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One-dimensional compressibility of intermediate non-plastic soil mixtures

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ONE-DIMENSIONAL COMPRESSIBILITY OF INTERMEDIATE

NON-PLASTIC SOIL MIXTURES

An Honors Thesis submitted in partial fulfillment
of the requirements for Honors Studies in
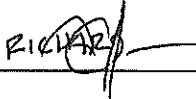Civil Engineering

By

Sean Elliott Salazar

2013
Department of Civil Engineering
College of Engineering
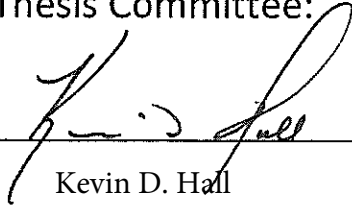**The University of Arkansas**

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One-dimensional Compressibility of Intermediate Non-plastic Soil Mixtures

SEAN E. SALAZAR

ABSTRACT

The results of high stress, one-dimensional compression testing on intermediate soils are presented. Nevada Sand and silica silt mixtures were subjected to very high vertical stresses (140 MPa) in one-dimensional, monotonic compression. Each soil mixture was tested in a nominally loose condition. A specially designed mold with an integrated sensor array was fabricated to contain the soil during pre-consolidation and loading. The 1-D compression curve was plotted for each mixture in the double-logarithmic void ratio (e), and vertical effective stress (σ'_v) space and characteristics of the Limiting Compression Curve (LCC) were identified. Initial and post test grain size distribution curves were plotted. Significant crushing of the soil grains was observed during one-dimensional loading. The influence of factors including initial density, mineralogy, particle shape, particle size, and grain size distribution on compression behavior of intermediate soil mixtures is discussed. Specimen preparation techniques and testing protocol are presented herein.

1.1 INTRODUCTION

Loose sand matrices tend to contract under cyclic, partially drained loading induced by earthquake shaking. If the soil is saturated and drainage is limited, stress may be transferred from the soil matrix to the pore water, causing the soil to lose strength and "liquefy". The concomitant effects are the loss of strength and stiffness of the soil and the seepage of water to the surface (Idriss and Boulanger 2008). Liquefaction may lead to settlement and bearing capacity failures of structures embedded in the soil, cause failure in earth structures, including earth dams and levees, trigger landslides and cause flotation of buried pipes and tanks (Cox et al. 2009). The evaluation of liquefaction potential in seismic zones is of high interest to geotechnical and earthquake engineers; a site may be characterized by means of in-situ and laboratory testing, in order to determine susceptibility to liquefaction.

There is a fundamental lack of understanding of the behavior of intermediate soils (silty sands, sandy silts, clayey sands, sandy clays, and low-plasticity silts); though the importance of intermediate soils is pervasive in earthquake engineering, particularly in liquefaction susceptibility assessments. There is a plethora of strength data for clean sands and pure clays and the strengths of intermediate soils are usually interpolated.

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However, these interpolations are not based on any solid theory or data that relate to the fundamental behavior of intermediate soils. For liquefaction analyses, fines content corrections have been formed empirically. Boulanger and DeJong (2012) have proposed a research program that contains laboratory testing including 1-D compression, Direct Simple Shear (DSS) and triaxial testing, numerical simulations using FLAC to implement the MIT-S1 constitutive model (Pestana and Whittle, 1999) using an Arbitrary Langragian-Eulerian (ALE) remeshing technique, and small centrifuge modeling, in order to meet the need for reliable intermediate soil strength data and characterization under cyclic seismic loading. Strength data measured in the laboratory will be used to calibrate the FLAC model to determine the relationship between cone penetration resistance (q_c) in cone penetration testing (CPT), and properties including monotonic strengths and cyclic resistance ratios (CRR). The model will be validated using centrifuge testing.

The correlation that will be obtained in this project aims to determine a triggering curve that describes the liquefaction potential of intermediate soils. It has been shown that plotting a curve with q_c as a monotonic strength indicator on the abscissa against CRR (the ratio between shear stress, τ_{cyc}, and the initial effective confining stress, σ'_{vc} required to cause liquefaction) on the ordinate, may predict a triggering curve that describes the potential for soils to liquefy as a function of earthquake induced stresses. This concept is represented in Figure 1.1. These plots are based only on case histories where liquefaction either occurred (solid points) or did not occur (hollow points); the triggering curve represents the boundary between these two conditions. The liquefaction correlations are determined using a combination of empirical data, lab testing, numerical modeling and physical modeling. Historically, such relationships have been developed only for clean sands and sedimentary clays. As a result, the goal of this project is to better characterize the liquefaction potential of intermediate soils.

(a)

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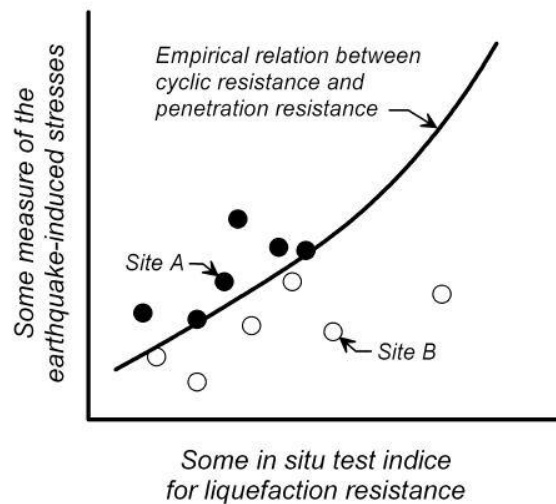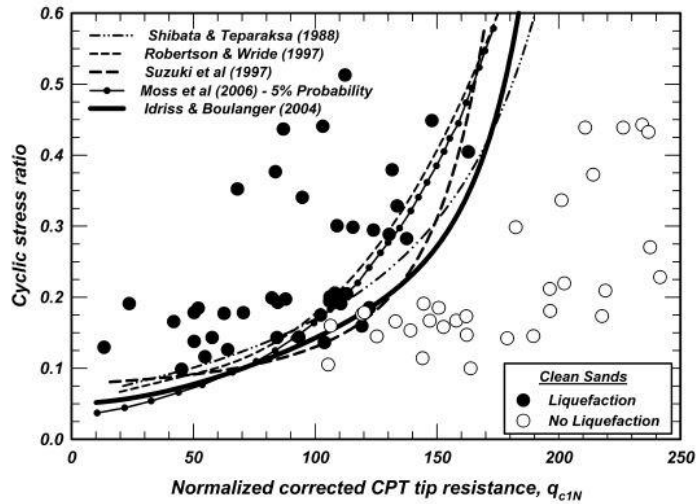
(b)

