Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0860

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Mechanical behaviour of polymer-coated sands

Comportement mécanique des sables avec revêtement polymèrique

D. Liu
The University of Hong Kong, Hong Kong SAR, China

S.D.N. Lourenço
The University of Hong Kong, Hong Kong SAR, China

ABSTRACT: The water repellent behaviour of polymers such as polydimethylsiloxane enables them to be utilized as coatings in grains to control wetting, with potential applications in barriers and fills. However, little exists on the mechanics of the polymer-coated soils. Here, the mechanical behaviour of a polymer-coated sand subjected to two mass ratios of dimethyldichlorosilane (0.05% and 3%) was investigated at the macro scale via the triaxial tests. Dimethyldichlorosilane is used to treat the particles surfaces and produce the water repellent polydimethylsiloxane coatings. Selected results from the triaxial tests show that when the mass ratio of dimethyldichlorosilane is low (i.e. 0.05%), the stress-strain behaviour is similar to that of natural sand. Therefore, the effect of the thin polymer-coatings on the mechanical behaviour is negligible. While when the mass ratio of dimethyldichlorosilane is high (3%), the reduction of shear strength is evident. Furthermore, quantification of the particle surface topologies prior to and after the triaxial tests clearly reflects the damage and crush of the polymer-coatings when the polymer-coated particles are subjected to relatively high stresses.

RÉSUMÉ: Le comportement hydrophobe de polymères tels que le polydiméthylsiloxane permet de les utiliser comme revetements dans les sols pour contrôler la infiltration, avec des applications potentielles dans les barrières et les remplissages. Ici, le comportement mécanique d'un sable revêtu de polymère soumis à deux rapports de masse de diméthyldichlorosilane (0,05% et 3%) a été étudié à l'échelle macro via les tests triaxiaux. Le diméthyldichlorosilane est utilisé pour traiter les surfaces des particules et produire les revêtements polydiméthylsiloxanes hydrofuges. Les résultats sélectionnés des essais triaxiaux montrent que lorsque le rapport en masse du diméthyldichlorosilane est faible (c'est-à-dire 0,05%), le comportement contrainte-déformation est similaire à celui du sable naturel. Tandis que lorsque le rapport en masse du diméthyldichlorosilane est élevé (3%), la réduction de la résistance au cisaillement est évidente. La quantification des topologies de surface des particules avant et après les tests triaxiaux reflète clairement les dommages et l’écrasement des revêtements de polymère lorsque les particules revêtues de polymère sont soumises à des contraintes.

Keywords: Shear strength; laboratory tests; particle-scale behaviour; PDMS coatings; water repellency

1 INTRODUCTION

Synthetic water repellent granular materials exhibit different hydraulic and mechanical behaviour from wettable granular materials (e.g. Byun et al., 2011; Lee et al., 2015). Potential geotechnical applications of artificial water repellent soils include their use in barriers or as fill materials (Zheng et al., 2017) among others. Therefore, predicting the mechanical behaviour of the polymer-coated water repellent soils is essential and is currently lacking in the literature.

From the literature addressing the mechanical behaviour of water repellent soils, Lee et al. (2015) and Byun et al. (2011) showed that the shear stress of water repellent soils decreases with the rise of the concentration of an organo-silane (n-octyltriethoxysilane). However, previous studies ignored the possible impacts of external forces on the polymer-coated granular materials. The polydimethylsiloxane (PDMS) coatings is a silicone rubber with water repellent behaviour. Lötters et al. (1997) showed that the mechanical properties of PDMS are influenced by the temperature and preparation conditions, with the Young′s modulus fluctuating between 360 kPa and 870 kPa.

