MECHANICAL CHARACTERISTICS OF SANDS WITH DIFFERENT PRIMARY PROPERTIES

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ABSTRACT

The mechanical behaviors of sands are notably influenced by their physical properties as well as by environmental conditions: stress and strain conditions, and drainage conditions. The physical properties of soils can be classified into primary properties and secondary properties; primary properties are permanent properties of soil grains such as density, hardness, shape and size of grains, and secondary properties are non-permanent properties of soil structures such as void ratio, packing and moisture content of soils. The objective of this study is to reveal the mechanical behaviors of soils with different primary properties.

The mechanical properties of sands were investigated extensively; the mechanical behaviors of some 200 granular materials were observed in a series of conventional triaxial compression tests. The significant influence of the primary properties on the deformation-strength characteristics was clarified. From the test results, the relationships of deformation-strength properties of sands with index physical properties are discussed; the significant influence of grain shape, grading and crushability on the mechanical behaviors are presented.

Key words: deformation, mechanical properties, primary properties, sand, strength, triaxial test (IGC: D6/D3)

INTRODUCTION

Because of the varieties of soil types and the complexity of the mechanical behaviors of soils, it is difficult to comprehend and model the mechanical behavior of soils. The mechanical properties of soils should be intrinsically determined by their physical and chemical properties; the factors controlling the mechanical behavior of soils were discussed by Spronck (1948) and Mikasa (1964). According to their considerations, permanent properties such as density, hardness, shape and size of grains are primary physical properties, and the non-permanent, changeable properties of soil fabric such as packing and orientation of grains, void ratio and moisture content are secondary properties.

In the accompanying paper (Miura et al., 1997b), the authors extensively investigated the physical properties of sands with different primary properties, and demonstrated the significance of primary properties in physical properties of sand. In that study physical properties of some 200 granular materials were examined, and the correlation among the physical properties was discussed.

Some index properties which characterize the physical properties of sands, such as maximum and minimum void ratios, crushability and the angle of repose, were chosen, and their correlation with the primary physical properties were presented.

As a next step, the objective of this study is to clarify the mechanical properties of sands with different primary physical properties and to present a correlation of mechanical properties with index physical properties. The same granular materials as used by Miura et al. (1997b) were tested in a series of conventional drained triaxial compression tests under the same conditions of confining stress, compressional strain rate and drainage. The observed deformation behaviors were examined comparatively with emphasis on the stiffness during consolidation and shearing, and shearing strength. As is well known, even under the same test conditions such as drainage and loading conditions, the deformation-failure behaviors are affected by secondary properties; void ratio and fabrics formed with constituent particles possess determinant effects on the mechanical behaviors. Thus, in this study all the specimens of granular material samples

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were prepared with the same sample preparation method, modified vibration, so as to attain the same relative density of $70 \pm 1\%$. It was, therefore, assumed that the influence of primary physical properties on the mechanical properties can be deduced from comparative examination of the observed behaviors of these specimens. The dependency of the mechanical properties of sands on relative density is investigated elsewhere by Maeda and Miura (1999b) on the same granular materials.

The significant influence of primary chemical and physical properties on mechanical properties seems to be recognized more in clayey soils than in sandy soils. Mitchell (1976), Schofield and Wroth (1968) and Skempton (1957) and many other researchers have presented useful estimation methods for some mechanical properties of clays such as shear strength, compressibility and consolidation feature, from indexes for chemical and physical properties, such as consistency limits and current moisture content.

Some attempts have been also made to establish for sands reliable estimation methods of mechanical properties on the basis of the primary physical properties and index physical properties. Terzaghi and Peck (1948) presented a list of the typical values of the internal friction angle ϕ for various sands with different grain shape and grading. Mogami (1965) and Moroto (1982) showed that ϕ should be given as a function of current void ratio e and minimum void ratio $e_{\min}$, where $e_{\min}$ is assumed to be a function of grain shape, grading and so on. Dunham (1954) proposed formulae for different types of sands to estimate ϕ from the blow value N by standard penetration test. It is also well known that the liquefaction potential of the ground is much influenced by the grading of the constituent grains. Hence, Iai et al. (1989) derived the criterion for liquefaction potential as a region on the grain size distribution chart, from the field observations and the laboratory tests on grading of the liquefied soils. Ishihara and Watanabe (1976) and Yoshimura and Ogawa (1994a, b) showed the significance of volume decrease potential ($e - e_{\min}$) in sand's mechanical properties, such as shear strength and liquefaction potential, from their experimental results.

