Physical modeling of railroad ballast using the parallel gradation scaling technique within the cyclical triaxial framework

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PHYSICAL MODELING OF RAILROAD BALLAST USING THE PARALLEL GRADATION SCALING TECHNIQUE WITHIN THE CYCLICAL TRIAXIAL FRAMEWORK

by

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ABSTRACT

Due to the difficulties involved with testing large particle granular materials such as rockfill and railroad ballast, several methods of testing scaled down model specimens have been introduced. Of these techniques, the parallel gradation model has been found to be most useful. The parallel gradation model states that a smaller grainsize distribution model granular material, of the same composition as the prototype material, can be used in triaxial testing at a scaled down grainsize, if the model materials grainsize is exactly parallel to the prototype material. Therefore, a model granular material composed of a smaller, but parallel, grainsize distribution can be used to predict shear and compressive properties of a larger rock fill material. Because railroad ballast is loaded in a cyclical fashion, cyclical triaxial testing is considered a reliable method of analysis of strength and deformation characteristics.

The objective of this study is to assess the suitability of the parallel gradation modeling technique for physically modeling permanent axial and volumetric strains, and resilient modulus of scaled down granular materials. Three gradations of railroad ballast will be tested, a prototype ballast material with a top grainsize of 2.5-inches, and two model gradations with top grainsizes of 1.5-inches and 0.75-inches. These three gradations will first be tested monotonically to assess the peak strength of the materials. Based on the monotonic strength, three cyclical stress ratios will be assigned for cyclical triaxial testing for 10,000 cycles. The similarity, or difference in cyclical response will form the basis of assessment for the parallel gradation modeling scheme within a cyclical framework. Cyclical triaxial results will be supplemented with particle shape, attrition, angle of repose, and Los Angeles abrasion analysis.
ACKNOWLEDGMENTS

I would like to first and foremost express my gratitude to my advisor Dr. Louis Ge for presenting me with this opportunity to again study at the Missouri University of Science and Technology in Rolla, Missouri. Additional gratitude is directed to the members of my committee, Dr. Richard Stephenson, Dr. Ronaldo Luna, Dr. David Richardson, Dr. Norbert Maerz and Dr. J. David Rogers who have assisted me not only in this study but in so many areas of interest.

Finally, I would like to thank Marcy and Sophia for the years of enjoyment they have given me.
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1. INTRODUCTION

1.1. MOTIVATION FOR RESEARCH

The movement of freight and persons is a critical component of a modern transportation system. In a given geographical area many forms of transportation may be used at any one time. North America is unique due to its land size and numerous industrial and population centers located throughout. Increasingly, industrial centers are no longer concentrated in coastal areas or navigable waterways. Therefore, both highways and railways play an increasing role in the transportation of goods. Even as the number of freight hauling trucks increase on US highways, 42% of the total freight ton miles moved in North America are moved by railroad (trucks are responsible for 28% of the ton miles carried, with pipelines, waterways and air moving the remaining 30%). Ton miles moved by rail are predicted to rise in the US by more than 50% by 2020 (Selig, 1994). Additionally, high speed rail may become more viable in the United States as airport congestion continues to rise.