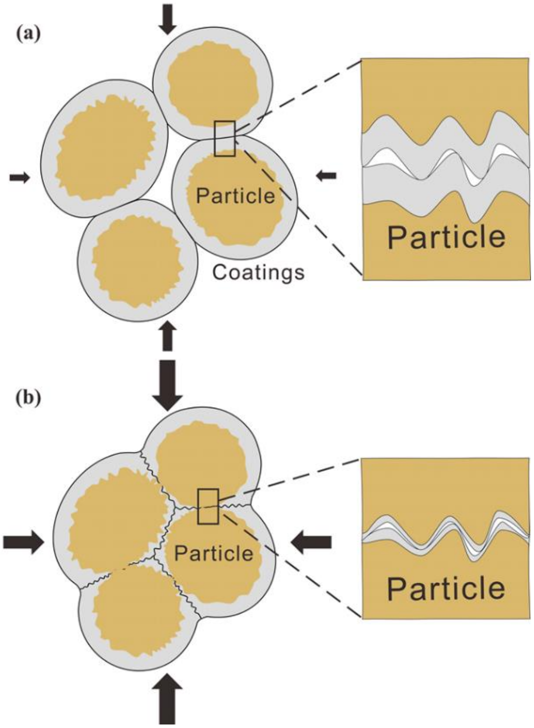


Figure 1. Possible mechanism controlling the mechanical behaviour of the polymer-coated granular material (not drawn to scale): (a) under relatively low stress; (b) under relatively high stess

Given the extremely low Young′s modulus of PDMS, it was hypothesized that as the polymer-coatings could be damaged during tests with an increase in the stresses. As shown in Figure 1a, when a polymer-coated granular material is subjected to relatively low stresses in the compression triaxial tests, the polymer-coatings which cover the grains remain intact with a smooth particle surface. On the contrary, as shown in Figure 1b, the relatively high stresses in the compression triaxial tests would crush the polymer-coatings, with the rough particle surface being identified.

The effect of the particle shape on the mechanical behaviour of granular materials is substantial (e.g. Yang and Luo, 2015). Moreover, the effect of particle roughness on the mechanical behaviour of granular materials is also significant (e.g. Nardelli et al., 2017). However, the research gaps subsists on the effect of the polymer-coatings on the particle shape, particle roughness and consequent effect on mechanical behaviour.

This work aims to present selected results on the (1) effect of polymer-coatings on the mechanical behaviour (by the compression triaxial apparatus), in both drained and undrained tests; (2) the effect of the polymer-coatings on the particle shape parameters (by QICPIC); (3) the the effect of polymer-coatings on particle surface (by white light interferometry) and identify the possible damage of the polymer-coatings under high stress. A detailed investigation into the critical state of polymer-coated sand is provided in Liu et al. (2018).

2 MATERIALS AND METHODS

2.1 Drop shape analyser and sessile drop method

The SDM can be used in soils to directly measure the contact angles (Figure 2a) (Leelamanie et al., 2008), which is the angle between the intersection of the liquid/solid interface and the liquid/air interface and is used to quantify the water repellency. A higher contact angle indicates higher water repellency and the water repellency threshold is 90˚.

In the SDM, loose soil particles are sprinkled on top of glass slides, followed by fixing on the stage of the drop shape analyser (DSA 25, KRÜSS GmbH, Germany) (Figure 2b). A droplet is deposited through the micropipette, followed by the analysis of the droplets shapes and contact angles through a semi-automatic technique proposed by Saulick et al. (2017).

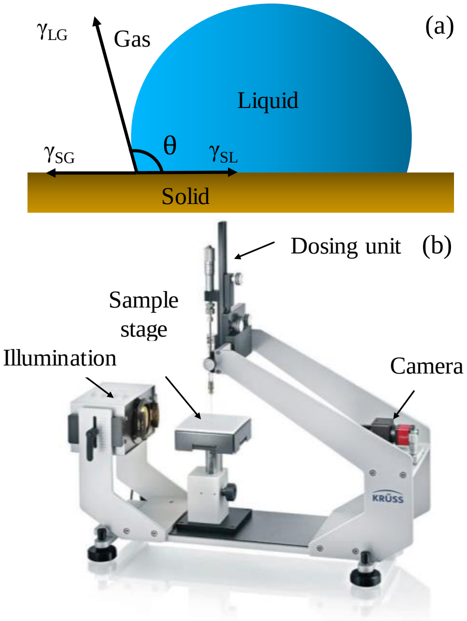


Figure 2. Sessile Drop Method: (a) Contact angles; (b) Drop Shape Analyser (DSA 25, KRÜSS GmbH, Germany)

2.2 Dynamic image analyser and white light interferometry

A dynamic image analyser (QICPI, Sympatec GmbH, Glausthal-Zellerfeld, Germany) was used to quantify the three particle shape parameters, i.e. aspect ratio (AS), convexity (C), sphericity (S) for testing materials, following the precedure proposed by Yang and Luo (2015).

