Characterization of geomechanical and hydraulic properties of non-wettable sands

Caractérisation des propriétés géomécaniques et hydrauliques des sables non mouillants

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ABSTRACT: Wildfire, diagenesis, and organic contamination often induce the non-wettability in soils which in turn dominate physico-mechanical behaviours and control the contact angle and capillary pressure. This study presents the characterization of hydraulic and geomechanical properties of non-wettable sands using artificially synthesized hydrophobic sands. The critical hydrostatic pressure that initiates the fluid intrusion into dry hydrophobic sands is measured to estimate permeation boundary. Hydraulic conductivity values of both hydrophilic and hydrophobic sands under fully saturated condition are examined to evaluate the drag force effect. For geomechanical study, a series of constant water content compression tests are performed to assess the mechanical behavior on a reconstituted specimen of unsaturated non-wettable sands. The stress-strain relationships according to the degree of saturation under confining pressure condition are observed so as to derive the suction stresses. Results highlight that the surface modification at nano-scale determine the spatial configuration of water phase in pore space and its impact on fluid flow and strength with varying degree of saturation prevails.

RÉSUMÉ : Les incendies, la diagenèse et la contamination organique induisent souvent une non-mouillabilité des sols qui, à son tour, domine leurs propriétés physico-mécaniques et contrôlent l'angle de contact et la pression capillaire. Cette étude présente la caractérisation des propriétés hydrauliques et géomécaniques de sables non mouillants en utilisant des sables hydrophobes synthétisés artificiellement. La pression hydrostatique critique qui déclenche l'intrusion de liquide dans les sables hydrophobes secs est mesurée pour estimer la limite de perméation. Les valeurs de conductivité hydraulique pour des sables hydrophiles et hydrophobes en conditions totalement saturées sont examinées afin d'évaluer l'effet de la force de traînée. Pour l'étude géomécanique, une série d'essais de compression à teneur en eau constante ont été réalisés pour évaluer le comportement mécanique d'éprouvettes reconstituées de sable non saturé et non mouillant. Les relations contrainte-déformation en fonction du degré de saturation sous condition de confinement sont étudiées afin de dériver les contraintes de succion. Les résultats soulignent que la modification de surface à l'échelle nanométrique détermine la configuration spatiale de la phase aqueuse dans l'espace poreux et son impact sur l'écoulement du fluide et sur la résistance avec la variation du degré de saturation.

KEYWORDS: non-wettable sands, water repellency, friction angle, critical pressure, hydraulic conductivity
MOTS-CLÉS : sables non mouillants, hydrophobie, angle de frottement, pression critique, conductivité hydraulique

1 INTRODUCTION

Soils in nature often become hydrophobic (non-wettable) features, due to organic pollutants, natural hazards such as wildfire and environmental pollution accidents such as oil spill, whereas the accumulated geotechnical knowledge tends to be somewhat limited to hydrophilic (wettable) soils, particularly in the field of unsaturated soil mechanics.

Rodriguez et al. (1997) defined that the cause of the soil particles property which draw water is the high surface free energy. On the contrary, surface of hydrophobic soil particle excludes water and acts as a diffusion barrier which disturb substances diffuse by water (Goebel et al., 2007). Water layer formed on the hydrophilic soil particle is 10 times thicker than the water layer of the hydrophobic soil particle (Derjaguin and Churaev, 1986). Such differences in surface properties of soils result in clear distinctions even in macro scale (Frattolillo et al., 2005; Nguyen et al., 1999). Therefore, the surface wettability at particle scale controls the macro scale manifestation in soils.

Previous studies have been carried out so as to examine the relationship between the suction and the shear strength using the direct shear test for natural soils (e.g., Donald, 1956; Escario, 1980; Escario and Saez, 1986; Gan et al., 1988; Kim et al., 2010a), exhibiting that the suction developed at inter-particle contact causes the unique evolution of shear strength in natural soils. The degree of saturation for both hydrophilic and hydrophobic sands imposes the different evolution of thermal and electrical conduction as well as the friction angle (Byun et al., 2011; Kim et al., 2010b), attributed to the surface wettability.

This paper presents the series of experimentation to capture the surface wettability effect with the scope of hydraulic and geomechanical behaviors of both hydrophilic and hydrophobic soils. Moreover, it is examined on how the existence of the meniscus water affects the shear behavior using a direct shear apparatus.