Serviceability of railway tracks requires the alignment and level of tracks to be maintained for the efficient movement and safety of railroad traffic. Alignment is maintained through the interaction of several components of the railroad cross section, generally divided into the superstructure and the substructure. The superstructure includes the rails, fasteners and the sleepers, and has received the vast majority of attention regarding maintenance and performance in the past. The substructure, including the ballast, subballast and the subgrade, functions to support the superstructure. The mechanical properties of the substructure are typically more variable than the superstructure, due to its granular composition. The substructure typically requires a considerable percentage of the maintenance attention for a given section of railroad. A typical track cross-section is shown in Figure 1.1. From the bottom up; the subgrade is composed of native soils and is overlaid by a sub-ballast layer. This sub-ballast layer is followed by ballast and finally the superstructure including railway sleepers, connectors and the track itself.
The subgrade consists of native soils, typically graded and made suitable for construction of the proposed railway. Sub-ballast is placed over the subgrade to reduce the stresses transmitted to the subgrade and form a separation, or filter layer, between the subgrade’s fine-grained material and the ballast. A geotextile can also be installed as a barrier to fine grained material infiltrating, or “fouling” the ballast. Ballast material functions to support the superstructure and traveling loads of the railway, and is placed over the sub-ballast. Ballast is also intended to absorb energy from traveling loads, prohibit vegetation growth and provide large voids to allow the free drainage of water and the movement of fine “fouling” materials underneath the track alignment. The ballast also needs to readily facilitate railway realignment maintenance activities, such as tamping and cleaning.
Track alignment irregularities are typically caused by progressive deformation of the railroad ballast material. Alignment problems are greatly accelerated when the ballast material becomes fouled by fines that are either rising from the subgrade or produced from the ballast material itself due to particle breakage, a process known as attrition (Selig, 1994).

1.2. BALLAST MATERIAL TESTED

The railroad ballast material used for all testing associated with this research project was Iron Mountain Trap Rock. Iron Mountain Trap Rock Company is a subsidiary of Fred Webber, Inc. and is located in Iron Mountain, Missouri. Gary Nickelson of Fred Webber, Inc. was instrumental in both allowing the material to be donated for this project and educating us on the mining, crushing and distribution of this finished material. This trap rock material is marketed as superpave aggregate, railroad ballast, floor hardener, and concrete aggregate. A summary of the material properties of this trap rock, as well as several other rock materials is presented in Table 1.1.

<table>
<thead>
<tr>
<th>Place of origin</th>
<th>Iron Mountain Trap Rock</th>
<th>Missouri Red Granite</th>
<th>Barre Gray Granite</th>
<th>Danby White Marble</th>
<th>Grand Rivers Limestone Ballast</th>
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<tr>
<td>Specific Gravity (C128)</td>
<td>2.65</td>
<td>2.6</td>
<td>2.64</td>
<td>2.73</td>
<td>2.671</td>
</tr>
<tr>
<td>Adsorption (C97) %</td>
<td>0.2</td>
<td>0.5</td>
<td>0.21</td>
<td>0.08</td>
<td>0.28</td>
</tr>
<tr>
<td>L. A. Abrasion (C131)</td>
<td>17</td>
<td>23.54</td>
<td>30.6</td>
<td>~47</td>
<td>22</td>
</tr>
<tr>
<td>MOHS Hardness</td>
<td>7</td>
<td>~6.5</td>
<td>~6.5</td>
<td>~4.5</td>
<td>~3.5</td>
</tr>
</tbody>
</table>
1.3. CYCLICAL BEHAVIOR OF RAILROAD BALLAST

Because of the large costs associated with maintaining track alignment, considerable effort has been made to understand the progressive failure of railway ballast. Several efforts have been focused on the measurement of stresses and deformations of ballast in the field. Field testing schemes; however, tend to be very expensive and difficult to perform on operational track sections. Due to this restriction, most research efforts regarding ballast material have focused on the geotechnical triaxial testing performed in the laboratory. Several examples of induces shear stress due to different loadings can be seen in Figure 1.2.

![Figure 1.2. Stresses due to different loadings (Ishihara, 1996)](image)

The loading of railway ballast, due to a traveling wheel, however, is more complex than simple triaxial compression. Figure 1.2 displays the stress path at a point subjected to earthquake, wave, and traffic loadings, respectively. It can be found that the traffic-induced stresses are highly non-proportional. As a wheel passes over the track an element of ballast is subjected to a stress pulse. This pulse consists of vertical, horizontal
and shear stresses as depicted in Figure 1.3. Additionally, this stress impulse occurs each time a wheel passes.

