtered water was used to avoid introducing other physico-chemical factors during mixing. Individual specimens were prepared within the container box in four lifts by compaction with a drop hammer furnished with an angular foot, which facilitates compaction in corner regions. In much the same way that a standard Proctor hammer is operated, the number of blows, the weight of the hammer and the drop height were controlled to achieve predictable and uniform specimen densities. During and after specimen preparation, thin plastic wraps were used to cover the top surface of the assembly to prevent evaporation of moisture.

3.4 Experimental Procedure

Loading was slowly and steadily applied by introducing water into the front loading container until failure occurred. The failure events were very brittle and visible, and they were manifested in terms of sudden movement or separation. The tensile strength was calculated by dividing the failure load by the separated area. Immediately after completion of each test, the density and moisture content of the entire sample were measured. For experiments on precompressed specimens, an overburden load calculated to induce an overconsolidation ratio (*OCR*) of 5 was imposed on the top of the specimen for durations of either 1 or 60 minutes. The overburden was then removed and the tension experiments were conducted as described earlier. By following these procedures, the tensile strength, water content, and relative density of the specimens were measured. Failure occurred at extremely small displacements (0.01 cm) and in a nearly perfectly brittle manner in all experiments with no discernable strain-softening slope or residual strength.

4. Results and Analysis

The direct tension experiments were conducted on specimens having three different relative densities, D_r (30%, 50%, 70%) and four different water contents in the range of 0.5%~4.0%. The results are summarized in Table 1. In these experiments, tensile strength, moisture content, and relative density were measured for each test. The magnitudes of the tensile strength of moist clean sand (F-75-C) and moist sand containing fines (F-75-F) were determined, and the influence of moisture content and relative density was analyzed. The fines and precompression (overconsolidation) effects on the tensile strength were also evaluated.

Table 1. Summary of direct tension test results

(a) F-75-C sand

Sample	w (%)	S (%)	D_r (%)	σ_t (Pa)
Loose1	0.46	1.73	32	409.68
Loose2	1.01	3.77	30	580.67
Loose3	1.07	3.96	28	586.11
Loose4	2.13	7.85	27	704.93
Loose5	4.04	14.83	26	873.03
Loose6	4.02	14.89	28	850.64
Medium1	0.46	1.91	52	473.35
Medium2	1.01	4.17	51	623.86
Medium3	2.05	8.37	49	886.48
Medium4	2.08	8.46	48	856.53
Medium5	4.11	17.04	52	1073.41
Dense1	0.47	2.15	71	498.52
Dense1	1.02	4.70	72	730.45
Dense1	1.04	4.74	70	732.94
Dense1	2.05	9.24	68	981.97
Dense1	3.89	17.53	68	1164.45
Dense1	4.06	18.00	65	1150.84

(b) F-75-F sand

Sample	w (%)	S (%)	D_r (%)	σ_t (Pa)
Loose1	0.47	1.76	30	425.51
Loose2	1.02	3.79	29	608.71
Loose3	2.05	7.56	27	811.37
Loose4	2.00	7.41	28	744.02
Loose5	4.03	14.99	29	951.11
Loose6	4.06	15.03	28	914.59
Medium1	0.46	1.91	52	460.17
Medium2	0.99	4.08	51	681.96
Medium3	1.00	4.15	52	697.69
Medium4	2.06	8.54	52	994.31
Medium5	4.02	16.50	50	1169.23
Dense1	0.41	1.89	72	524.13
Dense1	1.01	4.58	69	823.28
Dense1	2.03	9.16	70	1065.36
Dense1	2.03	9.25	70	1050.99
Dense1	4.00	18.12	69	1346.73

