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Effects of sandy soil structure on various mechanical behaviors

Effets de la structure du sol sableux sur divers comportements mécaniques

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ABSTRACT: In the present paper, the effects of the structure of sandy soil on several loading behaviors (e.g., static undrained shear strength, stress paths, and liquefaction strength) are discussed. Sandy soil specimens with different soil structures were produced using the air-pluviation or wet-tamping method by varying the initial water content. A series of triaxial tests was performed on artificial structural sand specimens using both monotonic and cyclic loadings under undrained conditions. Furthermore, a series of simple shear tests under monotonic loading was conducted using the same specimens. Although the specimens were completely saturated before consolidation, their shear behavior changed remarkably with different initial water contents. In the case of monotonic loading of triaxial tests, highly structural soil characteristics (i.e., a significant elastic response at the beginning of loading, the large maximum deviator stress, and the rapid catastrophic failure after peak stress) were observed in the specimen with high initial water content. In addition, the specimens with a high initial water content exhibited high liquefaction strength in the cyclic loading of triaxial test.

RÉSUMÉ : Dans le présent article, les effets de la structure du sol sableux sur plusieurs comportements de chargement (par exemple, la résistance au cisaillement statique non drainé, les chemins de contrainte et la résistance à la liquéfaction) sont discutés. Des spécimens de sol sablonneux avec différentes structures de sol ont été produits en utilisant la méthode de pluviation dans l'air ou du tassement humide et en faisant varier la teneur en eau initiale. Une série d'essais triaxiaux a été réalisée sur des échantillons de sable structurel artificiel en utilisant à la fois des charges monotones et cycliques dans des conditions non drainées. De plus, une série d'essais de cisaillement simple sous charge monotone a été réalisée en utilisant les mêmes éprouvettes. Bien que les spécimens aient été complètement saturés avant la consolidation, leur comportement au cisaillement a changé de façon remarquable avec différentes teneurs en eau initiales. Dans le cas du chargement monotone des essais triaxiaux, des caractéristiques hautement structurelles du sol ont été observées dans le spécimen à haute teneur en eau initiale. De plus, les spécimens avec une teneur en eau initiale élevée ont présenté une haute résistance à la liquéfaction dans le chargement cyclique de l'essai triaxial.

KEYWORDS: soil structure, triaxial test, simple shear test, liquefaction, sandy soil

1 INTRODUCTION

In conventional and classical soil mechanics, the shear strength of soils is determined by their void ratio without considering the soil structure. However, the difference in the soil structure affects their shear behavior despite the same void ratio. For example, a series of triaxial tests was performed using gravel-mixed sand specimens with the same void ratio; however, considerably different shear behaviors were observed by varying the initial water content during specimen preparation (Kodaka et al. 2013). Moreover, the same study showed that the difference in shear behavior could be explained by changing the soil structure through numerical simulation using the SYS Cam-clay model. As it is possible to prepare sandy soil specimens with the same void ratio but considerably different soil structures, this study demonstrates the effects of soil structure on its mechanical behavior under monotonic and cyclic loadings through triaxial tests.

Ishihara (1993) showed that each type of undrained shear behavior of the Toyoura sand specimens obtained by several specimen preparation methods was different from the others. In their study, the void ratios of all specimens were different because of the initial structure of sand particles. However, because the specimens in the present study were reconstituted using well-graded sand, the initial void ratios of all specimens were largely the same.

Tokimatsu et al. (1986a) stated that the liquefaction strength of clean sand strongly correlated with its elastic shear modulus, which reflects the soil fabric. In addition, Tokimatsu et al. (1986b) showed that sample disturbances affected the dynamic properties of sand. Therefore, these studies suggested that the sample disturbance of sand was related to the degradation of the soil structure.

A reconstituted structural sand specimen containing certain fine fractions was used in this study, which is different from the aforementioned studies that used clean sand. However, we can systematically discuss the effects of the soil structure of sandy soil on its mechanical behavior using artificial structural sand.