Figure 1.1 **Liquefaction triggering curves: (a) conceptual curve, (b) curves relating the CRR to q_{c1N} for clean sands with M = 7.5 and σ_{vc} = 1 atm. (from Idriss and Boulanger 2008).**

The testing program of this project includes 1-D compression testing that comprises three stages: testing on mixtures of clean Nevada Sand with non-plastic fines, non-plastic silica flour with Kaolin clay, and clean Nevada Sand and Yolo loam. The first stage of laboratory testing, presented in this paper, investigates the influence of the proportion of non-plastic fines content on the compressibility of granular soils. In this context, non-plastic fines are defined as non-cohesive silt particles. The testing program loosely follows previous testing conducted at the Soil Interactions Laboratory at the University of California Davis by Erickson (2013); however, attempts were made to reduce uncertainty due to equipment limitations, by improving testing equipment and establishing a revised testing protocol that will be the standard for future one-dimensional compression testing.

1.2 BACKGROUND

Previous work on the influence of factors including initial density, mineralogy, particle shape, particle size, and grain size distribution on compression behavior of soils is discussed.

1.2.1 Limiting Compression Curve (LCC)

Monotonic soil strength tests have been conducted for decades. Roberts and de Souza (1958) investigated the one-dimensional compressibility of sands up to stresses of 10,000 psi (69 MPa) and observed significant deformation in specimens after the onset of

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crushing and fracturing of particles. It was observed that the initial void ratio (e_o) had a significant effect on the "breakdown stress", defined as the point at which the sand started to crush significantly. Vesić and Clough (1968) investigated the compressibility of uniformly graded sand in Standard Triaxial compression. The specimens were loaded up to 1000 kg/cm^2 (98 MPa) and it was observed that the granular material behaved in a dilative manner at low confining pressures, eventually reaching a state of high relative compressibility at high stresses, where linear deformation was observed, regardless of e_o. The initial dilative behavior of the specimens was explained as a rearrangement of particles (rolling and sliding). The observed behavior at high stresses was in good agreement with the work of Roberts and de Souza (1958). Given a set of soil specimens prepared at varying initial densities, when subjected to high compressive stresses, the void ratio-effective stress behavior of the specimens has been shown to converge (Pestana and Whittle 1995). In double logarithmic void ratio-effective stress space, the LCC is characterized as the linear portion of the compression curve during which the primary means of volumetric strain development is particle crushing. A conceptual depiction of the LCC is presented in Figure 1.2. Hagerty et al. (1993) showed that the steeper and more linear the portion of the curve after the soil has yielded, the more the material is being crushed. It was also observed that as the angularity of particles increased, the break-point stress decreased and became more difficult to define. Very significant crushing of particles was observed at stress levels above 138 MPa.
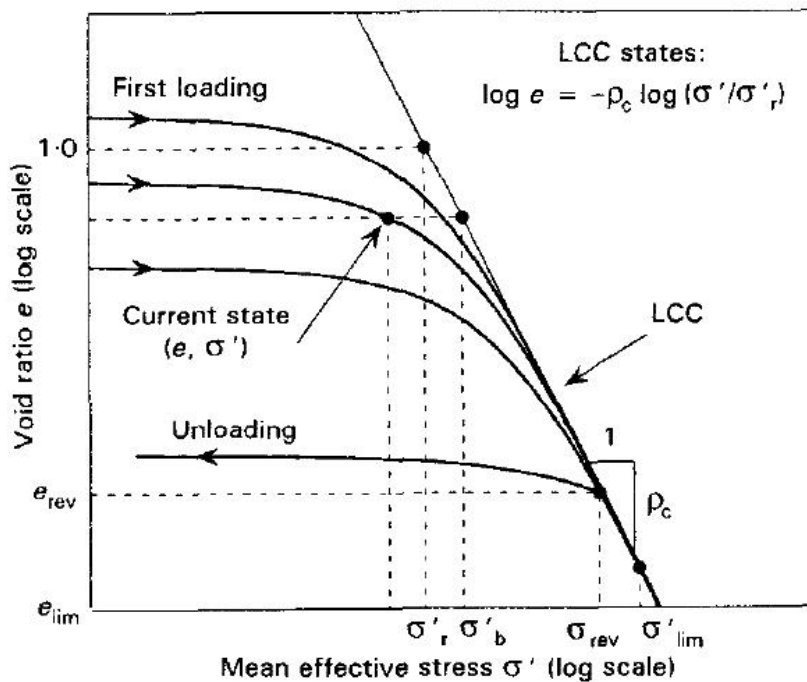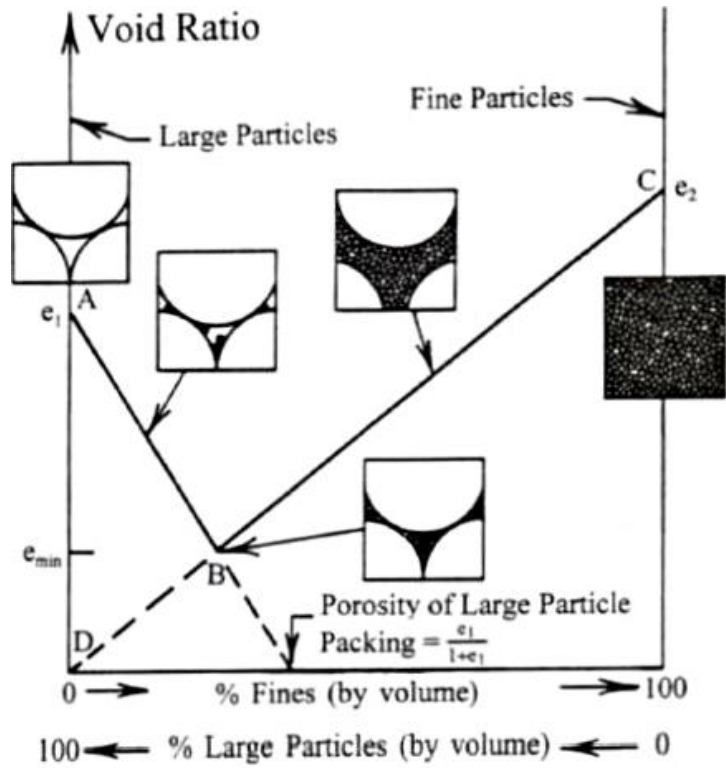