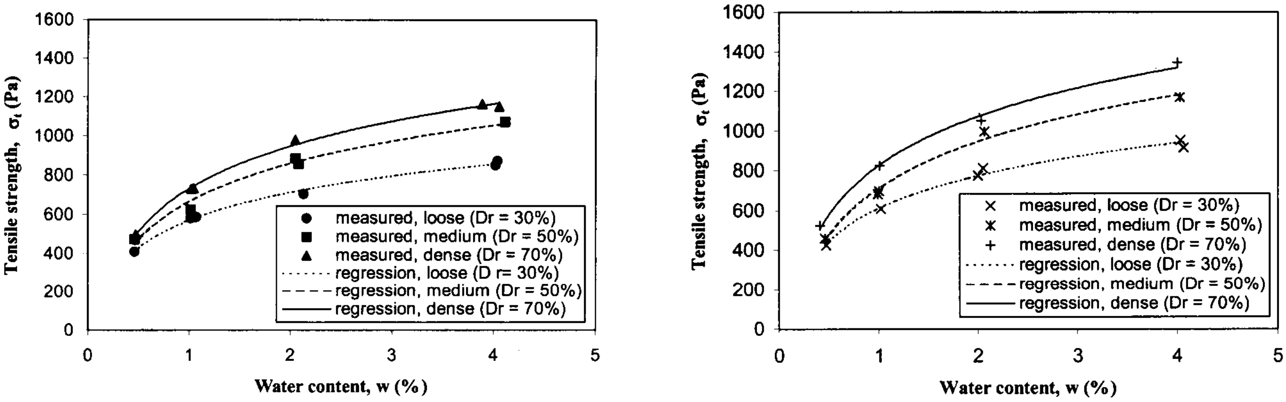
4.1 Effect of Moisture Content

The results of the experiments performed on F-75-C and F-75-F sands are shown in Fig. 4. The data clearly show that the tensile strength tends to increase as the water content increases. This can be explained by considering the capillary bonding forces between the particles. At low moisture levels, water-bridges form at the particle-particle contact points. This results in capillary bonding forces between the particles, which lead not only to cohesion, but also certain amounts of tensile strength in the soil. As discussed earlier, the total capillary bonding force consists of two components; the surface tension, F_S, and the force due to the negative capillary pressure in water-bridge, F_C. These two force components act together to generate tensile strength in the soil. As the moisture level increases, the water-bridges become more developed in the contact geometries, and the tensile strength increases.

4.2 Effect of Relative Density

Higher relative densities lead to more contacts between soil particles, thus increased number of water-bridges, and this causes higher measured tensile strengths, and this phenomenon becomes more pronounced as the moisture content increases (Fig. 4). The tensile strength varies with density because the density affects the coordination number (a measure of the number of particles that are in contact with one another and thus available for capillary bonding) for each particle and capillary action.

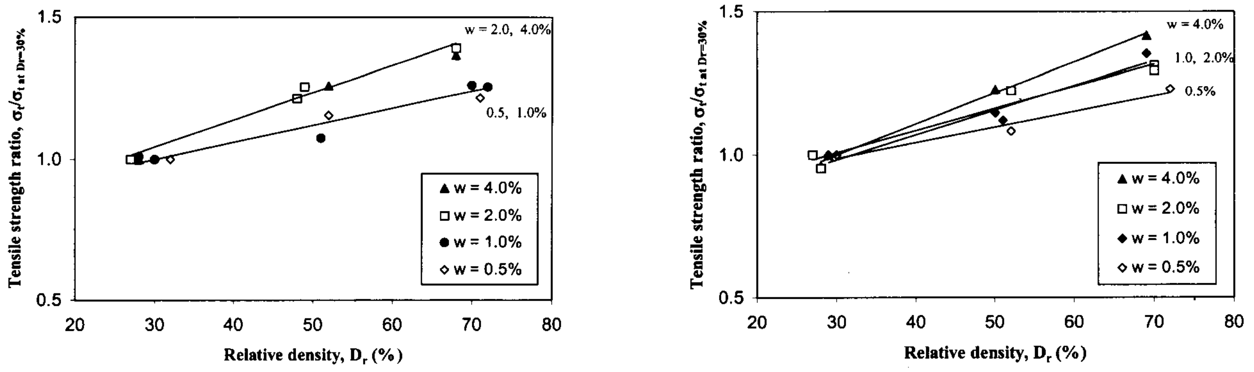
However, the influence of relative density on the tensile strength is diminished at low moisture levels. This is clearly shown in Fig. 5, which describes tensile strength ratio versus relative density. The data points were obtained by dividing the tensile strengths by the



(a) F-75-C sand

(b) F-75-F sand

Fig. 4. Relationship between tensile strength versus water content for different relative densities



(a) F-75-C sand

(b) F-75-F sand

Fig. 5. Relationship between tensile strength ratio versus relative density for different water contents