2 TEST CONDITIONS

The test sample consisted of a mixture of Mikawa silica sand Nos. 4 and 6 and silt-rich Noma sand mixed in proportions of 3:1:3 by mass. Figure 1 shows the grain size distribution of the mixed samples used in the tests. In addition, the figure shows the results for actual levee sand (sand collected at the Kitajima Levee on the Chitose River). The grain size of the mixed sample was artificially adjusted to resemble that of natural sand, including the fine fraction content.

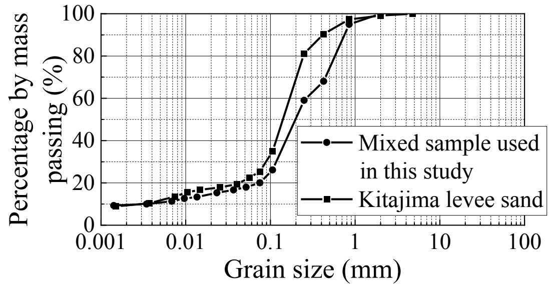


Figure 1. Grain size distribution of the test sample.

Table 1. Specifications of each specimen used in the triaxial test.

Test conditions	Initial water content, w_0 [%]	Initial effective confining pressure [kPa]	Void ratios after consolidation
Monotonic loading	0	50	0.637
		100	0.614
		150	0.608
	5	50	0.679
		100	0.645
		150	0.651
	10	50	0.659
		100_no 1	0.656
		100_no 2	0.645
		150	0.638
Cyclic loading	0	100	0.622
	5		0.614
	10		0.624

Table 1 lists the specifications of each specimen used in triaxial tests. The specimens used in monotonic and cyclic loadings were prepared to ensure that their void ratios were largely the same, as indicated in Table 1.

In this test, specimens with the same dry density (i.e., void ratio), but with different soil structures, were prepared using the mixed sample with the same grain size and three different initial water contents (i.e., 0%, 5%, and 10%) during the preparation. Specifically, in specimens with 5% and 10% initial water content, distilled water was added to the mixed sample in the dry state until the desired water content was reached. The sample was stirred thoroughly until uniformly mixed. Specimens (50 mm in diameter and 100 mm in height) were prepared by compacting the mixed sample in five layers in a mold until it reached the desired density. Because the unsaturated specimens prepared in this manner were self-supporting after demolding, they were carefully covered with a rubber sleeve and subsequently set up in the triaxial testing apparatus. In the case of 0% initial water content (i.e., dry sand), a two-piece split mold covered with a rubber sleeve was set up in the triaxial testing apparatus. The specimen was prepared in the dry state using the air-pluviation method. After applying a confining negative pore pressure of -20kPa to the specimen covered with the rubber membrane, it was removed from the two-piece split mold and the test was conducted. Although all specimens were prepared in a dry or unsaturated state, they were completely saturated using a double vacuum pressure method after being installed in the triaxial testing apparatus.

Figure 2 shows optical microscopy images of surfaces of the three types of specimens prepared by varying the initial water content. The specimens with initial water contents of 5% and 10% were self-supporting in the unsaturated state, and their surfaces were observed directly. However, the specimen with 0% initial water content was prepared inside a transparent acrylic cylinder with an inner diameter of 50 mm by the air-pluviation method as carried out for the actual tested specimens. In Figure 2, grains of various sizes appear tightly packed in the specimen with an initial water content of 0%. The specimen with an initial water content of 5% displayed aggregation of the fine fraction in a particle-like manner. In the specimen with an initial water content of 10%, as the aggregation of the fine fraction progressed, aggregates containing a high volume of water attached to the large sand particles, and the gaps between the particles widened.