Figure 1.3. Stresses on ballast due to a traveling wheel load (Lekarp, 1997)

The deformation of ballast material due to a single wheel load pulse is due to both elastic (recoverable) and plastic (permanent) strains as depicted in the following Figure 1.4. Both elastic and plastic strains are largely depending on the ratio of the load magnitude applied to the maximum load the material can carry (peak load in the static test). Ballast behavior also depends on load history where the plastic strain increment generally decreases with increasing number of load cycles for a specific cyclical stress ratio. Lowering of the stress ratio, the ratio of stress applied versus the maximum stress the material can support, typically halts plastic strain accumulation. Furthermore, when the stress ratio is increased beyond what the material has previously experienced, plastic
strain continues to accumulate until a new equilibrium point is reached. Other factors influencing deformation due to cyclical compressions include ballast gradation, moisture content, ballast material type, particle surface roughness and particle shape.

![Diagram: Stress vs. Strain with labels for permanent and resilient strain](image)

**Figure 1.4.** Strains in granular material due to the application of one load cycle (Lekarp, 1997)

The elasto-plastic behavior of railroad ballast is characterized as the gradual accumulation of permanent strain with each load application. The accumulation rate of the plastic strain generally decreases as the number of loads applied increases. However, plastic strain is observed to continue on without end in some cases, and approach zero in others. This behavior has been used to explain the concept of “shakedown”. Shakedown is defined as the behavior of ballast material exhibiting elastic strain only as further cyclical loading is applied. In this case plastic deformation is no longer accumulated, and
the material is said to be at “shakedown”. The stabilization of plastic deformation, or shakedown, is associated with lower dynamic shear stress ratios.

The loading and unloading cyclical action of a train passing over a ballast type material is non-proportional loading. Loading of this sort can be closely reproduced using a hollow cylinder, a directional shear cell, or a cyclical simple shear device. All of these testing machines allow control of all around pressure, axial stress and a shear stress applied at the base, or top of the sample. The hollow cylinder is limited to sand sized material or finer, due to the thin sample width required by this apparatus. Additionally, there are no directional shear, nor cyclical simple shear devices of the scale required for testing prototype railroad ballast. Therefore, the geotechnical triaxial machine has been used to simulate loading and unloading of granular materials in the laboratory. A triaxial machine capable of testing particles of the magnitude present in railroad ballast is conceivable. Therefore, the geotechnical triaxial apparatus presents the most promising method for testing prototype railroad ballast in a cyclical loading and unloading fashion.

1.4. PARALLEL GRADATION MODELING SCHEME

Two of the most important characteristics in the design of roadbeds, railroad structures and rockfill structures are shear strength and compressibility of the granular material. Testing of these properties is typically performed in the geotechnical discipline using the triaxial testing apparatus. This testing apparatus allows the closest simulation of field conditions in the laboratory, allowing a confining pressure applied through a flexible membrane surrounding the sample during axial loading. It has been demonstrated that the largest grainsize that can be accurately examined in the triaxial apparatus must be $1/6^{th}$ the diameter or the testing specimen. Additionally, a height to diameter ratio of two is necessary to alleviate end platen confinement of the specimen during testing (Marachi, Chan, & Bolton, 1972; ASTM D5311).

Because of the scale of triaxial specimens necessary for rockfill and ballast materials testing, the number of facilities that are capable of testing these large grainsize materials are few. Shear strength and compressibility of large grainsize materials are critical parameters regardless of grainsize, therefore a technique for estimating these
quantities for large grainsizes using smaller and more commonly available triaxial equipment is necessary.

The parallel gradation model was originally developed by John Lowe (Lowe, 1964). Numerous researchers have tested materials based on this model since. Emphasis has been focused on monotonic loading, where the material is loaded to failure. Cyclical testing of this model has been absent. The parallel gradation model states that a smaller grainsize distribution model rockfill, composed of the same material as the prototype material, can be used for triaxial testing at a scaled down grainsize, if the model materials grainsize is exactly parallel to the prototype material. Therefore, a model granular material composed of smaller, but parallel, grainsize distribution can be used to predict shear and compressive properties of a larger rock fill material.