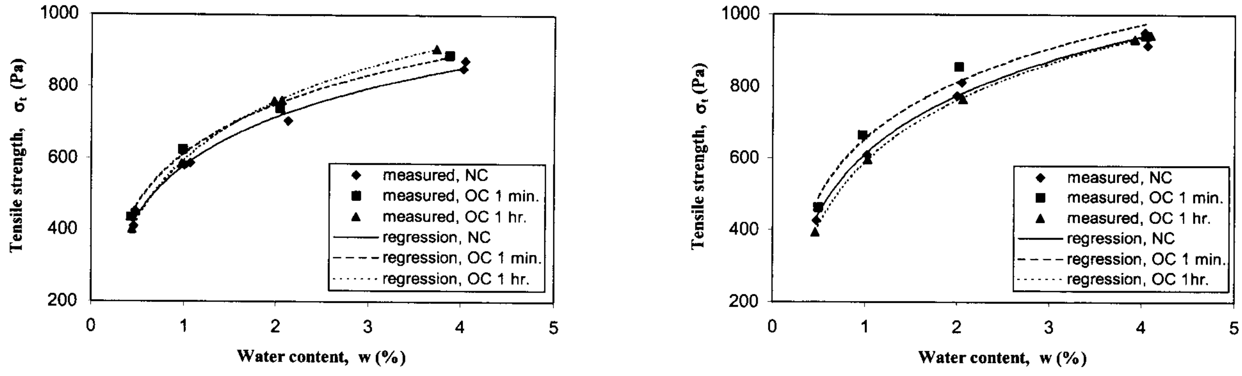
tensile strength of the loose specimen for each of different water contents. Approximated regression lines for the data are also shown. The slopes of the regression lines indicate increasing levels of tensile strength as the relative density increases. For F-75-C sand, the slope is relatively big for water contents in the range of 2.0 and 4.0% compared to the slope for low water content levels (below 1.0%). This means that the influence of relative density on the tensile strength is very much dependent on the water content level. The variations in tensile strength for the F-75-F sand are very similar to those observed for the F-75-C sand. As the moisture level decreases from 4.0 to 0.5%, the slope of the tensile strength ratio decreases as shown in Fig. 5 (b). The data support the assertion that the influence of relative density on the tensile strength gradually decreases with decreasing water content.

4.3 Effect of Precompression

Fig. 6 shows experimental data obtained for normally consolidated and precompressed loose specimens (D_r= 30%). Experiments on precompressed specimens were conducted with an *OCR* of 5 being applied for either 1 or 60 minutes. The 1 minute precompressed specimens for both F-75-C and F-75-F sands show higher tensile strength than the normally consolidated specimens in the entire range of water contents. This increase in strength is a result of both density changes and particle compression due to the overburden loading. The increased vertical stress gives rise to slightly increased tensile strength by pressing the particles closer together, thus increasing capillary action and surface tension in unsaturated sand specimens by decreasing the interparticle spacing, a, and increasing the filling height, *h* (Fig. 2). After removal of the overburden loading, the interparticle spacing will increase slightly, and not revert back to the original spacing, resulting in the small observed tensile strength increase.

For F-75-C sand, the tensile strengths obtained from the 60 minutes precompressed specimens are lower than the normally consolidated and 1 minute precompressed specimens at lower water content levels (w < 1.0%). Specimens precompressed for 60 minutes may lose moisture especially through the exposed boundaries. Another explanation for the observed lower tensile strength in the 60 minutes precompressed specimens may be due to the surface characteristic of the sand. Since the F-75 sand has ridges and fissures, moisture can migrate into them as a function of time, and the effect of moisture on the tensile strength may thus be decreased. These factors may affect all specimens depending on the moisture levels: at lower moisture levels (w < 1.0%) these effects are more critical.

As the water content increases, the tensile strengths for 60 minutes precompressed specimens increase, and at 4.0% of water content they are higher than the tensile strengths of the normally consolidated and 1 minute precompressed specimens. The increase in tensile strength due to the precompression might be the same for both



(a) Loose (D_r = 30%) F-75-C sand (b) Loose (D_r = 30%) F-75-F sand

Fig. 6. Tensile strength versus water content for different stress histories

the 1 and 60 minutes precompressed specimens, because the response of the density change of sandy soils is really instantaneous and almost constant and independent of the time duration of precompression. The increase in tensile strength of 60 minutes precompressed specimens may be caused by suction effects due to the moisture decrease in the specimen during testing. A soil may be rewetted or drained at a certain degree of saturation state (hysteresis effect). The resulting hysteresis can significantly change the capillary pressure with small changes in moisture. Although at low saturation levels (in the pendular state) the variation of the suction due to the hysteresis effect could not be observed for the soil water characteristic curve, it can be determined by the filter paper method developed in the field of soil science for measuring soil suction. The filter paper method is based on the assumption that a filter paper will come to equilibrium with a soil having a specific suction. Equilibrium can be reached by either liquid or vapor moisture exchange between the soil and the filter paper (Fredlund and Rahardjo, 1993).

For F-75-F sand, this suction effect was also expected at 4.0% water content, but the result showed that the tensile strength did not increase. The ability of fines to retain water is higher than that of coarse sands, thus the moisture may not vary much inside the specimens. It can be concluded that the loss in moisture due to the duration of the precompression can cause the decrease or the increase in the tensile strength, and it is totally dependent on the moisture levels of the specimens tested.

However, a close examination of Fig. 6 does not tend to indicate a strong linkage between *OCR*, duration of precompression and observed tensile strength. In general, it might be said that the stress history prior to failure in tension was strictly a secondary effect, and is less important than moisture content or initial density. This follows what would be expected for compressive strength in that these tests were measures of ultimate strength rather than stiffness, and it is generally acknowledged that density is the main parameter controlling strength, while stress history in combination with density tends to dictate stiffness.