2 EXPERIMENTAL STUDY

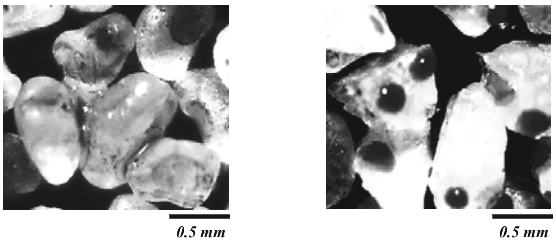
2.1 *Materials*

The granular materials used in this study were Jumunjin sands (specific gravity G_s=2.59, maximum porosity n_{max}= 0.465, minimum porosity n_{min}= 0.375). This materials are reletively uniformized (coefficient of uniformity C_u=1.16) with the mean particle size D_{50}=0.5mm. Sands without any treatment were tested for wettable (hydrophilic) samples whereas the non-wettable samples were sands chemically treated by silylation process (Zycosoil manufactured by Zydex industries, dilluted ratio=1:100 with water). Cleaned sands were fully submerged within the reactive solution and the reaction was allowed for 72 hours at room temperature condition. The recation formed

Alkylsiloxane on the particle surface with molecular level. Then, the mixture of sands and solution was oven-dried at 80°C.

2.2 *Optical observation*

Water distribution in hydrophilic and hydrophobic sand was observed by an optical microscope. Water exists mainly at the inter-particle contacts whereas hydrophobic sand induces the formation of water blobs on the surface attributed to the non-wettability (Figure 1). In order to obtain the contact angle, the glass slide was simultaneously treated with silane. Water droplets were dropped both on the non-treated glass slide and treated glass slide to observe the contact angle (θ) respectively (Figures 1-c and 1-d). The contact angle of hydrophobic surface is 85^{o} which is more than six times higher than that of hydrophilic sand.
Large contact angle indicates that the soil has large interfacial tension between soil and water. Therefore meaning the soil surface has high hydrophobicity.



(a) Spatial distribution of water in the wettable sands
(b) Spatial distribution of water in the non-wettable sands

(c) Contact angle on the wettable surface (~13°)
(d) Contact angle on the non-wettable surface (~85°)

Figure 1. Optical observations of water droplet formed on the weattable and non-wettable samples in the micro scale.

2.3 *Hydraulic properties*

2.3.1 *Critical hydrostatic pressure test*

Water needs to overcome the capillary pressure in hydrophobic sand so that the critical pressure exist over which water begins permeating into pore space. The experiment was conducted by using various particle sizes of non-wettable sands (Ottawa 20-30, Jumunjin sands and Ottawa F110). Dry samples seat in a cylinder with diameter 7 cm, height 15 cm. The water pressure is increased gradationally by 1 mm interval, and the height is measured when the water starts to permeate.

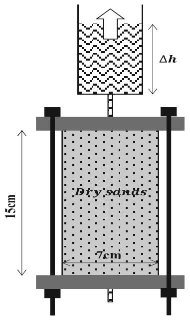


Figure 2. Experimental configuration of the critical hydrostatic pressures of non-wettable sands.

Figure 2 show the experimental configuration. The test was repeated three times for each specimen.

2.3.2 *Hydraulic conductivity test*

Although it is evident that the hydrophobic sand tends to repel water phase at unsaturated condition, caused by the modified surface wettability, the assessment of hydraulic conductivity at fully saturated condition is still required. Both hydrophilic and hydrophobic sands are subjected to constant head testing to obtain hydraulic conductivity values. The hydrophobic sands are forced for thoroughly mixing with water to attain 100% degree of saturation. The 147cm of head is maintained to the cell with the diameter of 15 cm and height 50 cm. The drained water was collected for 3 minutes and measured the weight

2.4 *Compression test*

A series of the direct shear tests were carried out under a constant pressure condition. The soil sample used was Jumunjin sand. The circular specimen is 60 mm in diameter and 20 mm in height, and has the relative density of about 75% for the maximum dry density. In case of a natural dried condition, the sand specimens were prepared by the air pluviation method. The vertical stresses of 20, 50, 80 kPa in the consolidation process were loaded. On the other hand, the sand specimens according to the degree of saturation under the unsaturated condition were prepared by the static compaction method. The vertical stress of 50 kPa in the consolidation process was loaded. The opening of 0.2 mm between the lower and upper shear boxes was set. The shearing rates of the natural dried condition and the unsaturated condition were 3.3x10^{-4} mm/sec and 3.3x10^{-5} mm/sec, respectively.