The identification and unification of the fundamental parameters for deformation-strength behaviors of sands, with the primary physical properties taken into account, is also the concern of this study. An estimation method for some mechanical properties of sands from their index physical properties is discussed in the latter part.

GRANULAR MATERIALS USED AND THEIR PHYSICAL PROPERTIES

Granular Material Samples Used

In order to examine the correlation between the primary physical properties of sands and their mechanical properties, different granular materials were used in this study. Some 200 granular materials including sands and various artificial materials were prepared; the same materials were used by Miura et al. (1997b). The granular

materials used are classified into three groups: natural sand samples, reconstituted sand samples and artificial granular samples.

(Natural sand samples)

Some 60 samples were selected from natural sand samples collected from rivers, beach areas, gravel pits, bridge foundation sites and so on. They were sieved and washed, so that these grains whose diameters are larger than 2.000 mm or smaller than 0.075 mm were removed. Mean diameter D_{50} ranges from 0.170 to 1.007 mm, uniformity coefficient U_c from 1.255 to 3.514 and void ra-

Fig. 1. Grain size accumulation curve: (a) uniform sand samples; (b) graded sand samples with common $D_{\max}$; (c) graded sand samples with common $D_{\min}$

ratio extent ($e_{\max} - e_{\min}$) from 0.267 to 0.517. Some of the materials are these used by other researchers; Toyoura sand (Japanese standard sand, TO-Sand: $D_{50}=0.200$ mm, $U_c=1.300$, $e_{\max}=0.991$, $e_{\min}=0.625$), Soma sand (SO-SAND: $D_{50}=0.740$ mm, $U_c=1.622$, $e_{\max}=0.797$, $e_{\min}=0.530$), Fujigawa sand ($D_{50}=0.510$ mm, $U_c=3.514$, $e_{\max}=0.942$, $e_{\min}=0.534$) and Sengenyama sand ($D_{50}=0.270$ mm, $U_c=1.676$, $e_{\max}=1.102$, $e_{\min}=0.688$) were included.

(Reconstituted sand samples)

Reconstituted sand samples were processed from 4 natural sands: TO-SAND, SO-SANDS and two commercially available siliceous sands (CA-SAND, CB-SAND). TO-SAND and SO-SAND were milled and sieved, and CA-SAND and CB-SAND were only sieved. Reconstituted samples were processed in order to attain the prescribed grain size distributions. The samples were designated from the maximum and minimum grain sizes in μm ; for example, the sand sample produced from CA-SAND, whose maximum and minimum grain sizes were 2000 μm and 75 μm , respectively, was designated CA-2000-75.

Reconstituted sand samples were classified into uniform samples and graded samples; their grain size distributions are presented in Figs. 1(a)–(c). The uniform sand samples have small values of uniformity coefficient U_c (less than 1.3 except for the sample CA-4750-2000 of 1.54) and cover a wide range of D_{50} from 0.089 to 3.082 mm. On the other hand, the graded samples were processed by mixing the uniform sand samples, so that the graded samples covered a wide range of U_c from 1.086 to 5.164.

(Artificial granular material samples)

In this study some artificial granular materials were employed: glass beads and light weight aggregates (L.W.A.) which were made of granulated chemical by-product. The constituent particles of both samples are quite spherical, and their grain sizes are rather uniform. The uniformity coefficient U_c is less than 1.54 for all the samples, and the mean grain size D_{50} ranges from 0.115 to 5.136 mm for 6 glass beads, and 0.714 to 3.082 mm for 4 L.W.A.

The detailed information for all the samples used is introduced in the associated doctoral thesis (Maeda, 1995) and the accompanying paper (Miura et al., 1997b).