(a) Initial water content of 0%, w_0 = 0%

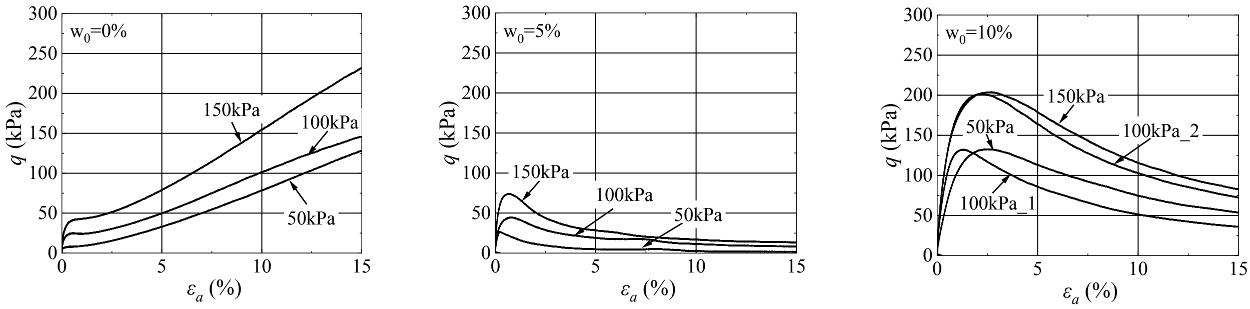
(b) Initial water content of 5%, w_0 = 5%

(c) Initial water content of 10%, w_0 = 10%

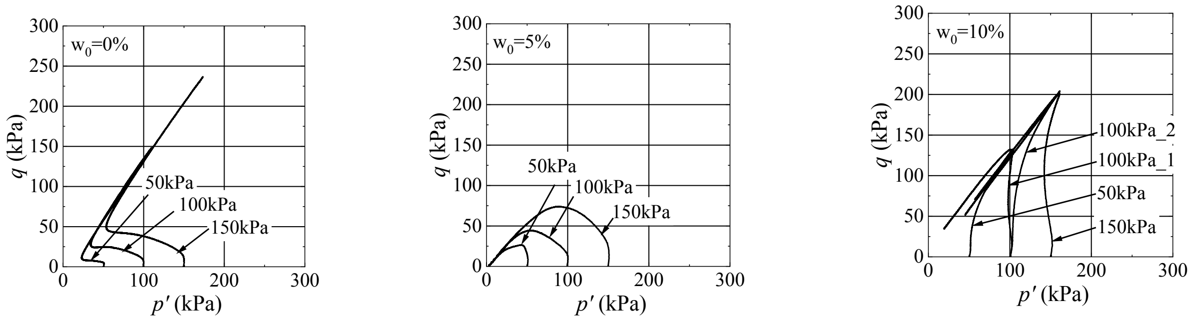
Figure 2. Observed surfaces of specimens via optical microscopy.

This shows that the soil structure of the specimen prepared by wet-tamping or air-pluviation method changed dramatically by varying the initial water content. In addition, Figure 2 shows that a higher initial water content led to larger gaps between the particles, implying that the particles were difficult to pack together in this case. Consequently, the higher initial water content increases the number of times a specimen needs to be tamped down. Moreover, it increases the amount of compaction energy required during tamping to achieve the same dry density.

We have already confirmed that the soil structures observed in the unsaturated state, such as those in Figure 2, were preserved after the specimens were completely saturated. Furthermore, to explain the notable differences in the mechanical behavior of the



(a) Deviator stress - axial strain relationships



(b) Effective stress paths

Figure 3. Test results of triaxial test under monotonic loading condition.

specimens in the test results discussed later, it is appropriate to consider that these soil structures were present even after the specimens were completely saturated.

In this study, consolidated undrained shear tests were conducted on specimens. Monotonic and cyclic loadings were applied in the triaxial test. In the monotonic loading test, three different initial effective confining pressures of 50, 100, and 150 kPa were applied, as shown in Table 1, and the specimens were sheared at an axial strain rate of 0.1%/min. In the cyclic loading test, the initial effective confining pressure was 100 kPa, and the specimens were loaded with three different deviator stress amplitudes at a frequency of 0.1 Hz.