Figure 1.2   **Conceptual representation of first loading and unloading of freshly deposited cohesionless soils (from Pestana and Whittle 1995).**

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Lade et al. (1998) investigated the effects of non-plastic fines on the minimum and maximum void ratios of sand. An illustration of the relationship between fines content and void ratio is depicted in Figure 1.3. There is an optimum grain-size ratio that will produce the maximum density in soil mixtures, but once this ratio is surpassed, the density of the soil may decrease. Nakata et al. (2001a) investigated the relationship between single particle crushing and collective crushing in one-dimensional, monotonic compression tests. The maximum compression index (C_c) characterized by major grain splitting was shown to be independent of initial void ratio. The compression index increased during the early stages of compression as the initial void ratio increased. Higher initial void ratio resulted in lower yield strengths. It was shown that single particle strength increased as particle size decreased and that collective crushing was dependent on particle angularity. The compression behavior was marked by the breakage of particle asperities during particle rearrangement before grain splitting occurred. The load was theorized to increasingly distribute and transfer throughout the soil matrix with increasing angularity of particles.

Nakata et al. (2001b) conducted one-dimensional, monotonic compression tests on silica sand. The LCC behavior indicated that the stress corresponding to the maximum curvature of the compression curve was greater for well-graded material than for uniformly graded material. The rate of increase in particle damage slowed down considerably in well-graded materials and it was therefore shown that as the coefficient of uniformity increased, so the curvature of the compression curve decreased. Nakata et al. (2001a) observed that ninety percent of particles sustained some kind of damage and fifty percent had undergone major splitting. Particle size analyses showed that the soils had a tendency to approach a stable gradation after full development of crushing.

Void Ratio

Large Particles

Fine Particles

e_1 A

e_{min}

B

C e_2

Porosity of Large Particle
Packing $= \dfrac{e_1}{1+e_1}$

D

0 → % Fines (by volume) → 100

100 ← % Large Particles (by volume) ← 0

Figure 1.3 **Theoretical representation of the effect of fine particle content on void ratio of granular material (from Lade et al. 1998).**

Erickson (2013) performed 13 one-dimensional, monotonic compression tests on loose and dense state soil mixtures of Nevada Sand and silica silt. Compliance was observed in testing equipment during compression, which may have affected the results. Additionally, the compression curves were only plotted up to 100 MPa in log void ratio (e), log effective vertical stress ($\sigma_v{}'$) space. The literature suggests that the lack of data above 100 MPa does not allow for full development of the slope in the critical region of the compression curve corresponding to the LCC.

1.3 TESTING MATERIALS AND APPARATUS

The testing materials and the testing apparatus used in this study for one-dimensional compression testing are described herein.

1.3.1 Soil Characteristics

Two types of soil were tested. Clean Nevada Sand (N) and ground silica (S), SIL-CO-SIL® 250, manufactured by US Silica. Erickson (2013) tested the same two soils and reported a specific gravity, G_s, of 2.66 for the Nevada Sand, according to an evaluation

by Cooper Testing Laboratory (August 2010). According to manufacturer specifications, the silica silt has a specific gravity of 2.65. To ensure as little fines content as possible, the batch of Nevada Sand was sieved mechanically to remove particles passing the #200 sieve (<0.075 mm diameter) following the general guidelines of American Society of Testing and Materials (ASTM) Standard D6913 (2006), Standard Test Method for *Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis.* The grain size distribution of the Nevada Sand batch was determined as per ASTM Standard D422 (2007), Standard Test Method for *Particle-Size Analysis of Soils.* A plot of the grain size distribution is presented in Figure 1.4. From the grain size distribution curves, it can be seen that the Nevada Sand is more uniformly graded with a $D_{50} = 0.11$ mm, whereas the silica silt is more well-graded with a $D_{50} = 0.045$ mm. The significant difference in median grain size allows for the smaller silt particles to fill the voids between the granular sand particles when mixed. Each soil mixture will have a unique grain size distribution and is thus expected to vary in density when prepared using the same method. Scanning electron microscope images of both types of soil are presented in Figure 1.4. From these images, the high angularity of the silt particles relative to the sand grains is apparent. Both types of soil possess essentially the same silicon dioxide mineralogy.

(a)   (b)   (c)
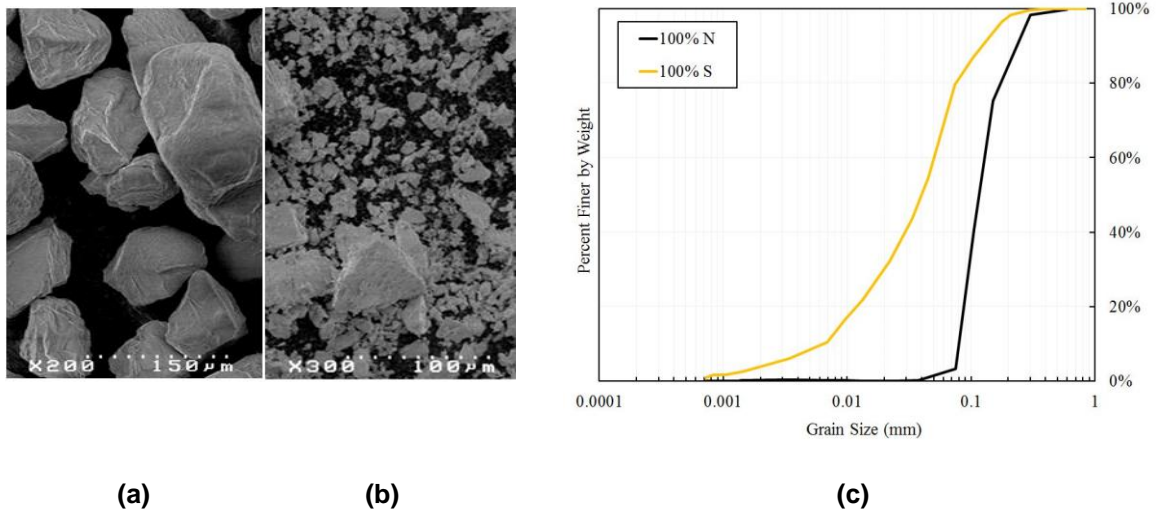
Figure 1.4   **SEM images: (a) Nevada Sand, (b) silica silt. (c) Initial grain-size distribution of Nevada Sand batch and silica silt.**

