Shearing and Compression Behavior of Compacted Sand-Clay Mixtures

W. Mun

Hushmand Associates Inc., Irvine, CA, USA

M.C. Balci

Department of Civil Engineering, Batman University, Turkey

F. Valente

Pontifical Catholic University of Rio De Janeiro, Brazil

J.S. McCartney

Department of Structural Engineering, University of California San Diego, USA

ABSTRACT: This study focuses on the impact of clay content on the undrained shear strength and compression curves of unsaturated sand-clay mixtures. The results from three testing programs on sand-clay mixtures are presented that build upon previous studies on sand and clay. These include unconsolidated-undrained triaxial compression tests to assess rate effects on the undrained shear strength tests, oedometer tests to assess suction effects on the compression curve, and isotropic compression tests to assess transitions in the compression curve up to mean effective stresses of 160 MPa. The triaxial compression tests indicate that sand-clay mixtures have lower undrained shear strength than the sand or clay, with an intermediate rate of increase in shear strength with strain rate. The oedometer tests indicate that suction in the clay matrix has an important effect on the preconsolidation stress of the sand-clay mixture. The isotropic compression tests indicate that all mixtures have a softer initial response than pure sand. At mean effective stresses greater than 30 MPa the specimens with clay contents less than 10% follow the compression curve of pure sand, while those with clay contents greater than 20% approach the compression curve of pure clay.

1 INTRODUCTION

Sand-clay mixtures are used in geotechnical engineering practice when a fill material must have aspects attributed to the sand fraction, such as high shear strength or low compressibility, and aspects attributed to the clay fraction, such as low permeability. They are also used when creating cost-effective hydraulic barriers by adding sand to sodium bentonite clay (Kinney et al. 1992; Howell et al. 1997), as sand typically has a much lower cost than sodium bentonite. Sand-clay mixtures may also be used in compacted fills that require a high dry unit weight, as clay particles can fill voids between sand particles. Further, mixing sand and clay may lead to a lower swelling pressure than that for clay alone (Komine and Ogata 1999). The primary applications in geotechnical engineering practice where sand-clay mixtures are used include hydraulic barriers on slopes, barriers for nuclear waste repositories, or thermo-hydraulic backfills for geothermal boreholes.

Although there have been several studies on the hydraulic and mechanical properties of sand-clay mixtures, the behavior of these mixtures having different percentages of sand and clay under a wider range of conditions, including variable shearing rates, different degrees of saturation, and high mean effective stresses may be useful when expanding the range of applications where these mixtures can be used. For example, some mining applications may require very large overburden stresses to be applied to the clay, and earthquake loading of hydraulic barriers may lead to shearing at different strain rates. In these situations, it is useful to understand the contributions of the sand and clay to the mixture behavior.

This study builds upon a series of previous studies on the behavior of Mason sand and Boulder clay under elevated strain rates and high mean effective stress ranges by investigating mixtures with different percentages of sand and clay. Strain rate effects on the shear strength of Mason sand were investigated by Svoboda and McCartney (2013), and the drained isotropic compression of Mason sand to high mean stresses was investigated by Mun and McCartney (2017). Strain rate effects on the shear strength of Boulder clay were investigated by Svoboda and McCartney (2014) and Mun et al. (2016), while the drained compression of unsaturated Boulder clay to high mean stresses was investigated by Mun and McCartney (2014, 2016). This study presents the results from a series of unconsolidated-undrained (UU) triaxial compression tests at different strain rates, a series of oedometric compression tests, and a series of drained isotropic compression tests on unsaturated mixtures of Mason sand and Boulder clay. Variables investigated include the percentage of Boulder clay (i.e., 0, 2.5, 5, 10, 20, and 100% clay) and the degree of saturation.