1.5. RESEARCH OUTLINE

This research is intended to investigate the possibility of using the parallel gradation modeling scheme in a cyclical triaxial framework. Three separate gradations of ballast material will be used in this research. The largest gradation contains a top particle size of 2.5-inches and is marketed as #3 modified railroad ballast. The second two gradations contain a top size of 1.5-inches and ¾-inches respectively. These gradations were manufactured to have a grainsize distribution curve parallel to the 2.5-inch prototype gradation.

Monotonic triaxial testing will be performed on all three gradations to assess the peak deviator stress capacity of these materials. Attrition was assessed after each triaxial test and the gradations brought back to the exact gradation before further testing. All triaxial testing was performed using a confining stress of 3 psi, typical of railroad ballast in the field. Initial testing density will also be controlled, with all samples compacted to 98 pcg. Monotonic triaxial testing will be performed on all three gradations of model and prototype railroad ballast material with stresses controlled to three stress ratios, based on the monotonic triaxial testing results. Cyclical triaxial testing will be analyzed for resilient modulus, permanent axial strain, and permanent volumetric strain.
At the conclusion of triaxial testing particle shape was assessed for both fresh ballast material as well as material that had been included in the triaxial testing program. Shape analysis will be focused on particle aspect ratio and angularity. The angle of repose of the three gradations of ballast was assessed using a tilting method. Finally, Los Angeles abrasion was assessed for the three gradations to confirm the abrasion resistance of this material and allow comparison with other aggregate materials.
2. LITERATURE REVIEW

2.1 PARALLEL GRADATION MODELING SCHEME

Lowe (1964) originally presented the framework for the parallel gradation modeling technique. A model sample of perfect spheres, regardless of grainsize, would closely duplicate the contact stresses and void ratio characteristics of a larger prototype gradation. Thus in models of coarse gradations, where the only difference between prototype and model sample is the difference in size of particles, the model sample should closely duplicate the behavior of the larger prototype. This theory was initially substantiated by the author testing granular materials using a six-inch triaxial cell monotonically loaded.

The theoretical basis of the parallel gradation modeling scheme is based on the Hertz formula for the maximum stress at the contact of two bodies. This stress is depicted in Figure 2.1, depicting contact stresses between two spheres.

Figure 2.1. Contact stresses between two spheres
Max 2 34 2(1) N a R σ aR σ N max = \frac{3P}{2\pi a^2} = \frac{4Ga}{(1-\nu)\pi R} \quad (1)

a = \left[ \frac{3P(1-\nu^2)R}{4E} \right]^{\frac{1}{3}} = \frac{1}{2} \left[ \frac{3(1-\nu)PR}{G} \right]^{\frac{1}{3}} \quad (2)

The maximum contact stress, \( \sigma_{N_{\text{max}}} \), is located at \( r = 0 \), where the radius of the contact area is \( a \). This calculation assumes the two objects are spherical and of the same radius, \( R \). \( P \) is the compressive force acting on the particles and \( G \) is the shear modulus of the materials. This equation assumes that both materials exhibit the same elasticity and Poisson’s ratio, \( \nu \) (Hertz, 1956).

This relationship for particles having a perfect geometric similarity shows that the values of contact stresses and strains are independent of particle size. Laboratory data of tests run on quartz, which is a highly elastic material, have found that the coefficient of friction is constant and independent of both contact area and normal load. Therefore, it appears that the deformational characteristics of elastic rock materials should not be dependent on the grainsize of the material tested.

In general, the validity of this modeled-gradation technique had been established in static triaxial testing (Lowe, 1964, and Marachi et al., 1969). Varadarajan et al. (2003) investigated four different modeling techniques to reduce the size of rockfill materials for testing. These scaling methods included a scalping technique, the parallel gradation technique, generation of quadratic grain-size distribution curve, and a particle replacement technique. Of these models, the parallel gradation technique was considered the most appropriate for assessing strength and deformation characteristics for granular fill dam materials.