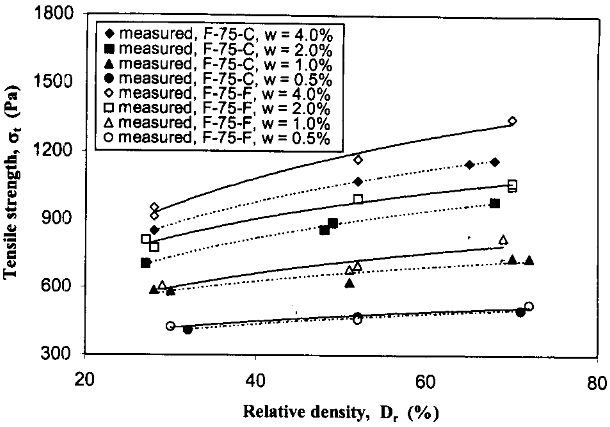


Fig. 7. Comparison of the relationship between tensile strength versus relative density for different water and fine contents

4.4 Effect of Fines

The effect of fines content on tensile strength is examined in Fig. 7, which shows tensile strength versus relative density for F-75-C and F-75-F sands at various water content levels. This figure clearly shows that the tensile strength of the sand containing fines is higher than that of the clean sand at the same relative density. This is likely due to the increased number of contacts caused by the fines, as well as the coating of larger particles by the finer particles. Further, capillary phenomena in a sand containing fines may become more pronounced, because fines can retain more water because of larger specific surface as well as their higher suction or capillary potential. Thus, fines can increase the degree of bonding action within the soil structure, resulting in higher tensile strengths.

However, the fines effects are also greatly influenced by the water content. The variation of the tensile strength of the sand with fines at the water content of 0.5% is almost identical to what is observed for the clean sand. Namely, no fines effects are observed at this level of water content. As the water content increases, the effect of fines on the tensile strength clearly appears, and it is more pronounced as the relative density increases.

5. Conclusions

This study was carried out to assess the tensile strength in quartz sand (F-75 Ottawa), and examine their variation as a function of moisture level, relative density, content of fines, and level of precompression. The following conclusions can be drawn for moisture contents in the range of $0.5\% < w < 4.0\%$.

The tensile strength of moist sand generally increased with increasing moisture content and relative density. The presence of fines also increased the degree of bonding action between the sand particles and resulted in higher tensile strengths. However, the influences of relative density and fines on the tensile strength are substantially dependent on the water content. These effects are reduced at low moisture levels ($w < 0.5\%$). Further, as the level and duration of precompression varied, tensile strength changed slightly, but precompression was judged to have less effect on tensile strength than moisture content, relative density, and fines content. The effects of relative density and fines were greatly influenced by the moisture condition. These effects were more pronounced at high water content levels.

References

1. Batiste, S. (1998), *Mechanics of granular materials at low confining stress*, M. S. thesis, University of Colorado at Boulder.
2. Fredlund, D. G. and Rahardjo, H. (1993), *Soil Mechanics for Unsaturated Soils*, John Wiley & Sons Inc., New York.
3. Heady, R. B and Cahn J. W. (1970), "An analysis of capillary forces in liquid-phase sintering of spherical particles", *Metallurgical Transactions*, Vol.1, pp.185-189.
4. Hong, W. P., IM, S. B. and Kim, H. T. (1993), "Treatments of Groundwater in Excavation Works for the Subway Construction", *Proc., 11th Southeast Asian Geotechnical Conference*, May 4-8, 1993, Singapore, pp.721-725.
5. Kim, T-H. (2002), "Experimental Investigations on Tensile strength of sand at low moisture contents" submitted to *Korean Geotechnical Society*.
6. Kim, T-H. (2001), Moisture-induced tensile strength and cohesion in sand, Ph. D. thesis, University of Colorado at Boulder.
7. Kim, S. K., Hong, W. P. and Kim, Y.M.(1992), "Prediction of Rainfall-Triggered Landslides in Korea", *Proc., 6th International Symposium on Landslides*, Christchurch, New Zealand, Feb.7-18, 1992, Vol.2, pp.989-994.
8. Pierrat, P. and Caram, H. S. (1997), "Tensile strength of wet granular materials", Powder Technology, Vol.91, pp.83-93.
9. Schubert, H. (1984), "Capillary forces-modeling and application in particulate technology", *Powder Technology*, Vol.37, pp.105-116.
10. Sture, S., Costes N. C., Batiste, S. N., Lankton, M. R., Alshibli, K. A., Jeremic, B., Swanson, R. A., and Frank, M. (1998), "Mechanics of granular materials at low effective stresses", *Journal of Aerospace Engineering*, ASCE, Vol.11, No.3, pp.67-72.

(received on Nov. 22, 2001, accepted on May 10, 2002)