2 BACKGROUND

Early studies on sand-clay mixtures focused on the behavior of sand-clay mixtures formed due to sedimentation, to understand the fundamental effects of the sand and clay on the shear stress-strain response of natural soils (e.g., Lupini et al. 1981; Shakoor and Cook, 1990; Georgiannou et al. 1990; 1991). Later studies focused on the behavior of compacted sand-clay mixtures to form hydraulic barriers for landfills or radioactive waste repositories (e.g., Kenney et al. 1992; Howell et al. 1997; Wiebe et al. 1998). Georgiannou et al. (1990) noted that the effect of a clay and a sand-clay mixture will depend on the grading of the sand, clay content, mineralogy of the clay, pore water chemistry, and distribution of clay within the soil, and the method of deposition in a natural setting (e.g., sedimentation of a suspended liquid or movement of fines into a sandy layer due to piping or other phenomena. Vallejo and Mawby (2000) tested sedimented specimens of Ottawa sand-kaolinite clay mixtures and found that when the percentage of clay in the sand-clay mixture was less than 25%, the shear strength was similar to that of the sand, while when the percentage of clay was greater than 60%, the shear strength was similar to that of the clay, and a transitional effect dominated by the sand was observed for intermediate clay percentages. They found that the porosity due to sedimentation under a given mean effective stress controlled the behavior. Wood and Kumar (2000) observed that the clay matrix dominates the shear strength for clay contents greater than 40%, while Shafiee et al. (2008) found that the clay plasticity leads to a decrease in shear strength. Prakasha and Chandrasekaran (2005) found that adding sand to clay leads to greater excess pore water pressures during undrained shearing, leading to decreases in undrained shear strength. Blatz et al. (2002) and Tang (2002) found that the initial suction and dry unit weight have an important effect on the shear strength of sand-bentonite mixtures, although the initial soil structure induced by compaction may play an equally important role.

For compacted sand-clay mixtures, the percentages of sand and clay will have an important effect on the soil structure and optimum water content and dry unit weight values. Kenney et al. (1992) observed that there may be an optimal clay content that would lead to an increase in the dry unit weight of a compacted sand-bentonite mixture, while Howell et al. (1997) found that the addition of clay may lead to an increase or decrease in the optimal water content and maximum dry unit weight under to the standard Proctor compaction effort. Kenney et al. (1992) observed that the hydraulic conductivity of sand-bentonite mixtures decreases nonlinearly on a log-linear plot over 4-5 orders of magnitude, while Watabe et al. (2011) observed a log-linear decrease in hydraulic conductivity with increasing bentonite content and decreasing void ratio due to isotropic compression.

While many researchers have been focused on the compression behavior of sand-clay mixtures (Wiebe et al. 1998; Blatz et al. 2002; Tang et al. 2002; Watabe et al. 2011; Fan et al. 2014), they focused on the compressibility of mixtures under saturated conditions with a maximum effective stress of 3 MPa. Watabe et al. (2011) found that the compression index increases linearly as the amount of clay increases. The role of sand-clay mixtures is expected to have an important effect the compression of soils to high stresses. Mun and McCartney (2015) developed an isotropic compression cell to investigate the compression behavior of soils to mean effective stresses up to 160 MPa, and several subsequent studies found that there are key transition points in the compression curves of clays due to pressurized saturation and the transition to void closure that depends on the drainage conditions (Mun and McCartney 2016) and in the compression curves of sands due to particle crushing (Mun and McCartney 2017). Unsaturated conditions are also expected to play a role in the compression response, primarily dominated by the unsaturated behavior of the clay (Wiebe et al. 1998; Blatz et al. 2002; Tang et al. 2002).

3 MATERIALS AND METHODS

3.1 *Materials*

The two soils investigated in this study are Mason sand (classified as SW according to the Unified Soil Classification Scheme, USCS), the properties of which have been reported in detail by Svoboda and McCartney (2013) and Mun and McCartney (2017), and Boulder clay (classified as CL according to the USCS), the properties of which have been reported in detail by Svoboda and McCartney (2014), Mun and McCartney (2014), Mun et al. (2016) and Mun and McCartney (2016a, 2016b). Mason sand has minimum and maximum void ratios of 0.50 and 0.78, and a specific gravity of 2.62. Boulder clay has a liquid limit of 41, a plastic limit of 18, and a specific gravity of 2.70.

Mason sand-Boulder clay mixtures with clay contents of 2.5, 5, 10, and 20% (and in one test 40%) were prepared by first oven drying the two soils. The oven-dry Boulder clay was crushed in a mortar and pestle to break up aggregates, and passed through a #16 sieve to remove large particles, while the oven-dry Mason sand was prepared without pre-processing. The two soils were carefully mixed in dry conditions to ensure uniformity without losing fines. Water was added to the mixtures to reach different gravimetric water contents and permitted to hydrate for 24 hours in a sealed bucket. Results from standard Proctor compaction tests for the sand, clay, and sand-clay mixtures are shown in Figure 1(a). The compaction curve for the sand was relatively flat, while the compaction curve for the clay followed a typical shape observed in the literature. The addition of clay to the mixtures led to greater dry unit weights, with the greatest dry unit weight observed for the mixture with 20% clay. The mixtures in this study were compared on the basis of the same dry unit weight, and the target dry unit weight (γ_d) for the sand-clay mixtures is 16.4 kN/m^3 (void ratio of 0.56). The specimens in the triaxial compression and isotropic compression tests were both prepared at a compaction water content of 10%, while the oedometric compression tests were performed on specimens with compaction water contents that correspond to S_r of 1.00 and 0.46 at 16.4 kN/m^3.