3 TRIAXIAL TEST RESULTS

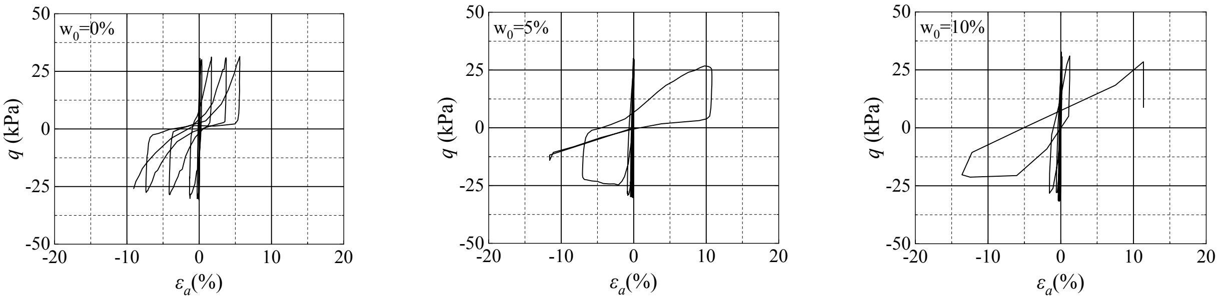
Figure 3 shows the results of the triaxial test under monotonic loading for specimens prepared at three different initial water contents. The top row shows the relationship between the deviator stress, $q = \sigma_1 - \sigma_3$, and axial strain ε_a, whereas the bottom row shows the effective stress path diagrams, that is, the relationship between q and mean effective stress p. The left-hand side, center, and right-hand side show the test results for specimens with 0%, 5%, and 10% initial water content, respectively.

Considering the effective stress path in the case of the initial water content of 0%, the specimens underwent rapid plastic compression and reached the phase transformation state in the early stage of shearing. Subsequently, the deviator stress increased significantly until the end of shearing due to the confinement of positive dilatancy. At an initial water content of 5%, the specimens exhibited plastic compression similar to that displayed by specimens with an initial water content of 0%. However, these showed relatively high stiffness compared to the 0% specimens until the peak deviator stress was rearched. However, the specimens abruptly demonstrated a softening behavior after the peak was reached and a final state similar to static liquefaction toward the origin. At an initial water content of 10%, the effective stress paths were similar to an elastic response, increasing vertically in the early stage of shearing compared to the 0% and 5% specimens. The specimens reached extremely large deviator stresses. However, after reaching the peak, the specimens exhibited rapid strain softening and underwent significant brittle collapse.

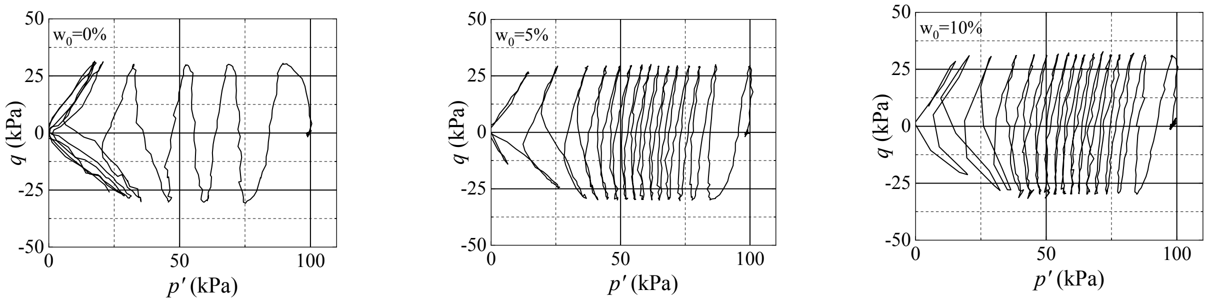
As the initial water content increased from 0% to 5% to 10%, an elastic response in the early stage of shearing was evident, and brittle strain softening after the peak load became pronounced. This occurs because the matrix suction causes the coarse and fine fractions to form a "strong" structure according to the initial water content during the specimen preparation. This type of structure is not formed in specimens with an initial water content of 0%. Therefore, these specimens demonstrate significant plastic compression from the early stage of shearing, despite having the smallest void ratio. However, after phase transformation, the specimens with an initial water content of 0% exhibited significantly heavy over consolidation characteristics owing to the confinement of positive dilatancy. Subsequently, the deviator stress considerably increased due to completely undrained conditions that do not commonly materialize under natural conditions. This does not directly indicate a high soil strength.