The white light interferometer (Fogale Nanotech, France) is used to measure and quantify the particle surface. Both S_q and S_a are used to represent the roughness of grains, following the procedure proposed by Yao et al. (2018).

2.3 Compression triaxial apparatus

Undrained and drained tests were conducted to investigate the mechanical behaviour of water repellent sand. All test specimens were prepared by the moist tamping method using under-compaction technique (Ladd, 1974). Back pressure fluctuates from 600 kPa to 800 kPa which meets the requirement from BS 1377-8-1990 with the sample being considered fully saturated when the B-value is greater than 0.98.

2.4 Natural sand

Fujian sand (Sinoma, China), a quartz sand, has been selected for this research. In this research, the particle size of the testing material is therefore strictly controlled in order to remove the effect of PSD on the mechanical behaviour, with the particle size ranging from 1.18 m to 2 mm.

2.5 The water repellent polymer-coated sands

DMDCS is a hydrophobizing agent which has been used in the treatment of soils (e.g. Ng and Lourenço, 2016). Zheng et al. (2017) showed that the contact angles of the polymer-coated sand increase in the first 3 days to allow for the completion of the chemical reaction (i.e. release of HCl) and maintain constant after that. The relationship between the mass ratio of DMDCS and the magnitude of soil water repellency is determined via contact angle measurements. Samples were prepared to different mass ratios by adding desired volumes of DMDCS solution to desired mass of natural sand.

To obtain consistent and reliable results, all testing (i.e. the compression triaxial tests, contact angle and roughness measurements, the inter-particle loading tests) was conducted after a 3-day waiting period. Figure 3 shows the relationship between contact angles and mass ratio of DMDCS, the results show that the maximum contact angle is approximately 114° when the mass ratio of DMDCS is higher than 0.05%. Taking 0.05% as a threshold, three materials were selected for this research: (1) natural sand, with particle size between 1.18 mm and 2 mm, without any treatment (i.e. wettable), (2) the polymer-coated sand (0.05% mass ratio), representing the lower mass ratio threshold to induce extreme water repellency, (3) the polymer-coated sand (3% mass ratio), to investigate the effect of the polymer-coatings thickness with water repellency remaining as high as in 0.05%. It is assumed that a higher mass ratio of DMDCS will produce thicker polymer-coatings.

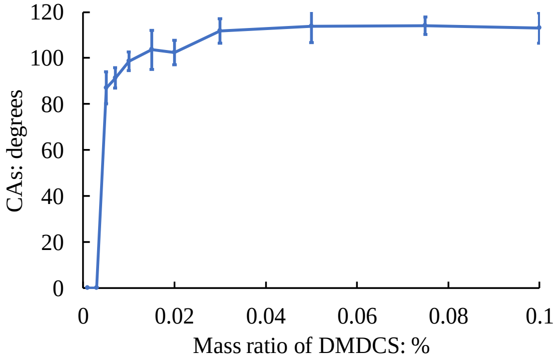


Figure 3. The relationship between mass ratio of DMDCS and contact angles

Given the inability in directly measuring the thickness of the polymer-coating, the polymer-coating thickness of the polymer-coated sand (i.e. 0.05%, 3%) is quantified through a technique proposed by Bardet et al. (2014) with the following assumptions: (1) the sand particles have an ideal spherical shape, (2) the thickness for each particle is uniform. Following Bardet and Sanchez (2011), the amount of the polymer-coating is described through the polymer content w' in Equation (1).

$$w' = \frac{m_{PDMS}}{m_s} \tag{1}$$

Where m_{PDMS} is the mass of the polymer-coating, m_s is the mass of the dry soil. Bardet et al. (2014) used N_i (D_i, P_i) to estimate the thickness of the polymer-coatings. N_i is the number of particles of certain diameter D_i, P_i is the percent by weight for a certain diameter D_i. The relationship between the polymer content w', diameter D_i and thickness of the polymer-coating t_i is established as shown in Equation (2).

$$\frac{p_{PDMS}}{p_s}\left[\sum_{i=1}^{N} p_i\left(1+\frac{t_i}{R}\right)^3 - 1\right] \tag{2}$$

Where R_i is the radius of particle, p_s is the unit mass of particle, p_{PDMS} is the unit mass of PDMS. In this research, the thickness of the polymer-coatings is estimated based on Equation (2). For a DMDCS mass ratio of 0.05%, the thickness of the polymer-coating varies between 163-277 nm. For a DMDCS mass ratio of 3%, the thickness of the polymer-coating varies between 9.636-16.331 µm. The polymer-coatings are rather thin compared to the grain size of particle. The G_s of three testing materials showed no influence of the coatings (i.e. 2.66).