(a) (b) (c)

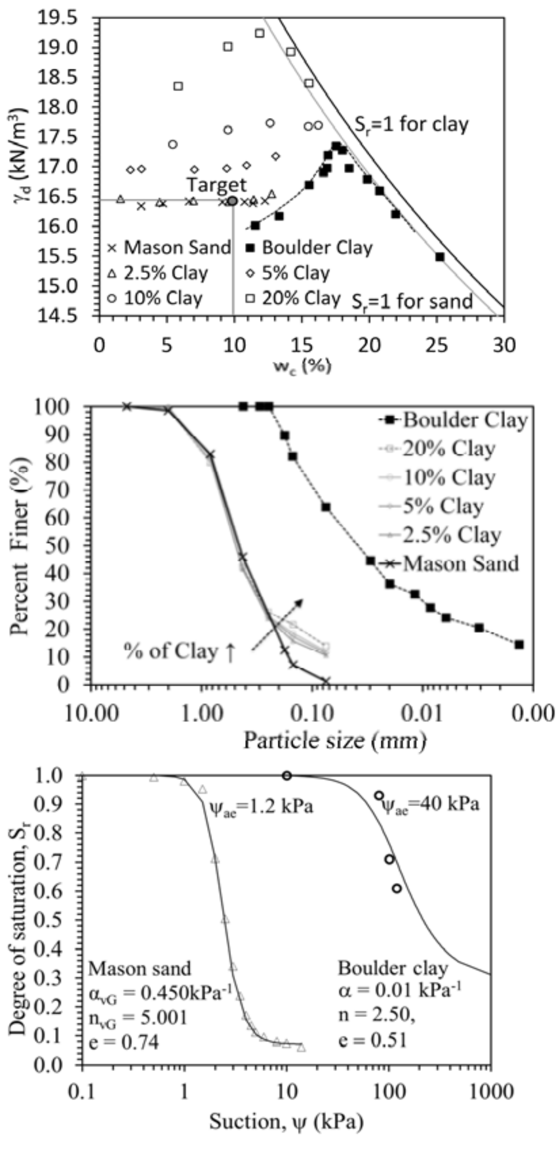


Figure 1. (a) Compaction curves for sand, clay and sand-clay mixtures; (b) Particle size distributions for sand, clay, and sand-clay mixtures; (c) SWRCs for sand and clay.

A sieve analysis was performed in accordance with ASTM D6913 to measure the particle size distributions of the sand-clay mixtures, which are shown in Figure 1(b). As expected, an increase in the fines content is observed with increasing clay percentage. Because the triaxial compression and oedometer tests were performed on unsaturated specimens of the sand-clay mixtures, the soil water retention curves (SWRC) for Mason sand and Boulder clay are shown in Figure 1(c). The parameters of the van Genuchten (1980) SWRC model are shown in the figure for comparison. Although the SWRCs of the mixtures were not measured, it is assumed that they are dominated by the clay SWRC.

3.2 *Experimental Approaches*

The undrained shearing behavior of compacted specimens of sand-clay mixtures was investigated by performing unconsolidated-undrained (UU) triaxial compression tests at different rates of shearing, without drainage of water or air. These tests were performed on as-compacted specimens in a triaxial cell with a frame that can apply axial strain rates of up to 150 %/min. The initial suction of the specimens can be estimated from the SWRC of the clay. The specimens are expected to have a flocculated structure as they were compacted dry of optimum.