Physical Properties of Granular Samples Used

For all the samples, primary physical properties such as grain densities, grain shapes, and grain size distributions and some index physical properties such as maximum and minimum void ratios, crushability and angle of repose ϕ_{rep} , were measured and presented in Miura et al. (1997b). The grain shapes were assessed by two-dimensional angularity A_{2D} proposed by Lees (1964a, 1964b); large values of A_{2D} are assigned to angular grains and A_{2D} is zero for spherical grains such as glass beads and light weight aggregate (L.W.A.). Crushability index I_{cr} and the angle of repose ϕ_{rep} were determined with the methods proposed by the authors (Miura et al., 1997a and 1997b).

The crushability index I_{cr} was calculated as

$$I_{cr} (= \log (D_{10}/D'_{10}))$$

where D_{10} and D'_{10} are measured before and after crushing in a mold by shearing samples under confining pressure of 98 kPa. Crushable soils have large values of I_{cr} . The angle of repose ϕ_{rep} was measured from the sand

Fig. 2. Relationship with angularity A_{2D} with mean grain size D_{50} as a parameter: (a) void ratio extent ($e_{\max} - e_{\min}$); (b) crushability I_{cr} ; (c) the angle of repose ϕ_{rep}

heap formed statically on the depressed pedestal; however, only a selected number of samples were tested for the angle of repose ϕ_{rep} .

The relationships between the primary properties and the index physical properties were presented in Figs. 2(a)–(c), in these figures fitting curves were drawn for only sand samples. The relationships were closely discussed in Miura et al. (1997b); the discussion is briefly summarized as follows;

- The void ratio extent ($e_{max} - e_{min}$), which implies the degree of possible change in soil structure, varies as a function of grain shape and grading; ($e_{max} - e_{min}$) increases with a decrease in mean grain size D_{50} and/or an increase in angularity A_{2D} as shown in Fig. 2(a).
- Crushability index I_{cr} increases with D_{50} and/or A_{2D} as shown in Fig. 2(b); sand consisting of angular and large grains, show high crushability.
- Angle of repose ϕ_{rep} is rather independent of D_{50} and U_c ; however, ϕ_{rep} increases with A_{2D} as shown in Fig. 2(c).

TESTING METHOD AND EQUIPMENT FOR OBSERVING MECHANICAL BEHAVIORS

—TRIAXIAL COMPRESSION TEST—

Drained triaxial compression tests were performed on all the granular materials used in this study to observe the deformation-failure behaviors of sands. The adopted apparatus was a conventional type for specimens 70 mm in diameter and 165 mm in height, as illustrated in Fig. 3. Pressure transducers, a dial gauge and a load cell, which are all linked to a scanning box, were used for automatic controlling and measuring system with a personal computer.

The change in axial stress was measured with the load cell mounted on the top cap, and radial principal stress, which is equal to cell pressure and pore water pressure,

was measured with the pressure transducers. Axial displacement was measured with a dial gauge, while volume change of the specimen was measured with the double burette system linked to a personal computer as introduced by Miura and Toki (1982).

Measured volume change is generally subjected to error due to the rubber membrane's penetration into the interstices between sand particles, when sand samples are tested under variable cell pressures (Newland and Allely, 1957). For this reason, only the axial strain is reliable during isotropic consolidation. On the other hand, the membrane penetration effects could be eliminated in the measurement of volume change during shear under constant effective cell pressure.

Testing Procedure

After the sand specimen prepared in dry state was set up in the triaxial cell, cell pressure was raised up to 19.6 kPa. In order to saturate the specimen, carbon dioxide was percolated through the specimen for about 15 minutes, and then de-aired water was permeated into the specimen with small water head difference so as not to disturb the initial fabric of the specimen. After the voids in the specimen were filled with water, a constant back pressure of 196 kPa was applied for 30 minutes. Consequently, Skempton's B-value of more than 0.95 was obtained in all the specimens.

The cell pressure was increased up to the prescribed value of initial isotropic stress. After consolidation for 30 minutes, drained triaxial compression loading was carried out under constant effective radial stress of 196 kPa, with a constant axial strain rate of 0.25%/min.