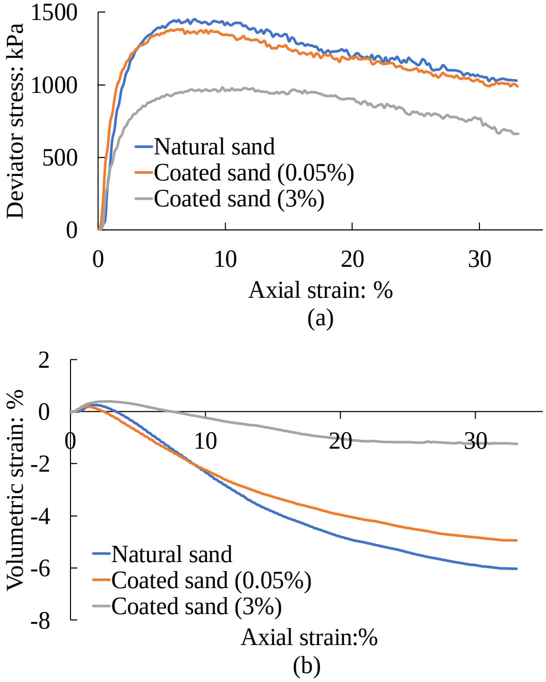
2.6 Testing programme

Standard undrained and drained tests were conducted on three materials (i.e. natural sand, 0.05% polymer-coated sand, 3% polymer-coated sand) with various void ratio (i.e. 0.62-0.74) and p'_0 (i.e. 50 kPa, 100 kPa, 200 kPa, 300 kPa, 500 kPa).

The QICPIC is used to quantify the change of particle shape due to the presence of the polymer-coatings. The same three testing materials were used. For each testing material, the particle shape measurement tests were repeated at least 10 times to ensure reproducibility and remove possible random error.

To investigate the effect of the polymer-coatings on the particle surface and possible variation of particle surface topologies when subjected to high stress level. The particle surface topologies were quantified by optical interferometry for natural and the polymer-coated sands (3%) collected prior to and after the compression triaxial tests following the techniques proposed Yao et al. (2018).

After each test, sand particles dried to the air followed by the quantification of the surface roughness under various p'_0 and simialr post-consolidation void ratio.



(a)

(b)

Figure 4. Drained shearing behaviour (p'_0 =500 kPa, e_p = 0.646): (a) stress-strain curves; (b) volumetric strain

3 RESULTS

3.1 *The effect of polymer-coatings on shearing behaviour*

Typical results of drained tests are presented to determine the effect of the polymer-coatings on shearing behaviour. Figure 4 shows the stress-strain curves for three testing materials (i.e. natural sand, 0.05% coated sand, 3% coated sand) at similar conditions (p'_0= 500 kPa, $e_p \approx$ 0.646).

In general, the drained tests reveal that the patterns of the stress-strain behaviour curves for the three materials are similar. All specimens show dilative and strain hardening behaviour without any strength loss. However, the shear strengths of the polymer-coated specimens are smaller than that of natural sand. Figure 5.5a shows that for a DMDCS mass ratio of 0.05%, the shear strength of the polymer-coated sand (0.05%) is approximately 5% smaller than that of natural sand. The peak shear strengths are clearly observed in both polymer-coated (0.05%) and natural sand when strains are approximately 7%. In contrast, when the mass ratio is 3%, an approximately 30% reduction of shear strength of polymer-coated sand (3%) is observed. In this case, no clear peak shear strength of the polymer-coated sand (3%) can be found. Therefore, given the identical testing conditions, the reduction of shear strength is larger with the increase of mass ratio of DMDCS.

The volumetric strain responses from the drained tests exhibit a similar dilative tendency. Figure 4b shows that all three specimens tend towards the critical state in which the volumetric strain is constant at axial strains of 25%-35%.

3.2 *Results of particle shape analysis*

Three types of testing materials (i.e. natural sand, 0.05% polymer-coated sand, 3% polymer-coated sand) were used to investigate the possible effect of polymer-coatings on particle shape.