Compression tests were performed in an oedometer for soil specimens with two different initial degrees of saturation (S_r of 1.00 and 0.46) up to axial stresses of 9.3 MPa. The saturated specimens were tested in drained conditions while the unsaturated specimens were tested in constant water content conditions. Mason sand-Boulder clay mixtures were prepared for the oedometer test using static compaction in a mechanical press in two lifts into the oedometer ring. The oedometer ring has an inside diameter of 38 mm and a height of 30 mm. In case of saturated conditions, the specimens were inundated with tap water for 24 hours after application of a seating load of 200 kPa. A pneumatic loading piston was used to apply axial stresses in stages. At each loading stage, time was permitted for the specimen to reach 90% consolidation using a root-time consolidation plot, or until settlement stopped. After this point, the final height of the specimen was recorded.

Finally, a series of drained isotropic compression tests under mean effective stresses up to 160 MPa were conducted for saturated specimens of the mixtures having the same initial void ratio with clay contents of 5, 10, 20, and 40%. The sand-clay specimens were prepared by tamping into a neoprene membrane, which was held in place with a metal mold and attached to the bottom pedestal of the cell described by Mun and McCartney (2015). The initial specimen dimensions were 76.2 mm in both diameter and height (1:1 ratio). The specimens were saturated following the approach described in Mun and McCartney (2015), and mean stresses were applied to the cell using a syringe pump. Brake fluid was used as the cell fluid. A constant volumetric strain rate of 1% hour in stress-controlled conditions was applied, which was observed to lead to drained conditions based on the water outflow volume during compression. The syringe pump position was used to infer the specimen volume during compression. A specimen of dry Mason sand tested by Mun and McCartney (2017) having the same void ratio as the mixtures and a specimen of saturated Boulder clay tested by Mun and McCartney (2016b) with a lower initial void ratio of 0.51 were used for comparison.

4 RESULTS

4.1 *Undrained Shearing Response*

The undrained shear strength values for sand-clay mixtures, along with sand and clay, as a function of the axial strain rate are shown in Figure 2(a). The clay was observed to have the highest undrained shear strength of all the specimens, likely due to negative pore water pressures generated during undrained shear as observed by Svoboda and McCartney (2014), although the shear strength of the dry sand was only slightly lower. The shear strength of the sand-clay mixtures was consistently lower than that of the sand or clay, with a nearly linear decrease in undrained shear strength with increasing clay content up to 20%, as shown in Figure 2(b). The rate of increase in the undrained shear strength of the sand-clay mixtures with axial strain rate was similar, with a slope that was between that of the clay and sand.

4.2 *Oedometric Compression Response*

The impact of suction on the apparent preconsolidation stress as well as the slope of the normal compression line on unsaturated sand-clay mixtures was investigated by comparing the results from the oedometer tests on mixtures with a different portion of clay under two different initial degrees of saturation. Compression curves for each mixture having initial S_r values of 1.00 and 0.46 are shown in Figures 3(a) and 3(b), respectively. As the clay content increases, the specimens exhibited a softer compression response, consistent with Watabe et al. (2011). Similar effects of the clay percentage for both initial degrees of saturation are observed.

The apparent preconsolidation stress values estimated using Casagrande's approach are shown in Figure 4(a). A greater preconsolidation stress was observed for specimens with a lower initial degree of saturation of 0.46 for all sand-clay specimens. Pure Mason sand was observed to have the greatest increase in preconsolidation stress due to the lower degree of saturation, and the increase in the preconsolidation stress was smaller for increasing clay percentages. This indicates that the incorporation of the sand into the mixture leads to a hardening effect.

(a)

(b)

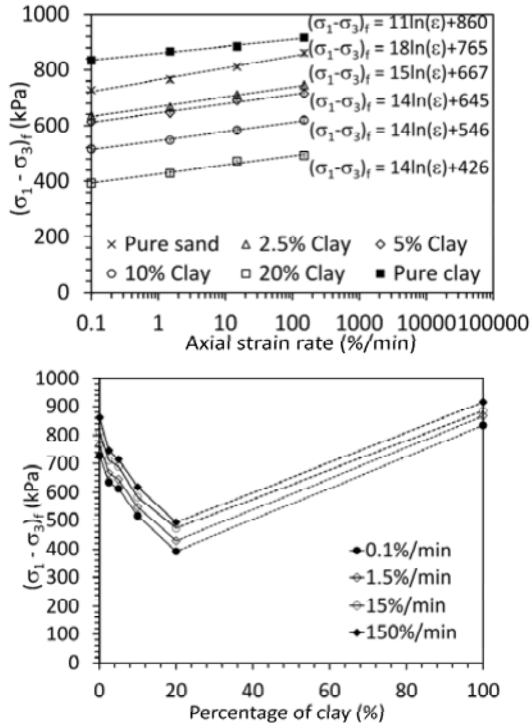


Figure 2. Undrained shear strength of sand-clay mixtures: (a) Effect of axial strain rate; (b) Effect of percentage of clay