3 RESULT AND DISSCUSSION

3.1 *Hydraulic properties*

The critical pressure sharply increases as the particle size decreases (e.g., the corresponding size of pore throat should decrease) in Figure 3. The denial of water permeation acts as a hydraulic barrier for a given critical pressure while it may cause the surface erosion. Once the water begins permeating, the preferential flow is predominant by forming fingering. The evolution of critical pressure follows the reciprocal relationship between capillary pressure and pore radius defined in Young's equation.

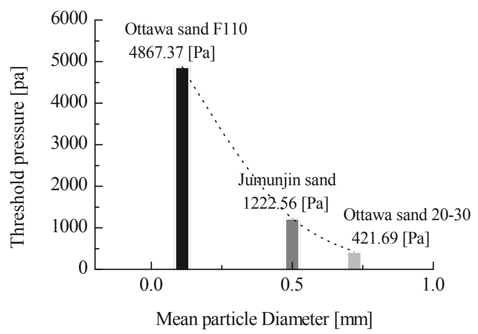


Figure 3. Critical hydrostatic pressures of non-wettable sands

The estimated hydraulic conductivity values increases with porosity whereas there is no noticeable difference between two specimens. It may be attributed that the surface modification by organic materials may not reduce the drag force in hydrophobic sands. It is noted that the feasibility of 100% saturation for hydrophobic sand is quite low so that the gathered hydraulic conductivity delineates the upper bound.

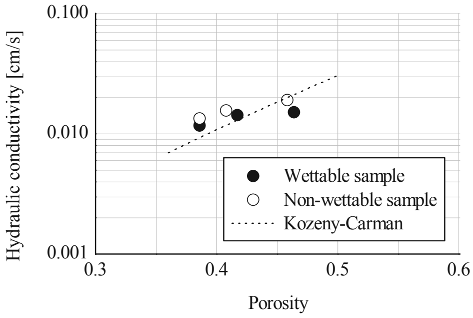


Figure 4. Hydraulic conductivity varied with porosity of wettable and non-wettable sands.

The dotted line in Figure 3 is made based on the Kozeny-Carman equation (Bear, 1972; Carman, 1956)

$$k = \frac{\rho g}{\mu} \cdot \frac{n^3}{(1-n)^2} \quad (1)$$

where ρ is the density of water, g is gravitational acceleration, and μ is the viscosity. The estimated value obtained by Kozeny-Carman equation show similar range and aspect to the values from the experiment, confirming validity of the experiment.

Wettable samples tend to adsorb water on the surface due to relatively strong capillary effect. On the other hand, non-wettable samples which have relatively low surface free energy, have characteristics that exclude water. So that the water flow at the interface between the particles is affected by the repellency of capillary pressure. It allows predicting faster fluid flow in non-wettable sands than the fluid flow in wettable Jumunjin sand. Results show that the hydraulic conductivity values of both soils run with nominal difference, which highlights that the wettability effect at particle scale seems negligible for fluid flow at pore scale.

3.2 *Geomechanical properties*

From the results of a series of the direct shear tests using the jumunjin sand under the natural dried condition, the cohesion and the angle of internal friction for the hydrophilic and hydrophobic sands were c=0, φ=36.1°, and c=0, φ=27.9°, respectively as shown in Figure. 5. The difference in friction angle is attributed to the surface modification grafted by organic component. The existence of silane on particle surface serves as lubricant to reduce the friction angle.

Figure 6 shows the comparison of the shear strength due to the suction between the hydrophilic and hydrophobic sands. The formation of meniscus inducing the suction pressure increases the shear strength of hydrophilic sand while the hydrophobic sand imposes less defined meniscus at the inter-particle which causes the quasi-constant value of strength regardless of saturation. It emphasizes the role of suction in hydrophilic sands on the geomechanical properties. This tendency can be obviously observed through the comparison of the maximum shear stresses between the hydrophilic and hydrophobic sands with varying degree of saturation in Figure. 7.