1.3.2 Compression Mold

A cylindrical, high-grade 4140 stainless steel alloy mold was designed and fabricated for compression testing of soil mixtures. The inner vessel of the mold has a depth of 31.7 mm (1.25 in.) and a diameter of 63.6 mm (2.50 in.). The wall thickness is 12.6 mm (0.50 in.) and is designed to withstand very high stresses. A top cap was designed to fit into the vessel of the mold and slide down into the vessel during compression. Two glands were

milled into the top cap to allow for the placement of two lubricated o-rings that help keep the cap level during pre-consolidation of the soil. An aluminum collar clamps around the upper circumference of the top cap, to provide a rigid platform for attachment of two position transducers. In addition, two holes on opposing sides of the mold have been tapped to allow for thumb screws to attach directly to the mold. Small holes in the heads of these bolts provide an anchor for the shafts of the two position transducers to screw into. There are porous stone inserts in the bottom of the vessel and in the top cap to allow for drainage during consolidation of wet soil mixtures. However, testing presented in this paper was conducted primarily on dry soil mixtures. Images of the mold are presented in Figure 1.5.

Figure 1.5   Stainless steel compression mold vessel and top cap.

1.3.3 Load Frames

A frame with a pneumatic piston and a GEOTAC 500 lb. capacity load cell was designed and fabricated for the pre-consolidation stage of testing. The purpose of the pre-consolidation stage is to obtain an accurate initial void ratio (e_o) for a specimen before compression testing. The frame is designed to load the specimen to 100 kPa, which serves as a reference stress. This reference stress simulates the in-situ effective stress condition at ten feet below the surface during CPT and is an input for calibration of cavity expansion modeling. In addition, the reference stress allows for a more consistent measurement of specimen height, since the specimens may be disturbed between transportation of the mold from preparation to compression stages of testing. A uniaxial MTS load frame (50/100 kip/model 311.21) with a capacity of 100 kips was used to load the specimens to approximately 428 kN (96 kips), which corresponds to a maximum of 135 MPa on the specimens. The full capacity of the machine was reached in order to maximize the range of testing data. Images of the testing apparatus are found in Figure 1.6.

(a)   **(b)**   **(c)**
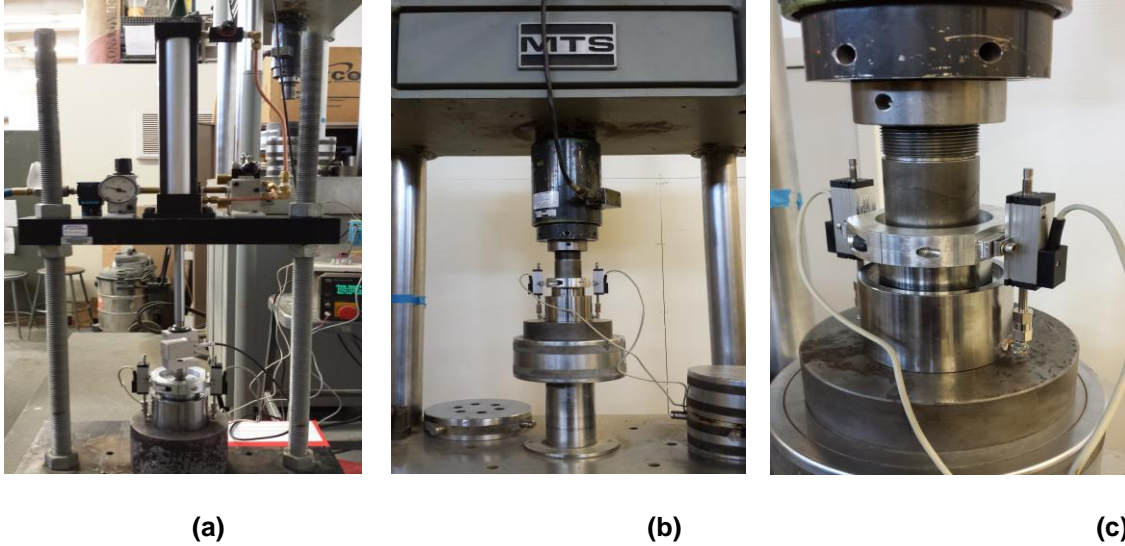
**Figure 1.6   Testing apparatus: (a) pre-consolidation load frame, (b) MTS
                    compression machine, (c) mold during compression of
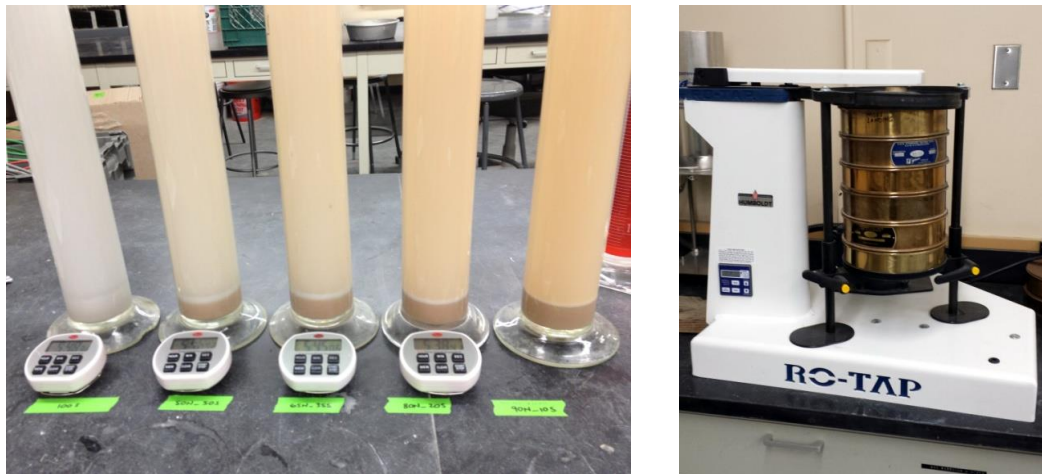   specimens.**

1.3.4 Data Acquisition

Voltage output signals from the GEOTAC load cell, during pre-consolidation, and from
the MTS load cell, during compression, were interpreted with a National Instruments
USB-6009 Interface and recorded with ResDAQ software. Output signals from both
Novotechnik T-series potentiometric position transducers (LPTS) were interpreted by the
same USB interface, so that data from all devices was captured simultaneously and could
be distinguished with assigned channels in the software.