Figure 5 quantifies the effect of polymer-coatings on the particle shape parameters. The aspect ratio of natural sand, polymer-coated sand (0.05%), polymer-coated sand (3%) is 0.7444, 0.7452, 0.7445, respectively, with no significant difference observed. In addition, the convexity of natural sand, polymer-coated sand (0.05%), polymer-coated sand (3%) is 0.9736, 0.9731, and 0.9720, respectively. The sphericity of natural sand, polymer-coated sand (0.05%), polymer-coated sand (3%) is 0.8875, 0.8866 and 0.8813, respectively. The results indicate that the effect of polymer-coatings (i.e. thin and thick polymer-coatings) on particle shape parameters is negligible which could be attributed to the thickness of the polymer-coatings being negligible compared to the grain size.

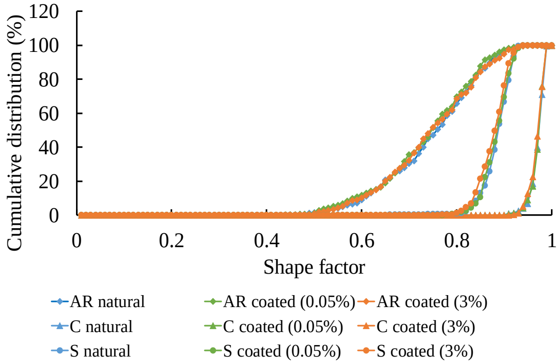


Figure 5. The effect of polymer-coatings on particle shape parameters

3.3 *Results of particle surface analysis*

The particle surface of natural and polymer-coated sand (3%) prior to and after the compression triaxial tests was also quantified to assess the damage of polymer-coatings under stress. Given the nano to micron-sized thickness of the polymer-coatings, the polymer-coated sand (0.05%) was not selected for the analysis of the particle surface.

3.3.1 *The effect of polymer-coatings on particle surface*

The surface topologies of natural sand and polymer-coated sand (3%) are shown in Figure 6, with Figure 6a revealing a rough surface for natural sand, while Figure 6b shows a smoother surface topology for the polymer-coated sand (3%). The roughness measurements show that the mean S_a and S_q of natural sand are 407.307 nm and 580.76 nm, respectively. While the mean S_a and S_q of polymer-coated sand (3%) are 95.526 nm and 189.38 nm, respectively. The alteration of roughness is significant which is attributed to the presence of the thick polymer-coatings (i.e. 3%).

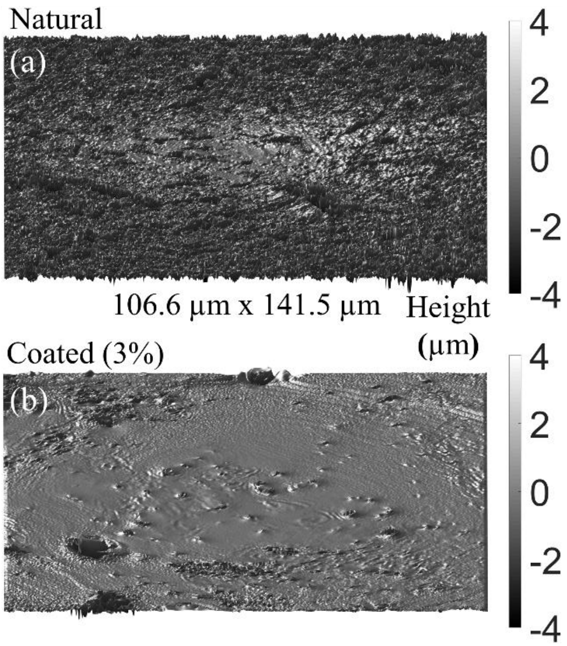


Figure 6. Surface roughness: (a) natural sand; (b) polymer-coated sand (3%)

3.3.2 *The effect of stress level on particle surface*

(1) Natural sand

Roughness of the natural sand prior to and after the compression triaxial tests in both drained and undrained conditions were measured and recorded. Figure 7 shows that the roughness (i.e. S_a, S_q) of natural sand remains constant regardless of the stress level. For instance, for the natural sands collected from drained triaxial tests when p'_0 are 50 kPa, 100 kPa, 200 kPa, 300 kPa, 500 kPa, the S_a of the natural sands are 404.16 nm, 391.05 nm, 392.70 nm, 400.09 nm, 397.84 nm, respectively, which are similar to that of natural sand prior to testing (394.35 nm).