In case of the hydrophobic sand, the maximum shear stress at varying degree of saturation follows the value at dry condition without significant deviation. On the other hand, the maximum shear stress of hydrophilic sand is captured at ~ 50% degree of saturation. Note that the previous research on the evolution of maximum shear stiffness (G_{max}) is attained at ~ 5~10% degree of saturation (Byun et al., 2011). Although the negative capillary pressure should increase with decreasing degree of saturation, the different strain regime between the small-strain stiffness and large-strain strength may result in the different peak saturation.

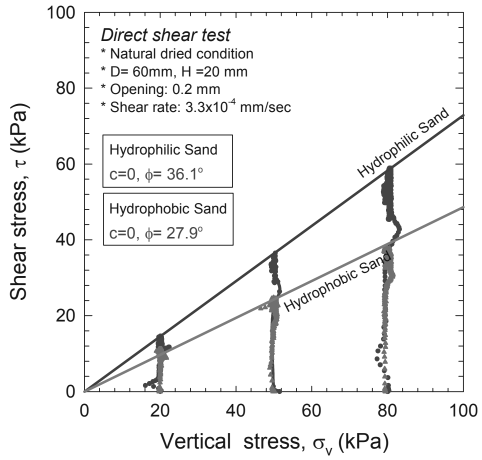


Figure 5. The relationship between vertical stress and shear stress under the natural dried condition.

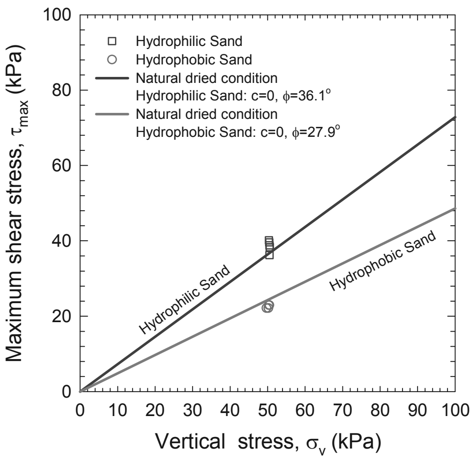


Figure 6. Comparison of the shear strength due to the suction between the hydrophilic and hydrophobic sands.

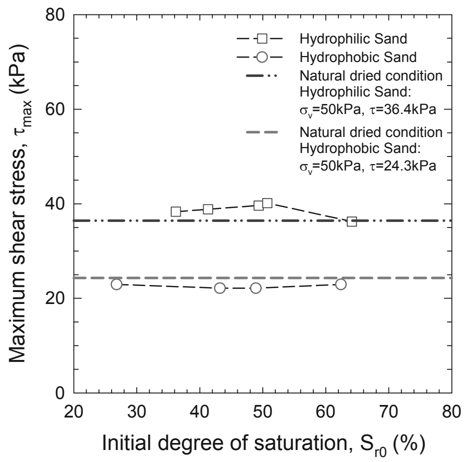


Figure 7. Variation of the maximum shear stresses between the hydrophilic and hydrophobic sands according to the initial degree of saturation.

4 CONCLUSIONS

Soils in geotechnical engineering have been regarded as the wettable condition while the non-wettable soils prevail in nature.

The water repellency and corresponding hydraulic and geomechnical aspects needs to be adopted in engineering practice to correctly estimate the overall behaviors. In this study, wettable and non-wettable specimens were artificially synthesized to preliminarily evaluate their basic properties. The following observations can be made:

1. The critical hydraulic pressure above which water begins permeating follows the Young's formula. The non-wettable sand exhibits the distinct water repellency and the critical pressure increases with decreasing pore size.
2. The hydraulic conductivity values of both hydrophilic and hydrophobic sands appear alike at fully saturated condition. Although the hydraulic conductivity with varying degree of saturation requires further study, the surface wettability may not affect the overall fluid flow behavior at macro-scale.
3. From a series of the direct shear tests using the hydrophilic and hydrophobic sands, the surface modification at sub-micrometer scale clearly reduce the shear strength of hydrophobic sand at dry condition. The effect of degree of saturation is minimized for hydrophobic sand due to the less defined meniscus at inter-particle contacts. Yet, the shear strength of hydrophilic sand evolves with varying degree of saturation, exhibiting the maximum value at ~ 50%.

5 ACKNOWLEDGEMENTS

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