1.4   TESTING PROCEDURE

Below is an outline of the testing procedures from specimen preparation through post-
compression grain-size analyses:

1.4.1 Initial Grain Size Distribution

Six soil mixtures were prepared in the following proportions: 100% N, 90% N/10% S,
80% N/20% S, 65% N/35% S, 50% N/50% S, and 100% S. The initial grain size
distributions for each soil mixture were obtained following the guidelines of ASTM
Standard D422 (2007), Standard Test Method for *Particle-Size Analysis of Soils* as shown
in Figure 1.7. A plot of the grain size distribution curves is shown in Figure 1.8.

Figure 1.7   Particle size analyses performed using hydrometer and sieve analyses tests.
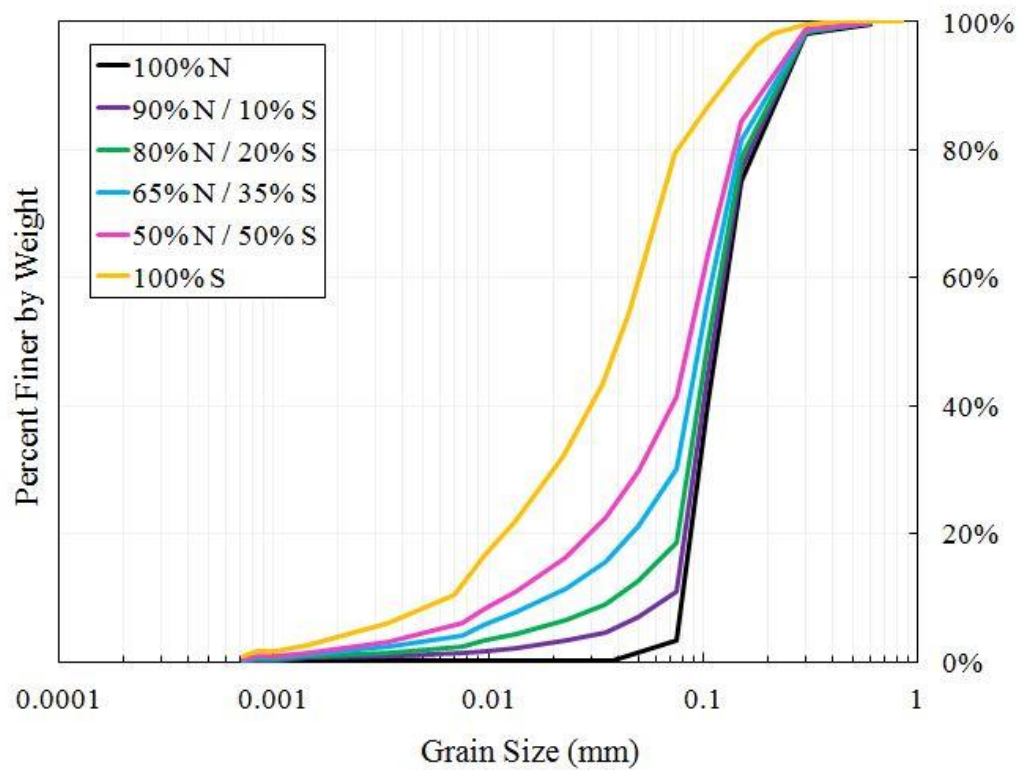
Figure 1.8   Initial grain size distribution curves for each soil mixture.

1.4.2 Specimen Preparation

Loose state specimens were prepared according to ASTM Standard D4254 (2000), Standard Test Method for *Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density*. The remaining soil in the upper half of the mold vessel was trimmed with use of a vacuum. The specimens were prepared with much caution because sample disturbance was a concern between each stage of preparation. Any disturbance could influence the initial void ratios of the specimens. In order to calculate the initial void ratio of a specimen, a consistent specimen mass was ensured in each test. Soil mixtures were prepared proportionally by mass percent of overall specimen mass and mixed with a spatula until homogeneity was evident. Controlling the mass of each soil specimen proved to be a more accurate and repeatable alternative to controlling the height of the specimen. Christoph (2005) established, by means of a parametric study, the ideal specimen height to be approximately 20 mm (0.79 in.) as this would maximize sample size and the accuracy of height measurements. Taking this into account and the dimensions of the compression mold, a height to diameter (H/D) ratio of approximately 0.3 was achieved in all tests. Another benefit of this ratio lies in minimizing frictional effects of the specimen on the inside walls of the mold during compression. To provide some perspective on the loose, dry specimens, some compression tests were also run on initially dense 100% silica silt and 100% Nevada Sand specimens. In order to achieve dense specimens, the 100% silt specimens were prepared in a slurry and poured into the mold. Dense sand specimens were prepared following the same procedures as the loose specimen preparation; however, were densified with a series of hammer taps under overburden pressure applied to the mold top cap. Both methods of preparing dense specimens produced significantly smaller initial void ratios.

1.4.3 Compression Loading

The specimens were pre-consolidated to 100 kPa (1 atmosphere) prior to compression loading. This allowed for a higher resolution, due to limitations in the MTS compression machine. The specimens were then transferred from the pre-consolidation load frame to the MTS compression machine. The integration of linear potentiometers on the mold ensured that changes in specimen height were recorded during the entire process of loading, including the transfer of specimens from the pre-consolidation load frame to the compression machine. The specimens were then loaded at a displacement rate of 0.025 in./min. for the dry specimens and at a rate of 0.007 in./min. for the wet samples to allow for the drained testing condition during consolidation.