With particle shape playing a critical role in the strength and deformation characteristics of a granular material, consistency of shape over the particle sizes tested and modeled must be monitored. Kirkpatrick (1965), working with uniformly graded sands from 2mm – 0.3 mm, found limiting porosities for all materials to be the same. This indicated that similar particle shapes were found over the different sizes of sands
investigated. For these materials Kirkpatrick concluded that the angle of internal friction decreases as the particle size increases. Glass bead testing indicates this same trend (Marachi et al., 1969). Leslie (1963) found densities to increase as the maximum particle size increased. This difference in densities was used to partially explain differences found in testing results from different sized materials.

Single particle crushing strength is often used to measure tensile strength. Tests of this nature typically find tensile strength going down with increased particle size, indicating a scaling effect common in rock mechanics (Indraratna et al., 2005). Additionally, recycled grains are noted to exhibit a lower strength than fresh material.

Indraratna and Christie (1998) pessimistically state in a study of several railroad ballast materials: “In the analysis and design of railway track structures, tests on scaled-down aggregates cannot be relied upon for the prediction of deformation parameters. Therefore large-scale testing is imperative….”

Raymond and Davies (1978), tested ballast materials using a 9 and an 18-inch diameter triaxial apparatus. Bulk specimen density was controlled during the placement of four equal lifts. The surface of the lift was covered with a wood disk and “gently” vibrated to the required density. Two different gradations between 1.5” to #4 were used, one just within the coarse limit and the other just within the fine limit for Canadian National railroad grading specifications at the time. “No measurable differences were observed between the tests at the two gradings.” Breakdown of particles was measured as the particles passing the #4 sieve. About 0.6% breakdown was observed irrespective of cell pressure, with some tendency for breakdown to increase with the increase in cell pressure. Among their conclusions was the ballast breakdown is only slightly related to cell pressure.
2.2 MONOTONIC TRIAXIAL TESTING

Considerable effort has been focused on the testing of granular materials using the triaxial apparatus. The following review will focus primarily on the testing of rockfill and ballast materials in the triaxial framework. Regarding the use of the triaxial apparatus for the assessment of railroad ballast properties Raymond and Davies (1978) state:

“Because the compaction below a tie is only performed about 300 mm (12 in) on either side of the rail and the ballast is about 300 mm (12 in) deep below the tie, the ability to resist vertical forces is probably best assessed in the laboratory by means of standard compression triaxial tests, and is partially dependant on the strength of the subgrade.”

Here we will look at a few of the more important issues involved with this method of testing.

2.2.1. Particle Size/ Specimen Size. The dimensions a triaxial specimen needs to be, related to the particle sizes included in the specimen, has been quite soundly established (Marachi et al., 1972, ASTM D5311). Marachi also notes large specimens tend to be slightly more compressive under monotonic loading than smaller specimens. While this characteristic is not considered pronounced, it is noticeable.

Marachi, Chan, Seed, and Duncan, 1969 conclude:

“… when the ratio of the specimen diameter to the maximum particle size becomes small, about 5 to 10, and there is a high proportion of the larger particles present in the specimen, there is an increase in the measured strength caused by interference between the larger particles. Judging from the data presented by Holtz and Gibbs (1956), it seems reasonable to conclude that if the material gradation are such that the proportion of particles in the maximum sieve size range is 30% or less and the ratio of the sample diameter to the largest particle size is 6, no effect of the specimen size on test results should exist.”

If the above specification is not met in a triaxial test, unreasonably high angles of friction would be expected by this group of researchers.
2.2.2. Compaction of Granular Materials. Compaction of granular material has traditionally been performed using some form of vibratory hammer. Marachi et al. (1969) used black washers in the sample with clear latex to investigate density during specimen building. Vibratory compaction methods typically create considerable membrane rupture as well as concerns of uniform density ((Knutson, 1976; Frenkel, 2000). Burmister (1948) clearly states that relative density is a far better indicator of strength than density for granular materials.