(a)

(b)

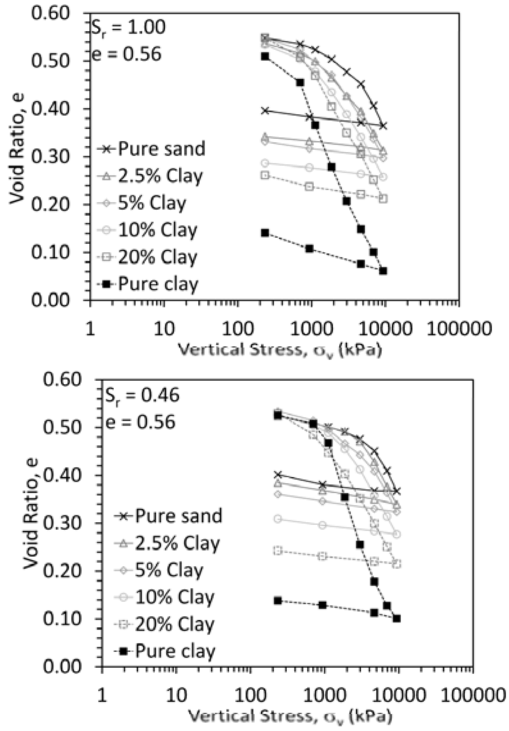
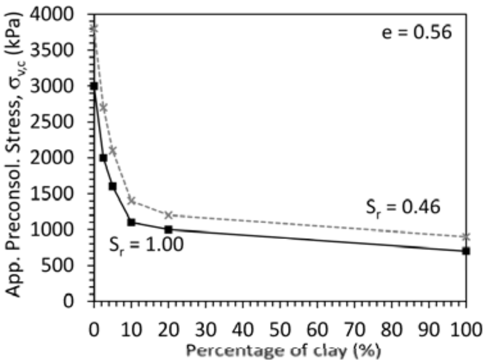


Figure 3. Compression behaviour of sand-clay mixtures from oedometer tests under different initial degrees of saturation: (a) $S_r = 1.00$ (drained) (b) $S_r = 0.46$ (constant water content)

The compression indices for the loading and unloading paths of the oedometer tests are shown in Figure 4(b). The slope of the normally-consolidated portion of the sand-clay mixtures was observed to increase slightly with the clay content, reflecting a softer response. The slopes of the unloading curves are similar, with a softer response for the pure clay. Similar trends in the compression indices are observed for both degrees of saturation tested. Mun and McCartney (2016) observed that some studies observed a negligible change in the values of λ and κ with suction for mean stresses less than 10 MPa.

(a)



(b)

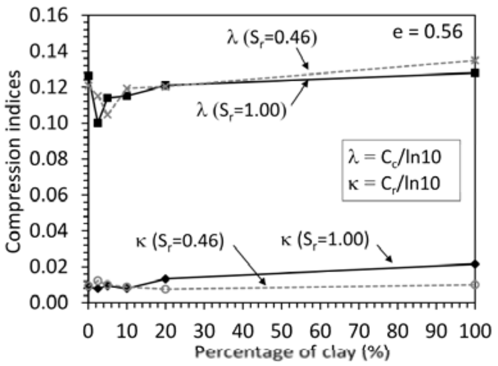
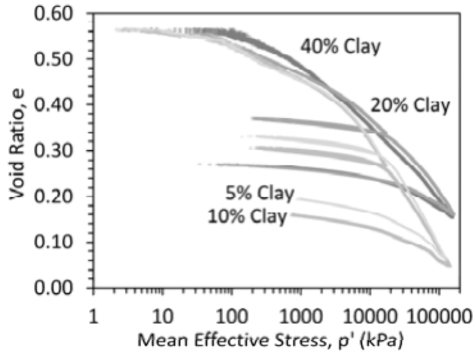


Figure 4. Compression characteristics of sand-clay mixtures from oedometer tests: (a) Vertical effective preconsolidation stress; (b) Compression indices