Roughness of the polymer-coated sand (3%) prior to and after the compression triaxial tests in both drained and undrained condition was also quantified. Significant variation of roughness is observed from the surface topologies for polymer-coated sand (3%) when subjected to various p'_0.

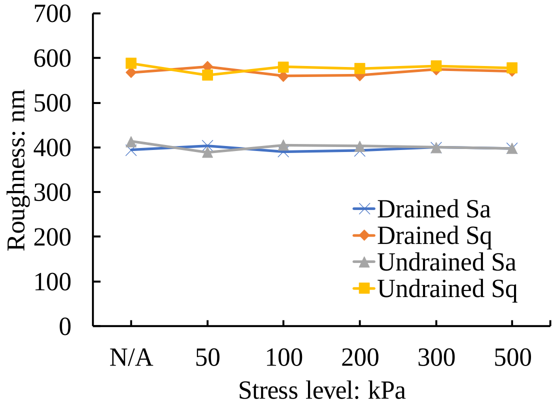


Figure 7. Roughness of natural sand at increasing stress levels

Figure 8 shows that the effect of stress level on the roughness of polymer-coated sand (3%) is significant, both S_a and S_q of the polymer-coated sands (3%) increase and converge towards those of natural sand (i.e. 407.307 nm and 580.76 nm) with the rise of p_0', which reflects the damage of polymer-coatings under stress. For instance, S_q of polymer-coated sand (3%) prior to testing is 189.38 nm, while the S_q of polymer-coated sand (3%) subjected to 50 kPa, 100 kPa, 200 kPa, 300 kPa, 500 kPa is 207.31 nm, 222.01 nm, 278.06 nm, 332.85 nm, 400.16 nm, respectively.

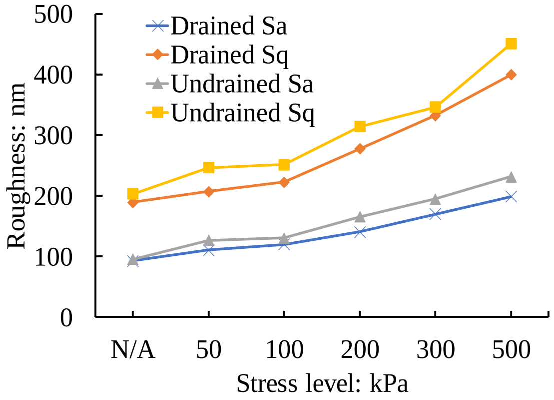


Figure 8. Roughness of polymer-coated sand (3%) at increasing stress levels

Figure 9 shows the typical surface topologies of polymer-coated sand (3%) when subjected to two different stress level (i.e. $p_0' = 100$ kPa, $p_0' = 500$ kPa). A significant contrast and damage of the polymer-coatings can be identified.

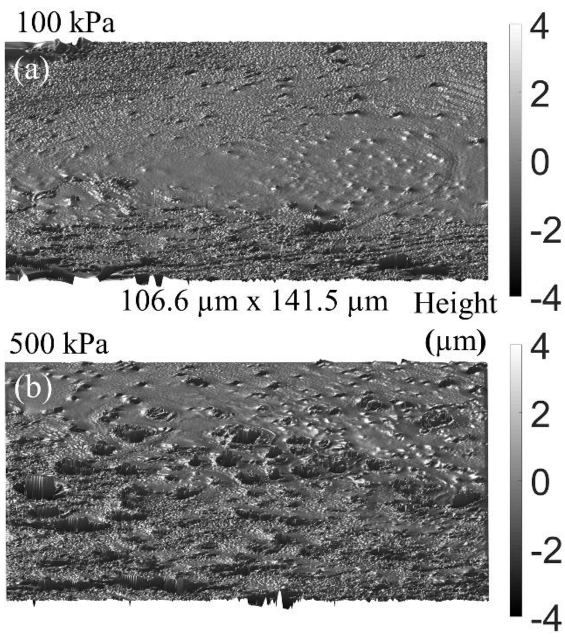


Figure 9. Effect of stress level (100 kPa and 500 kPa) on particle surface of polymer-coated sand (3%)