Representation of Stress-Strain Behavior

The axial and radial effective principal stresses are denoted as σ'_a and σ'_r , respectively, and axial strain and radial strain are denoted as ϵ_a and ϵ_r , respectively. The stress and strain parameters employed for analysis of the observed deformation behaviors are

$$\sigma'_m = (\sigma'_a + \sigma'_r)/2, \quad \tau_m = |\sigma'_a - \sigma'_r|/2, \quad \tau_m/\sigma'_m = \sin \phi_m \quad (2)$$

$$\epsilon_v = \epsilon_a + 2\epsilon_r \quad (3)$$

where σ'_m and τ_m are effective mean principal stress and maximum shear stress, respectively, and ϵ_v is volumetric strain. Compressive stresses and strains are taken as positive quantities. Shear stress ratio τ_m/σ'_m gives mobilized friction angle ϕ_m , and ϕ_m at failure state corresponds to the internal friction angle ϕ_d . The effective radial stress after isotropic consolidation, which is called effective confining pressure, is denoted as σ'_c .

A schematic diagram for the typical observed stress-strain behavior is shown in Fig. 4. Stress ratio τ_m/σ'_m was employed as an index for shear stress level. The axial strain at failure is given as ϵ_{af} . The stiffness is represented by the normalized secant modulus E'_{50} , and the dilatancy behavior is represented by the volumetric strain ϵ_{vv} and the mobilized internal friction angle ϕ_{cv} when the maximum volume contraction is reached; the definitions of

Fig. 3. Section of triaxial compression testing device equipped with inner load cell

Fig. 4. Definition of parameters for observed mechanical properties in triaxial test

the parameters are illustrated in Fig. 4.

Axial strain occurring during the isotropic consolidation ϵ_{ac} , where effective stress σ'_c is increased from 19.6 kPa to 196.0 kPa, is also employed as an index for representing compressibility or stiffness during consolidation.

Specimen Preparation Method

In order to examine the mechanical properties of granular materials with different primary properties, a preparation method for triaxial specimens, which needs to be applicable to samples with a wide range of grain size distribution, was desired.

Miura and Toki (1982) proposed the multiple sieving pluviation method (MSP Method) for producing relatively uniform specimens with excellent reproducibility and density controllability; in this method dry sand grains are deposited by air pluviation through piled sieves. This method, however, is not applicable to well graded materials, due to the segregation between particles with different diameters during pluviating in the air. In this study, then, the modified vibration method of specimen preparation was adopted (see Fig. 5). The procedure is as follows:

- Pour dried sample into a mold by means of a funnel with zero falling height so as to obtain the loosest sand heap. This procedure with a funnel is employed in the test for minimum density of sand (JGS, 1990).
- Compact the sample up to the prescribed density under the surcharge of 1 kPa with a small vibrator with a frequency of 120 Hz, an amplitude of 0.3 mm and power

Fig. 5. Preparation method of specimen by modified vibration method

of 10 W.

The good controllability of the density and reproducibility of the specimen preparation method were examined in the preliminary study, where a series of triaxial compression and extension tests was carried out on Toyoura sand (TO-SAND). It is possible to control the relative density D_r of specimens with an error of 1% by continuous vibration while monitoring the subsidence of the cap.

It is well known that the specimen preparation method determines the fabric of the specimen and also has a remarkable effect on the mechanical behaviors of sands even with the same density; see Miura and Toki (1982), Tatsuoka et al. (1986) and Ishihara (1993). To characterize the mechanical properties of sand specimen by the modified vibration method, drained triaxial compression

Fig. 6. Comparison of deformation-failure behaviors of sand specimens prepared by two different methods: Modified vibration method and multiple sieving pluviation (MSP) method (Miura and Toki, 1982)

and extension tests were performed on the specimens prepared by this method and the MSP method. Shown in Fig. 6 are the stress-strain relationships of TO-SAND with the initial relative density of 50% and under constant confining pressure σ'_c of 196 kPa; the values of some indexes of mechanical properties obtained are listed in Table 1. A comparative examination of the results is summarized as follows:

- In both compression and extension sides, the specimens prepared by the modified vibration method show smaller volume contract strains and higher shear stiffness than the specimens prepared by MSP.
- In both kinds of specimens, strength evaluated by the internal friction angle ϕ_d is higher on the compression side than on the extension side. In addition, the difference in the strengths between compression and extension sides is larger in the specimens prepared by MSP

Table 1. Comparison of indexes of mechanical properties sand specimen prepared by two different methods: Modified vibration method and multiple sieving pluviation (MSP) method (Miura and Toki, 1982)

D_r (%)		Modified vibration meth.			MSP meth.		
		E'_{50}	ε_{vcv} (%)	ϕ_d (deg.)	E'_{50}	ε_{vcv} (%)	ϕ_d (deg.)
90	Comp.	274	0.123	40.6	253	0.126	41.2
	Ext.	138	0.153	39.2	119	0.230	37.1
70	Comp.	195	0.158	37.9	190	0.212	38.4
	Ext.	99	0.209	36.2	84	0.314	34.9
50	Comp.	158	0.185	35.0	141	0.274	35.7
	Ext.	76	0.563	34.2	61	0.845	32.1

Fig. 7. Typical stress-strain relationships observed for uniform samples: (a) CA-SAND; (b) CB-SAND; (c) SO-SAND; (d) TO-SAND

than in the specimens prepared by the modified vibration method. This suggests that while MSP specimens have notable anisotropy in mechanical properties as reported by Miura and Toki (1982), modified vibration method specimens are less anisotropic in shear strength.

DEFORMATION-FAILURE BEHAVIORS OF SANDS

The deformation-failure behaviors of granular materials with different primary physical properties, which were observed in a series of triaxial compression tests, are presented. The correlation between the primary physical properties and the deformation-failure behavior will be clarified by the comparative examination of the observed behaviors.

The conventional drained triaxial compression tests

were performed on all the granular materials under the same conditions. All the test specimens were prepared by the modified vibration method so as to possess the same relative density of 70%; the scatter of the measured relative density after isotropic consolidation of 196 kPa was less than 1%. Moreover, all the specimens were subjected to axial compression with the same axial strain rate of 0.25%/min under the same constant effective confining pressure σ'_c of 196 kPa.

Typical stress-strain relationships of the uniform sand samples and the graded sand samples are shown in Figs. 7(a)–(d) and Figs. 8(a)–(c), respectively, and typical stress-strain relationships of natural samples and some artificial granular materials are shown in Figs. 9(a)–(b). Although all the materials were tested under the same conditions, the observed behaviors are significantly different; the large effects of the primary physical properties of

Fig. 8. Typical stress-strain relationships observed for graded samples: (a) CA-SAND; (b) CB-SAND; (c) SO-SAND

Fig. 9. Typical stress-strain relationships observed for artificial granular samples and natural sand samples: (a) TO-SAND, SO-SAND, light weight aggregates and glass beads; (b) four natural sand samples

Fig. 10. Relationships of normalized secant shear modulus E'_{50} with: (a) axial strain under consolidation ϵ_{ac} ; (b) maximum volume contraction under shear ϵ_{vcc} ; (c) axial strain at failure ϵ_{af}

granular materials on the mechanical properties are recognized.

Deformation Characteristics

The axial strain ε_{ac} which occurred during isotropic consolidation of σ'_c from 19.6 to 196 kPa, is plotted

against the normalized secant modulus E'_{50} in Fig. 10(a). There is negative linear correlation between ε_{ac} and E'_{50} in logarithmic scale for all the samples including sands, glass beads and L.W.A., which indicates that sand with higher compressibility during consolidation exhibits lower stiffness against shear stress. This clear correlation sug-

Fig. 11. Relationships of normalized secant shear modulus E'_{50} with: (a) mobilized friction angle at maximum volume contraction under shear ϕ_{cv} ; (b) internal friction angle at failure ϕ_d

Fig. 12. Relationships of axial strain under isotropic compression ε_{ac} with: (a) angularity A_{2D} ; (b) void ratio extent ($e_{max} - e_{min}$); (c) crushability index I_{cr}

gests the strong mutual dependency between the stiffness in consolidation and that in shearing. Although deformation behaviors of sands are sometimes treated separately during consolidation and during shear, this experimental result suggests the possibility that these two types of deformation behaviors during consolidation and shear can both be modeled based on a unified mechanism.