4.3 *Drained Isotropic Compression*

The isotropic compression response of saturated sand-clay mixtures in drained, constant rate of strain conditions up to mean effective stresses of 160 MPa was assessed for sand-clay mixtures of 5, 10, 20, and 40% having the same initial void ratio. The drained compression curves for the sand-clay mixtures are shown in Figure 5(a) with the mean effective stress plotted on a logarithmic scale and in Figure 5(b) with the mean effective stress plotted on a natural scale. The two specimens having clay contents of 5 and 10% have similar shapes, while the two specimens having clay contents of 20 and 40% have similar shapes. A conclusion that may be different from that expected from compression studies to lower stresses is that the specimens with lower clay content show greater reductions in void ratio at high mean effective stresses. This may be because the soil structure is able to rearrange more when the clay content is smaller (for which there is a greater number of open voids), meaning that particle crushing is more likely. Particle crushing was observed in tests on pure Mason reported by Mun and McCartney (2017), which may be mitigated by the presence of the clay in the voids. Due to the range of mean effective stresses, a bi-log-linear interpretation of the compression curves cannot be used, as noted by Mun and McCartney (2016b). Evaluating the compression curves on a natural scale indicates that the specimens are transitioning toward a constant void ratio, referred to as a transition to void closure.

(a)



(b)

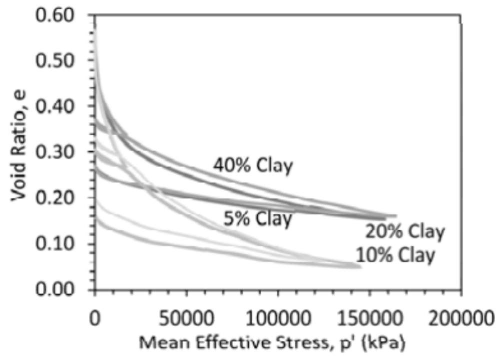


Figure 5. Drained compression curves of sand-clay mixtures with different percentages of clay: (a) e-logp′; (b) e-p′

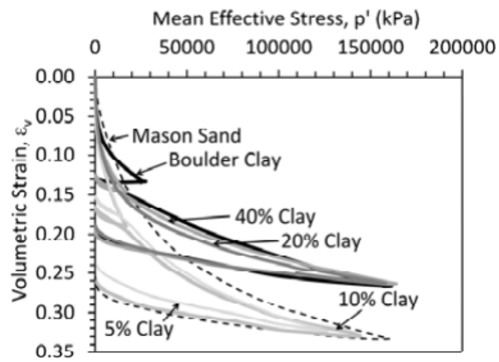


Figure 6. Drained compression curves of saturated sand-clay mixtures, dry Mason sand and saturated Boulder clay

Because the specimen of saturated Boulder clay tested by Mun and McCartney (2016) has a lower initial void ratio than the sand-clay mixtures (0.51 vs. 0.56), the compression curves of the mixtures are compared with those of dry Mason Sand and saturated Boulder clay in terms of the volumetric strain in Figure 6. The compression curves of the mixtures follow that of Boulder clay for mean effective stresses less than 3 MPa. At mean effective stresses greater than 30 MPa, the compression curves for the sand-clay mixtures with 5 and 10% clay are similar to that for pure Mason sand, while the compression curves for the sand-clay mixtures with 20 and 40% clay are similar to that for pure Boulder clay. The slightly stiffer response of the clay at low mean effective stresses is due to the lower initial void ratio.

5 CONCLUSIONS

This study focuses on the impact of clay content on the undrained shear strength and compression curves of saturated and unsaturated sand-clay mixtures, with testing programs that build upon previous studies on pure sand and pure clay. The triaxial compression tests indicate that unsaturated sand-clay mixtures have lower undrained shear strength than the sand or clay themselves, but with an intermediate rate of increase in shear strength with increasing strain rate. The oedometric compression tests on saturated and unsaturated specimens indicate that hardening due to the initial unsaturated conditions, expressed as a greater preconsolidation stress, decreases as the percentage of clay increases. The compression indices of the normally-consolidated portion of the compression curves for the sand-clay mixtures increased with clay content, reflecting a softer response, but were not sensitive to the unsaturated conditions. The drained isotropic compression tests indicate that transitional behavior between the compression curves for sand and clay occurs only for clay contents less than 10%. The drained isotropic compression curves indicate that higher sand contents may lead to a stiffer response for low mean effective stresses, but may result in higher reductions in void ratio when compressed to high mean effective stresses near the transition to void closure (i.e., greater than 30 MPa).

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