1.5   RESULTS

1.5.1   Limiting Compression Curves

Compression curves for six different soil mixtures prepared in a loose state are presented in Figure 1.9. A comparison of compression curves for loosely and densely prepared specimens of 100% Nevada Sand and 100% silica silt are presented in Figure 1.10.
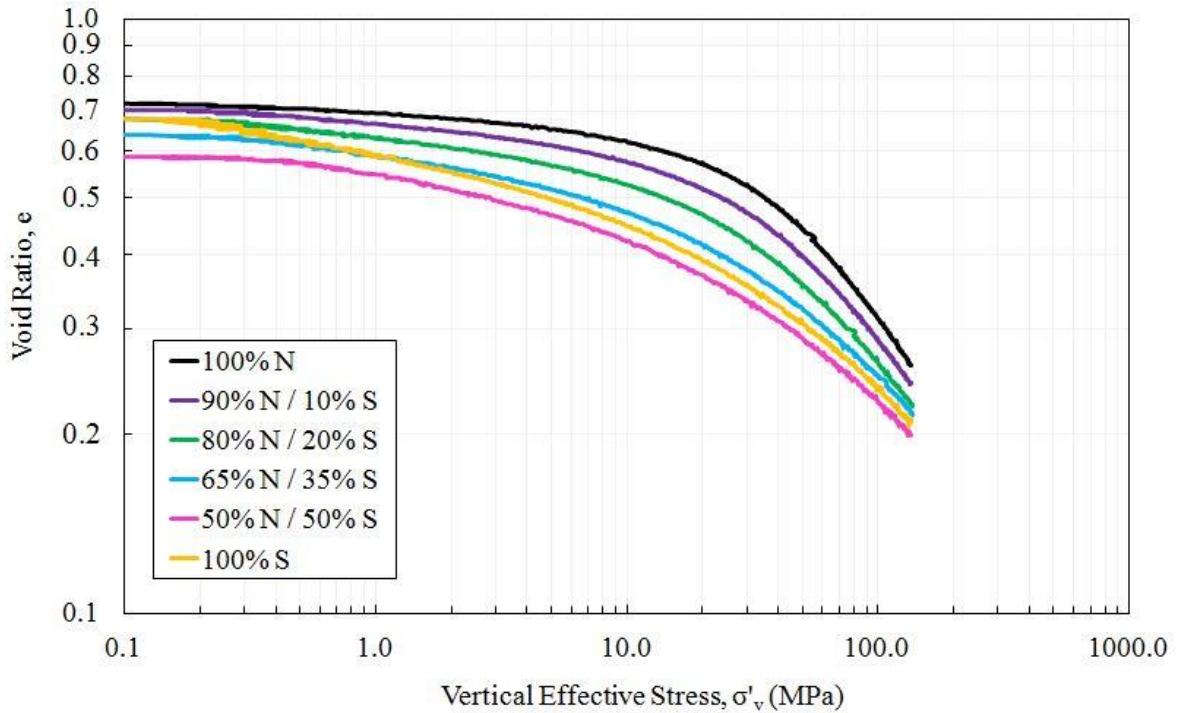
Figure 1.9   Compression curves for each soil mixture prepared at similar densities.
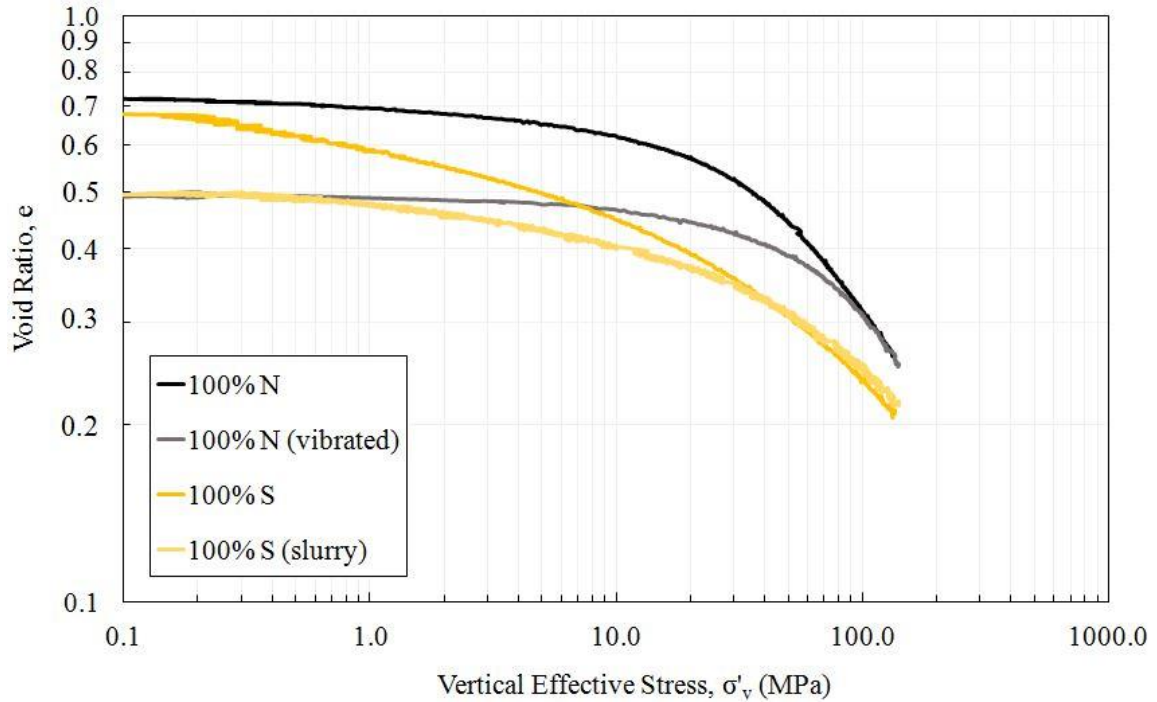
Figure 1.10   Compression curves for loose and dense 100% Nevada Sand (N) and 100% silica silt (S) specimens.

1.5.2 Influence of Fines Content

From the increased smoothness of the compression curves as they approach the LCC in Figure 1.9 it appears that as the proportion of silica fines increases, the yield point becomes less defined. 100% silica silt specimens exhibited high compressibility in the early loading stages during plastic rearrangement of particles. Due to the angularity of the silt particles, it is hypothesized that bridging caused large stable voids in the specimens during loose, dry preparation.