Based on these findings, a more developed soil structure in the sandy soil resulted in a highly characterized soil due to a high elastic response and shear resistance in the small strain range. A rapid brittle failure occurred with the collapse of the soil structure.

Figure 4 shows the results of the triaxial tests under cyclic loading. The top row shows the relationship between the deviator stress and axial strain, whereas the bottom row shows the effective stress path diagrams. The left-hand side, center, and right-hand side show the test results for specimens with 0%, 5%, and 10% initial water contents, respectively. These diagrams show only the test results corresponding to a cyclic stress amplitude ratio of 0.15 at a maximum deviator stress of 30 kPa for each specimen.



(a) Deviator stress - axial strain relationships



(b) Effective stress paths

Figure 4. Test results of triaxial test under cyclic loading condition.

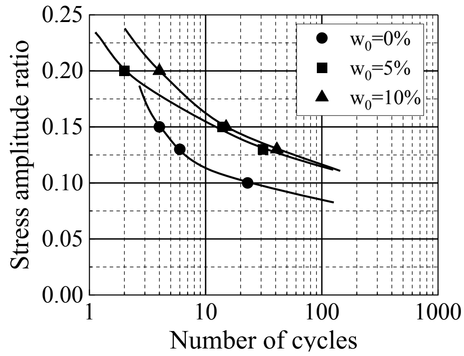


Figure 5. Liquefaction strength curves

At initial water contents of 5% and 10%, the decrease in the effective stress in each cyclic loading was small. Moreover, the axial strain was extremely small. However, as soon as the effective stress approached zero and liquefaction occurred, a large axial strain was observed. This finding is the same as the tendency for brittle failure under monotonic loading. At an initial water content of 0%, the decrease in the effective stress in each cyclic loading was large from the early stage of shearing, and a relatively large axial strain was produced from the loading onset.

Figure 5 shows the liquefaction strength curves, including the test results at other stress amplitude ratios. The liquefaction strength of specimens prepared with an initial water content of 0%, that is, dry sand, was low compared to that of specimens prepared with an initial water content of 5% and 10% due to the differences in the initial behavior during cyclic loading. Thus, the specimens that formed soil structures had higher liquefaction strengths.