4 CONCLUSIONS

The present paper investigates the mechanical behaviour of polymer-coated sands by presenting selected results from three testing materials (natural sand, 0.05% and 3% polymer-coated sand) by compression triaxial testing. For a mass ratio of 0.05% DMDCS, the shearing behaviour of polymer-coated sand is similar to that of natural sand. The quantification of water repellency shows that 0.05% mass ratio of DMDCS is sufficiently high to make the sand extremely water repellent. This suggests that 0.05% polymer-coated sand is appropriate for use in geotechnical structures. For a mass ratio of 3% DMDCS, the reduction of shear strength is evident compared to that of natural sand which is due to the thick polymer-coatings. The polymer-coatings do not change the particle shape due to their micron-range thickness. On the contrary, the polymer-coatings smoothen the particle surface and significantly decrease the roughness of polymer-coated sand (i.e. S_a and S_q). Moreover, the roughness of the polymer-coated sand (3%) converges towards that of natural sand with the rise of stress level, which suggests that the effect of polymer-coatings (i.e. 3%) also diminishes gradually which can be attributed to the damage of polymer-coatings at high stress levels (e.g. $p_0' = 500$ kPa).

5 ACKNOWLEDGEMENTS

Financial support provided by the General Research Fund, Research Grants Council, Hong Kong (17200114, 17221016, T22-603/15-N) is acknowledged.

6 REFERENCES

Bardet, J.P., Sanchez, J. 2011. Soxhlet extraction determination of composition of synthetic soils, *Geotechnical Testing Journal*, **34**, 3, 198-207.

Bardet, J.P., Jesmani, M., Jabbari, N., Lourenco, S.D., 2014. Permeability and compressibility of wax-coated sands, *Géotechnique* **64**, 9, 752–755.

Byun, Y.H., Tran, M.K., Yun, T.S., Lee, J.S., 2011. Strength and stiffness characteristics of unsaturated hydrophobic granular media, *Geotechnical Testing Journal*, **35,** 1, 193-200.

Ladd, R.S., 1974. Specimen preparation and liquefaction of sands, *Journal of Geotechnical and Geoenvironmental Engineering*, **100**, 10, 1180-1184.

Lee, C., Yang, H.J., Yun, T.S., Choi, Y., Yang, S., 2015. Water-entry pressure and friction angle in an artificially synthesized water-repellent silty soil, *Vadose Zone Journal*, **14**, 4.

Leelamanie, D.A.L., Karube, J., Yoshida, A., 2008. Characterizing water repellency indices: Contact angle and water drop penetration time of hydrophobized sand, *Soil Science & Plant Nutrition*, **54**, 2, 179-187.

Liu, D., Lourenço, S.D.N., Yang, J., 2018. Critical state of polymer-coated sands, *Géotechnique*, 10.1680/jgeot.18.P.015.

Lötters, J.C., Olthuis, W., Veltink, P.H., Bergveld, P., 1997. The mechanical properties of the rubber elastic polymer polydimethylsiloxane for sensor applications, *Journal of micromechanics and microengineering*, **7**, 3, 145-147.

Nardelli, V., Coop, M.R., Andrade, J.E., Paccagnella, F., 2017. An experimental investigation of the micromechanics of Eglin sand, *Powder Technology*, **312**, 166-174.

Ng, S.H.Y., Lourenco, S.D.N., 2016. Conditions to induce water repellency in soils with dimethyldichlorosilane, *Géotechnique* **66**, 5, 441–444.

Saulick, Y., Lourenço, S.D.N., Baudet, B.A., 2017. A semi-automated technique for repeatable and reproducible contact angle measurements in granular materials using the sessile drop method, *Soil Science Society of America Journal*, **81**, 2, 241-249.

Yang, J., Luo, X.D., 2015. Exploring the relationship between critical state and particle shape for granular materials, *Journal of the Mechanics and Physics of Solids*, **84**, 196-213.

Yao, T., Baudet, B.A., Lourenço, S.D.N., 2018. Quantification of the surface roughness of quartz sand using optical interferometry, *Meccanica*, 10.1007/s11012-018-0879-2.

Zheng, S., Lourenço, S.D., Cleall, P.J., Chui, T.F.M., Ng, A.K., Millis, S.W., 2017. Hydrologic behavior of model slopes with synthetic water repellent soils, *Journal of Hydrology*, **554**, 582-599.