2.2.3. Triaxial Membrane Corrections. The effects of the triaxial membrane on material characteristics has typically been addressed in the triaxial setting assuming the sample deforms as a right cylinder, rather than the relatively unpredictable, but often observed bulging at the middle of the sample (Bishop and Henkel, 1952). A generalized correction \( \sigma_{lm} \) to the measured confinement due to the effect of the rubber membrane is given by Duncan and Seed (1967) as:

\[
\Delta \sigma_{lm} = -\frac{2E_m}{3} \left[ 2 + \varepsilon_{at} - 2 \sqrt{\frac{1 - \varepsilon_v}{1 - \varepsilon_{at}}} \right] \frac{t_{om}}{\gamma_{os}(1 - \varepsilon_v)}
\]

Where \( \Delta \sigma_{lm} \) = correction to lateral stress for membrane strength, \( E_m \) = Young’s modulus of the membrane, \( t_{om} \) = initial thickness of the membrane, \( \gamma_{os} \) = initial radius of the sample, \( \varepsilon_{at} \) = axial strain due to consolidation and/or undrained deformation and \( \varepsilon_v \) = volumetric strain. The membrane confinement, as calculated here, is derived from hoop tension theory, and hereby used for the confining stress of the membrane in extension.

The studies associated with this membrane effect have been primarily soft clays from the London area. Henke and Gilbert, 1953 conclude: “(t)hese corrections are appreciable compared with the strengths of soft clays, and it is essential that they should be applied to the test results. … The correction will, however, be of significance only when the effective stresses are small.” Marachi et al. (1969) similarly conclude when rockfill material was tested, “The magnitude of the membrane corrections were generally
Penetrating effects of the latex membrane are most problematic during volumetric measurements in drained situations. Baldi and Nova (1984) conclude “It has been found that the apparent volumetric strain due to merely the membrane penetration decreases linearly with increasing sample diameter.” It was also concluded the factor having major influence on membrane penetration is the grainsize. Confining pressure, “… rigidity and thickness of the membrane have less influence on the penetrating effects of the membrane. Values of the normalized membrane penetration, back calculated from the derived theoretical expressions are in qualitative agreement with published experimental data.”

2.3 CYCLICAL TRIAXIAL TESTING

Cyclical triaxial testing is useful in assessing repeated loading and unloading of granular materials. A review of the primary issues associated with this method of testing follows.

2.3.1. Permanent Strain. Generally, researchers have shied away from permanent strain studies, preferring resilient behavior, largely due to the destructive nature of permanent strain testing. When testing for permanent strain, separate samples are required for each stress state probe. Resilient behavior testing allows the same sample to be used to investigate several different stress states (Brown and Hyde, 1975).

Essentially, there are three camps regarding the prediction of plastic strain accumulation in granular materials under repeated loading. These predictions are generally based on the applied repeated stress condition, number of load applications, and the “shakedown” concept. Stress condition modeling schemes attempt to relate the repeated stress loading magnitude and static load testing results to predict plastic strains. Predictions based on the number of load applications estimate the plastic strain by separating loading into situations where the repeated load can be considered “small” in magnitude, or “large”. This approach leads to the “shakedown” concept. The shakedown concept predicts that, in the case of a small repeating load, the incremental plastic strain
of the granular material diminishes to an asymptotic value. In the case of large cyclical stresses, the shakedown concept predicts a ratcheting effect where plastics strain persists and the sample is soon destroyed.

2.3.2. Stress Conditions. Permanent strain predictions based on stress conditions attempt to predict permanent strain based on cyclical loading magnitude in reference to the maximum load capacity of the material.

\[ \text{cyclical stress ratio} = n = \frac{(\sigma_1 - \sigma_3)_{\text{cyclical}}}{(\sigma_1 - \sigma_3)_{\text{failure}}} \]  

Repeated load tests performed by Morgan (1966) clearly showed accumulation of axial strain is directly related to deviator stress and inversely related to confining pressure.

More recently, predictions based on the cyclical stress ratio alone are generally considered overly simplistic. Lekarp and Dawson (1998) convincingly argue that “failure in granular materials under repeated loading is a gradual process and not a sudden collapse as in static failure tests. Therefore, ultimate shear strength and stress levels that cause sudden failure are of no great interest for analysis of material behavior when the increase in permanent strain is incremental.”