The volumetric strain at maximum volume contraction ε_{vcv} and the axial strain at failure ε_{af} are plotted against E'_{50} in Fig. 10(b) and Fig. 10(c), respectively; for L.W.A. ε_{af} could not be determined because of its consistent increase in stress ratio τ_m/σ'_m during shearing. Both ε_{vcv} and ε_{af} tend to decrease with E'_{50} linearly in logarithmic scale; however, the correlation is not strong compared with that between ε_{ac} and E'_{50} .

From the above examination of the observed deformation-failure behaviors, it is clear that the deformation behaviors in consolidation and shear can be explained in a unique manner. The strains ε_{ac} , ε_{vcv} and ε_{af} can be related to the value of E'_{50} ; this correlation may be useful for the identification or unification of the mechanical parameters in constitutive models for sands.

Strength Characteristics

The mobilized internal friction angle at maximum volume contract ϕ_{cv} and the internal friction angle ϕ_d are

plotted against E'_{50} in Figs. 11(a), (b), respectively; distribution of ϕ_{cv} and ϕ_d are shown by broken curves for sands excluding artificial samples, glass beads and L.W.A. The angles ϕ_{cv} and ϕ_d both tend to decrease with an increase in E'_{50} ; although the dependency between ϕ_d and E'_{50} is not clear, a negative correlation could be found.

It is widely believed that the soils with higher shear stiffness also exhibit higher shear strength. In the estimation of shear stiffness and shear strength of grounds from the blow value by standard penetration test, the positive correlation between shear stiffness and shear strength through relative density is implicitly accepted as a backbone. This tendency can be readily confirmed, as long as only a single soil is concerned under different densities and/or different confining pressures, as demonstrated by Bishop (1966), Maeda (1995) and Maeda and Miura (1999a, 1999b). On the other hand, if plural sands with different primary physical properties are considered, the positive correlation between shear stiffness and shear strength cannot be supported.

This negative correlation between shear stiffness and strength for sands under the same conditions, would be worthy of note for some practical problems; this tendency will be discussed in the following section with regard to the influence of primary physical properties.

Fig. 13. Relationships of normalized shear secant modulus E'_{50} with: (a) angularity A_{2D} ; (b) void ratio extent $(e_{max} - e_{min})$; (c) crushability index I_{cr}

CORRELATION BETWEEN MECHANICAL PROPERTIES AND INDEX PROPERTIES

Deformation Characteristics

Axial strain during isotropic consolidation ε_{ac} is plotted against angularity A_{2D} , void ratio extent ($e_{\max} - e_{\min}$) and crushability I_{cr} in Figs. 12(a)–(c), respectively. While ε_{ac} is dependent on A_{2D} and ($e_{\max} - e_{\min}$), ε_{ac} is rather independent of I_{cr} . It can be said that the value of ε_{ac} increases with A_{2D} and/or ($e_{\max} - e_{\min}$) for all the samples.

Normalized secant modulus E'_{50} is plotted against A_{2D} , ($e_{\max} - e_{\min}$) and I_{cr} in Figs. 13(a)–(c), respectively. The modulus E'_{50} depends most strongly on ($e_{\max} - e_{\min}$); E'_{50} decreases by 200 with an increase in ($e_{\max} - e_{\min}$) of 0.2. The normalized secant modulus E'_{50} decreases with A_{2D} but, does not depend on I_{cr} . As suggested by Figs. 10(b), (c), volumetric strain at maximum volume contract ε_{vcv} and the axial strain at failure ε_{af} both change also as functions of ($e_{\max} - e_{\min}$) and A_{2D} , and rather independent of I_{cr} .