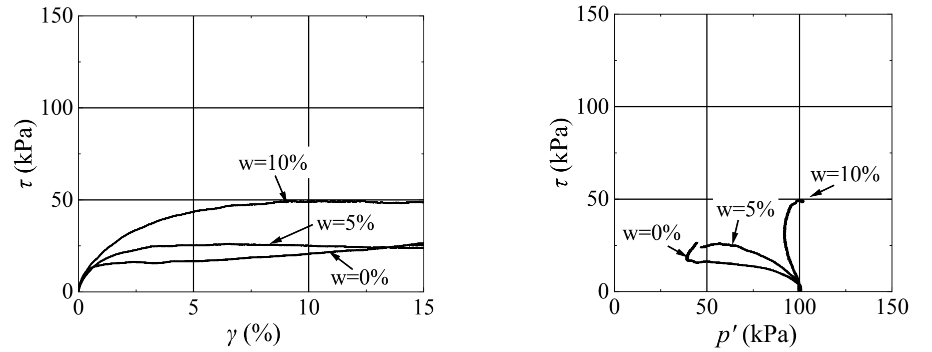
In the past, the difference in liquefaction strength between naturally deposited undisturbed sand and sand that had been reconstituted at the in situ density was measured based on the level of disturbance (Tokimatsu et al. 1986b, Kiyota et al. 2009). Thus, the common understanding was that it was difficult to accurately predict the liquefaction strength in the field without performing liquefaction tests using high-quality undisturbed frozen samples. The test results in this study suggested that soil disturbance was closely related to the soil structure in sandy soils. If we clarified the formation mechanism of the soil structure and artificially reproduced the soil structure by considering disturbance as a deterioration in the soil structure, it would be possible to obtain high-quality test results from reconstituted specimens using disturbed samples collected using an inexpensive method.

4 SIMPLE SHEAR TEST RESULTS

Table 2 lists the specifications of the specimens used in the simple shear test. As in the triaxial test, specimens were prepared using three different initial water contents. However, the specimens in the simple shear test were cylinders of 60 mm in diameter and 30 mm in height and were prepared in three layers. After the specimens had been completely saturated using a double vacuum method, they were consolidated isotropically to initial effective stress of 100 kPa. Afterward, a simple shear test under undrained conditions was performed by monotonically loading the upper pedestal horizontally at a constant displacement rate, with the lower pedestal still in place. Figure 6 shows the effective stress paths and shear stress–shear strain relationships obtained from the simple shear test.

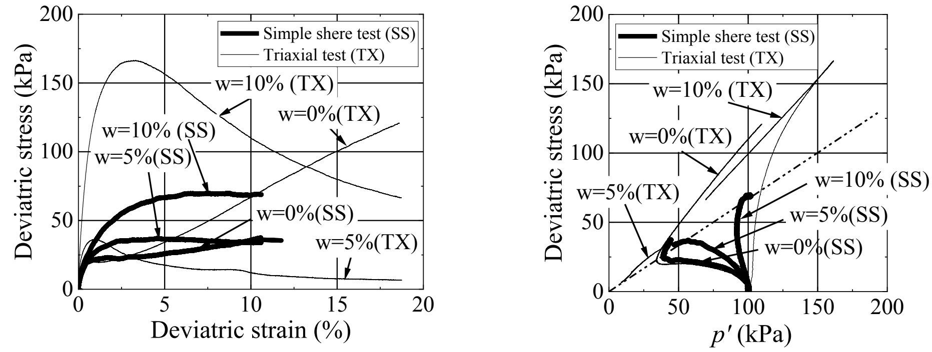
Table 2. Specifications of each specimen used in the simple shear test.

Test conditions	Initial water content, w_0 [%]	Initial effective confining pressure [kPa]	Void ratios after consolidation
Monotonic loading	0	100	0.637
	5		0.636
	10		0.636