It was observed that during loose, dry preparation of specimens, the mixtures had a natural tendency toward smaller initial void ratios as the proportion of silica silt to Nevada Sand increased (up to 50%). This supports the findings presented by Lade et al. (1998). In the early loading stage, the specimens showed increasing compressibility with increasing fines content, despite typically lower initial void ratios. This phenomenon may be explained by metastable contacts in the sand skeleton during dry specimen preparation. These contacts are highly unstable until force is applied to the specimen, causing the silt particles to get lodged between the larger sand particles (Monkul 2010). The specimen preparation methods likely produced substantially different overall soil fabrics. The slurry preparation method eliminated the stable voids observed in the loose, dry preparation method of the silt specimens.

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The difference in preparation methods is well represented by comparing the slopes of the compressions curves in the low stress region for 100% N and 100% S specimens in Figure 1.10. The compression curve for the dense 100% S (slurry) specimen exhibits an almost horizontal slope in the early stages of loading. Similarly, the compression curve for the dense 100% N (vibrated) specimen exhibits a flat slope. Both loose and dense specimen compression curves approach unique LCCs for 100% N and 100% S, respectively.

1.5.3 Crushing Behavior

The grain size distribution of each of the soil mixtures was determined prior to testing and after testing was complete. These distributions are compared in Figure 1.11. The distributions all clearly show that the percent of fines increased during testing, proving that crushing occurred; however, some doubt may be cast on the accuracy of the grain size analyses performed. The grain size evolution curves are indicative of procedural error during the hydrometer portion of the analyses. Single particle breakage was not investigated in this testing program.

After loading to high stresses, it was observed that the slurry-prepared specimens had cemented in place, which proved difficult to remove from the compression mold. None of the dry specimens showed any indication of cementation.

(a)

(b)
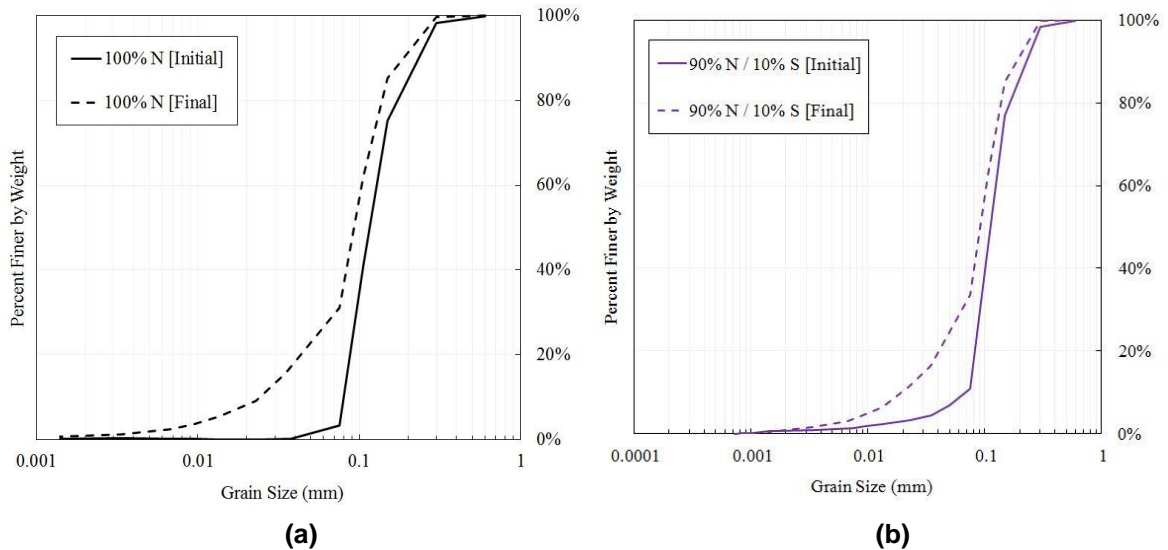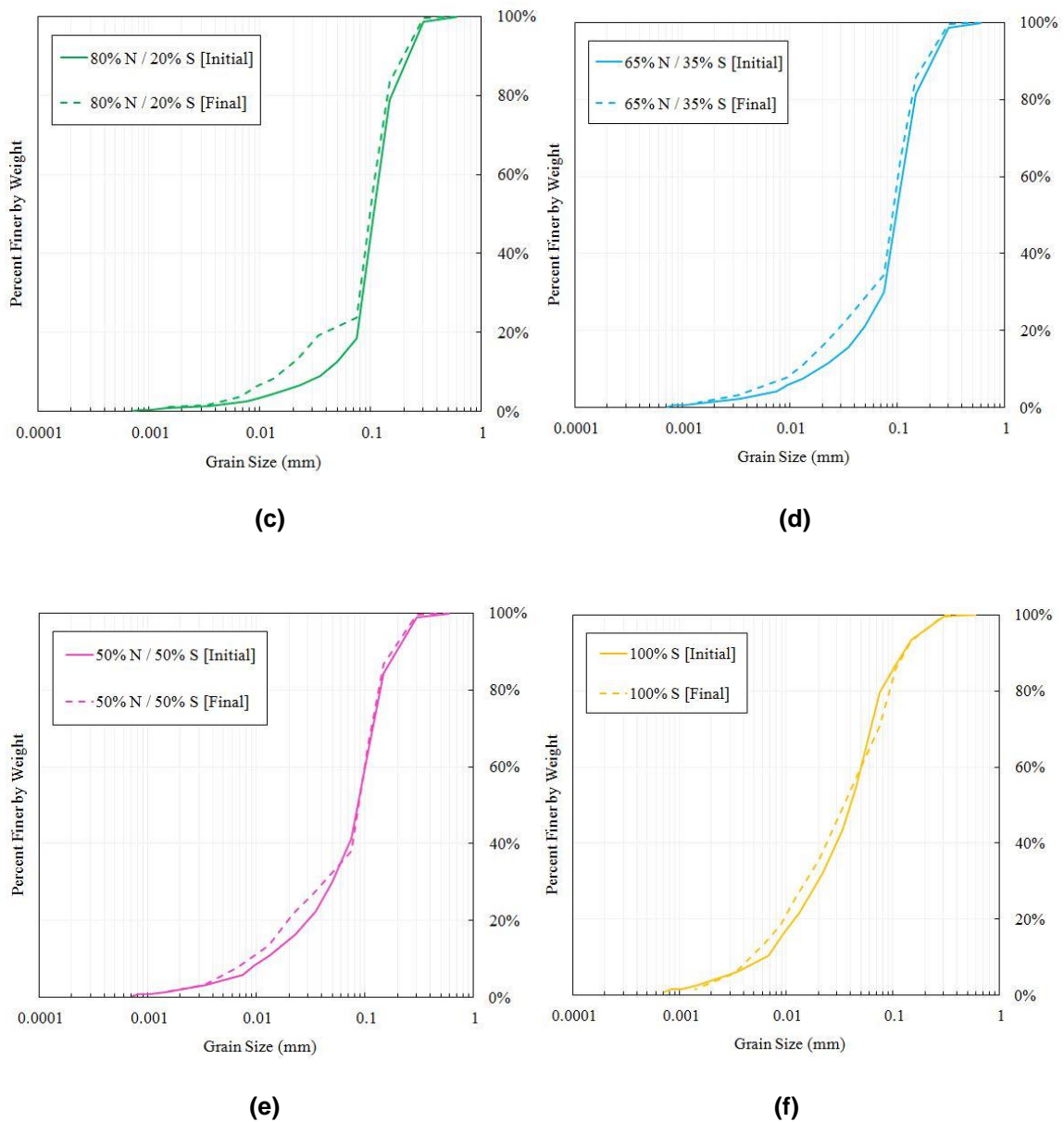
Figure 1.11   Grain size evolution curves for soil mixtures before and after testing: (a) 100% N, (b) 90% N / 10% S, (c) 80% N / 20% S, (d) 65% N / 35% S, (e) 50% N / 50% S, (f) 100% S.