As a result of the above examination, it is clear that the deformation behaviors of granular materials during shearing and consolidation are influenced significantly by their primary properties. It can be said that the deformation properties vary as functions of the void ratio extent ($e_{\max} - e_{\min}$), which is controlled not only by the grain

shape but also by the grain size distribution, as shown in Fig. 2(a); see also Miura et al. (1997b). This tendency indicates that a granular material with larger ($e_{\max} - e_{\min}$) value shows higher deformability or lower stiffness during consolidation and shearing. The values of parameters ε_{ac} , E'_{50} , ε_{vcv} and ε_{af} can be roughly evaluated from the value of ($e_{\max} - e_{\min}$) for practical purposes.

Strength Characteristics

The angle of internal friction mobilized at maximum volume contract ϕ_{cv} is plotted against angularity A_{2D} , void ratio extent ($e_{\max} - e_{\min}$) and crushability I_{cr} in Figs. 14(a)–(c), respectively. The parameter ϕ_{cv} is dependent on ($e_{\max} - e_{\min}$) and A_{2D} , but not on I_{cr} , in a similar manner to the parameters for the deformation properties such as ε_{ac} , E'_{50} , ε_{vcv} and ε_{af} ; unique ϕ_{cv} vs. ($e_{\max} - e_{\min}$) and ϕ_{cv} vs. A_{2D} correlations can be recognized for sands.

The relationships of the angle of internal friction ϕ_d with A_{2D} , ($e_{\max} - e_{\min}$) and I_{cr} are shown in Figs. 15(a)–(c), respectively. It can be said that ϕ_d somewhat increases with ($e_{\max} - e_{\min}$) and A_{2D} , and decreases with an increase in I_{cr} ; ϕ_d is more dependent on I_{cr} than on ($e_{\max} - e_{\min}$) and A_{2D} . The range of the variation of ϕ_d is shown by dotted curves for sands in these figures. It may not be possible to estimate the value of ϕ_d from the crushability index I_{cr} with an accuracy of 2 degrees; nevertheless, it is apparent

Fig. 14. Relationships of mobilized friction angle at maximum volume contraction under shear ϕ_{cv} with: (a) angularity A_{2D} ; (b) void ratio extent ($e_{\max} - e_{\min}$); (c) crushability index I_{cr}

Fig. 15. Relationships of internal friction angle at failure ϕ_d with: (a) angularity A_{2D} ; (b) void ratio extent ($e_{\max} - e_{\min}$); (c) crushability index I_{cr}

Fig. 16. Relationships of angle of repose ϕ_{rep} with: (a) mobilized friction angle at the maximum volume contraction under shear ϕ_{cv} ; (b) internal friction angle at failure ϕ_d

that I_{cr} is the most reliable index for the estimation of ϕ_d .

The negative correlation of the angle of internal friction ϕ_d with normalized secant modulus E'_{50} , i.e. that of shear strength with shear stiffness, which was pointed out in Fig. 11(b), may be explained through their correlation with angularity A_{2D} and void ratio extent ($e_{\max} - e_{\min}$).

Sands consisting of angular grains possess a high degree of possible change in their soil structure, as suggested by the large value of ($e_{\max} - e_{\min}$) shown in Fig. 2(a). It appears that in sands of this type a certain degree of stress concentration at sharp contact points will cause the deformation and/or small-scaled fracture of sand grains at

contact points; the associated change of soil structure will be triggered. This mechanism would result in a reduction in stiffness and a negative correlation of stiffness with A_{2D} and $(e_{\max} - e_{\min})$ shown in Figs. 13(a), (b). On the other hand, in sands with angular grains, a high degree of interlocking between grains will be easily obtained compared with the case of spherical grains; this interlocking will result in the rise of shear strength and the positive correlation of shear stiffness with A_{2D} shown in Fig. 15(a). From the above discussion it can be understood that a negative correlation between shear stiffness and shear strength exists for sands with different primary physical properties under the same conditions. It should be noted that the grass beads provide an extreme case among the granular material samples used in this study; $(e_{\max} - e_{\min})$ and A_{2D} are smallest for grass beads in Fig. 2(a), and the highest shear stiffness in Figs. 13(a)–(c) and the lowest shear strength are attained in Figs. 15(a)–(c).