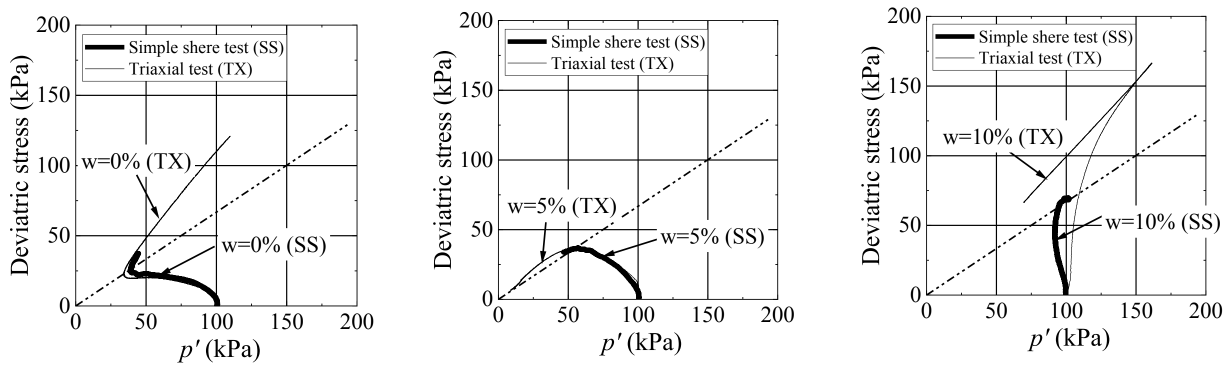


(a) Shear stress - shear strain relationships (b) Effective stress paths

Figure 6. Simple shear test results.



(a) Deviatoric stress - deviatoric strain relationships (b) Effective stress paths



(b)-1 Effective stress paths (w0=0%) (b)-2 Effective stress paths (w0=5%) (b)-3 Effective stress paths (w0=10%)

Figure 7. Results of triaxial test and simple shear test

Although the type of strain softening observed in the triaxial test results was not found, the behavior before phase transformation resembled that observed in the triaxial test in all specimens, irrespective of the initial water content. Specifically, the higher initial water content of the specimen resulted in a higher vertical increase in the effective stress path in the early stage of shearing. These specimens can be considered highly structured.

Because the shear modes differed greatly in the triaxial and simple shear tests, the results of both tests were required for comparison using the same parameters. That is, the results were reorganized (Figure 7) by calculating both the second invariant of the deviatoric stress tensor, here called “deviatoric stress” for convenience, for the vertical axis and the second invariant of the deviatoric strain tensor, here called “deviatoric strain” for the horizontal axis. The effective stress paths in Figure 7 show that in addition to the roughly coinciding phase transformation lines, the phase transformation points coincided to a large extent in specimens with initial water contents of 0% and 5%, despite different shear modes in the triaxial and simple shear tests. In the specimen with an initial water content of 10%, the effective stress path increased vertically and the specimen that exhibited an elastic behavior in the early stage of shearing is the same. However, the maximum shear stress was considerably higher in the triaxial test. This test result for specimens with an initial water content of 10% is consistent with the finding that the remarkable strain softening of sensitive clays with excellent soil structures is observed only in triaxial tests (Kodaka et al. 2011). In addition, the effective stress path after phase transformation differed considerably in both tests at all initial water contents.

Specifically, in the triaxial test, the degree of strain softening was evident in specimens possessing excellent soil structures with initial water contents of 5% and 10%, whereas a degree of strain hardening was present in specimens possessing poor soil structures with an initial water content of 0%. Because the shear modes differed greatly, it is believed that major differences appeared in the shear stress—a response value—owing to a loss in homogeneity in the specimens, particularly in the latter half of shearing. At present, it is difficult to conclude which test is appropriate.

5 CONCLUSIONS

Specimens with different soil structures were prepared by varying the initial water content, followed by performing triaxial and simple shear tests. The results were compared by studying the effective stress paths. In the triaxial test, the shear behavior differed greatly under both monotonic and cyclic loadings. Because the matrix suction between soil particles varied depending on the water content during specimen preparation, it is believed that as the water content increased, and the fine fraction coagulated around the coarse particles to form a soil structure, confirmed using optical microscopy. In addition, the cyclic loading test results showed that this soil structure and the sample disturbance were closely related, suggesting that artificial quasi-undisturbed samples can be prepared by understanding the soil structures of natural sand deposits. Furthermore, despite the shear modes differing greatly in the triaxial and simple shear tests, the paths up until phase transformation were relatively consistent. High maximum shear stress and subsequent large strain softening observed in the specimens with an initial water content of 10%, having superior soil structures, was observed only in the triaxial test.

6 ACKNOWLEDGMENTS

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