1.6   CONCLUSIONS

A one-dimensional, monotonic compression testing program has been presented. Six intermediate soil mixtures with varying amounts of non-plastic fines were prepared and loaded to 140 MPa. Soil mixtures consisted of rounded granular Nevada Sand and angular silica silt. Both types of soil are quartzitic in composition and non-plastic. It was found that there was good correlation among all soil specimens in the linear LCC portion

of each of the compression curves, suggesting that any remaining structure in each of the specimens had little or no influence on specimen behavior at high stresses. Results indicate that the following occur under one-dimensional loading as presented: (i) all intermediate soil mixtures approach a unique LCC, regardless of mix proportions and initial void ratio; however, testing to higher stresses would be necessary to confirm this; (ii) the onset of crushing was observed in all tests and verified by grain size analyses; and (iii) sample preparation methods were shown to influence initial specimen density significantly.

Due to the high amount of variance in the initial void ratios of specimens during the loose preparation method presented, it is suggested that an alternative, more controlled method be used to produce more consistent initial void ratios. This would allow for more direct comparison of compression curves among different soil mixtures. Additional tests on densely prepared specimens would add more perspective on the LCC behavior of loosely prepared specimens. Slurry preparation of 100% silica silt specimens has been shown to be reliable; however, it is believed that preparing a sand specimen in a slurry would prove problematic in terms of homogeneity and workability. Vibration has been shown to be a more effective method for preparing dense, dry sand specimens.

ACKNOWLEDGMENTS

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ADDENDUM

The following discussion has been prompted based on requests for clarification:

1. Incorrectly stated in the Abstract is the claim that: *characteristics of the Limiting Compression Curve (LCC) were identified*. This should be followed with: apparent slopes of the high-stress, linear portions of compression curves, indicative of LCC behavior, were visually inspected.

2. It is unclear whether a unique LCC slope was achieved for the tests performed. It may be argued that the compression curves were not fully developed and that the high-stress, linear portions of the compression curves in fact approached different slopes, depending on soil mixture. As stated in Section 1.6, further testing to higher stresses may be required to confirm this phenomenon. The term LCC is used interchangeably in the document to describe both the behavior of soil under high stress, one-dimensional compression and the slope of the apparently linear portion of compression curves. It was stated in Section 1.6 that there existed a *good correlation among all soil specimens in the linear LCC portion of each of the compression curves*. This should instead read: The slopes of the apparent linear portions of the compression curves show good correlation upon visual inspection, suggesting that a unique LCC slope exists for these curves. Further testing is needed to confirm this.

3. In Section 1.5.2, it was stated that: *From the increased smoothness of the compression curves…become less defined.* This statement does not accurately explain the relationship between increased fines content and compression curve shape. The phenomenon of particle rearrangement (rolling and sliding) is a likely cause of dilation in those specimens that showed a gentler slope in the earlier stages of loading. It is hypothesized that the rearrangement of larger, rounded Nevada Sand granules resulted in a dilatory effect and is the cause of flatter slopes in the early stages of loading. The more abrupt break-point stresses, as discussed in Section 1.2.1, in those mixtures with increasing Nevada Sand content may be explained by the onset of full particle breakage. The findings agree with Hagerty (1993) that as the angularity of particles increases, the break-point stress becomes more difficult to define. This may be seen in the compression curves of those soil mixtures with increasing silica silt content. Additionally, the slopes of these curves increase in the early stages of loading with increasing silica silt content. This is due to the interlocking nature of the angular silica silt particles, providing less opportunity for rearrangement of particles before the breakage of asperities and particle breakage. Curvature and slope of the compression curves were not evaluated mathematically or evaluated according to the Pestana and Whittle (1995) LCC framework as this was beyond the scope of this Honors Thesis.

4. The term *procedural error* used in Section 1.5.3 should be more clearly explained. It is believed that not all of the fines were washed through a No. 200 sieve after conducting

hydrometer analyses on specimens after compression testing. This does not meet all requirements of ASTM Standard D422 (2007), Standard Test Method for *Particle-Size Analysis of Soils.* Additionally, as visually observed during testing, some of the silicon oil used to lubricate the o-rings was pushed into the soil specimen around the inside walls of the compression mold. This caused some of the fine-grained material to clump together forming larger particles. In addition, obtaining the full specimen from the compression mold after testing proved to be difficult and may have reduced the overall amount of fine material in post-test grain size analyses.