In Figs. 16(a), (b), ϕ_{cv} and ϕ_d are plotted against the angle of repose ϕ_{rep} . The plots are rather scattered, and it is difficult to find clear tendencies among them. If glass beads are taken into consideration, the positive correlation may be found between ϕ_{cv} and ϕ_{rep} , and between ϕ_d and ϕ_{rep} ; however, this correlation is not applicable to sands with sufficient reliability.

As discussed by Miura, et al. (1997a), the angle of repose ϕ_{rep} can be defined as a kind of angle of internal friction ϕ_d under extreme condition; ϕ_{rep} will correspond to ϕ_d in the loosest state under negligibly small confining pressure. As reported by Maeda and Miura (1999a, 1999b), the angle of internal friction ϕ_d reduces with a decrease in density, and rises, however, with a decrease in confining pressure. The dependencies of ϕ_d on density and confining pressure of the sands with different primary properties were discussed in associated papers (Maeda and Miura, 1999a, b). In order to establish a reliable estimation method for the internal friction angle ϕ_d from the angle of repose ϕ_{rep} and other parameters, further investigations into the effects of density and confining pressure on ϕ_d will be needed.

CONCLUSIONS

The mechanical properties of sands with different primary properties were investigated in this study. The deformation-failure behaviors of all the granular materials were observed in a series of conventional drained triaxial compression tests under the same conditions of relative density and confining pressure. The correlation between mechanical properties and physical properties are summarized in Table 2. From the test results, the mechanical properties of sands are summarized as follows:

—Deformation-strength characteristics of sands are correlated with primary physical properties; this correlation was deduced from the deformation-failure behaviors of many sands with different primary properties under the same condition of confining pressure and relative density.

Table 2. Relationships between primary properties and mechanical properties

	ε_{ac}	E'_{50}	ε_{vcv}	ε_{af}	ϕ_{cv}	ϕ_d
A_{2D}	○ ↗	○ ↘	○ ↗	△ ↗	○ ↗	△ ↗
$(e_{\max} - e_{\min})$	◎ ↗	◎ ↘	◎ ↗	◎ ↗	○ ↗	○ ↗
I_{cr}	—	—	—	—	—	◎ ↘
ϕ_{rep}	—	—	—	—	○ ↗	○ ↗
ε_{ac}	—	◎ ↘	◎ ↗	◎ ↗	◎ ↗	○ ↗
E'_{50}	◎ ↘	—	◎ ↘	◎ ↘	◎ ↘	○ ↘
ε_{vcv}	◎ ↗	◎ ↘	—	◎ ↗	○ ↗	○ ↗
ε_{af}	◎ ↗	◎ ↘	◎ ↗	—	—	—
ϕ_{cv}	◎ ↗	◎ ↘	○ ↗	—	—	◎ ↗
ϕ_d	○ ↗	○ ↘	○ ↗	—	◎ ↗	—

Grades of correlation: ◎, good; ○, fair; △, weak; —, independent.
Signs of correlation: ↗, positive; ↘, negative.

- The deformation behaviors during consolidation and shearing are closely related to each other. Clear correlation is recognized among the axial strain during consolidation ε_{ac} , the normalized secant modulus E'_{50} , the volumetric strain at maximum volume contraction ε_{vcv} and the axial strain at failure ε_{af} . The values of ε_{ac} , ε_{vcv} , ε_{af} and E'_{50} can be roughly related mutually.
- The values of E'_{50} , ε_{ac} , ε_{vcv} and ε_{af} may be evaluated from the value of void ratio extent $(e_{\max} - e_{\min})$ which can be obtained by simple laboratory tests for maximum and minimum densities.
- The mobilized internal friction angle at maximum volume contract ϕ_{cv} is closely related to E'_{50} .
- The angle of internal friction ϕ_d decreases with an increase in E'_{50} ; however, this negative correlation is not strong. It can be said that ϕ_d changes as a function of crushability index I_{cr} ; ϕ_d tends to decrease with an increase in I_{cr} .
- The relationships of ϕ_d and ϕ_{cv} with the angle of repose ϕ_{rep} are not clear. In order to estimate the value of ϕ_d from the value of ϕ_{rep} , the dependency of ϕ_d on density and confining pressure must be investigated more closely.

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