2.3.3 Number of Load Applications. Predictions based on the number of load cycles (N) have found that there is generally a critical cyclical stress ratio (n) that divides stresses that eventually lead to a stable situation from stress ratios that will lead to a rapid demise of the sample. If the cyclical deviator stress is below this critical value the sample will eventually reach a stable configuration where further plastic strains can be predicted. On the other hand if the cyclical deviatoric stress ratio is greater than this critical stress ratio the sample will continue to accumulate plastic strains with the demise of the sample arriving rather soon. Generally, three methods of predicting plastic strain using the number of load applications method include predictions that the plastic strain will stabilize to a constantly increasing rate when plotted on a semi-log scale, plastic strain can be predicted using a power function, or that plastic strain will stabilize altogether at some number of loadings.
2.3.3.1. Log method. Barksdale (1972) found that plastic strain in granular materials accumulates linearly with the logarithm of the number of load cycles. Possibly the most wide spread method for predicting permanent strain based on number of loadings was introduced by Selig and Waters (1994) and is expressed as:

\[ \varepsilon_n = 0.082(100n - 38.2)(\sigma_1 - \sigma_3)^2(1 + 0.2\log N) \]  

Where \( \varepsilon_n \) is the plastic strain after \( N \) loadings, \( n \) is the initial porosity of the sample, \( \sigma_1 - \sigma_3 \) is the cyclical deviator stress, and \( N \), the number of load applications.

2.3.3.2. Power law method. Vuong (1992) gives the three major parameters of interest in the study of granular materials as stiffness/ strength, permanent deformation and durability. In this study, a power law is introduced for prediction of plastic strain:

\[ \varepsilon_p = \varepsilon_1(\mu/\alpha)N^\alpha \]  

Where \( \varepsilon_p \) is the vertical plastic strain, \( \varepsilon_1 \) is vertical elastic strain, \( N \) is the number of loadings, and \( \mu \) and \( \alpha \) are material parameters that are found experimentally for a particular granular material.

2.3.3.3. Plastic strain stabilization. Paute et al. (1996) indicate the rate of increase of plastic strain in granular materials under repeated loading decreases continuously. It is possible to define a limit value to the plastic strain. Similar conclusions are drawn by other authors (Lekarp, 1997; Lekarp and Dawson, 1998).

Conversely, Kolisoja (1998), in a study including large numbers of load cycles, found that permanent deformation is a complex material response. In this study, test specimens that appeared to be approaching a stable condition may then again become unstable under further loadings.

2.3.4. Shakedown Concept. The shakedown concept has been used frequently to describe the plastic deformation characteristics of ballast material due to repeated loading. Four zones can be characterized at various stress level as depicted in Figure 2.2.
Figure 2.2. Illustration of the shakedown concept to describe stress-strain response due to repeated loading (Werkmeister et al., 2001)

(1) Pure elastic
This is the zone where applied repeated stress is sufficiently small that no element of the material enters the yield condition. From the first stress-strain excursion, all deformation is fully recovered and the response is termed purely elastic.

(2) Elastic shakedown
This is the zone where the applied repeated stress is slightly less than that required to produce plastic shakedown. The material response is plastic for a finite number of stress-strain excursions. The ultimate response is elastic. The material is said to have achieved “shakedown” and the maximum stress level at which this condition is achieved is termed the “elastic shakedown limit”.
(3) Plastic shakedown

This is the zone where the applied repeated stress is slightly less than that required to produce a rapid incremental collapse. The material achieves a long-term steady state condition. After this steady state is reached, no further accumulation of plastic strain is observed and each load response is hysteretic. This implies that a finite amount of energy is absorbed by the material on each stress-strain excursion. Once a pure resilient response has been obtained, the material is said to have achieved “shakedown” and the maximum stress level at which this condition is achieved is termed the “plastic shakedown limit”.

(4) Ratcheting

This is the zone where the applied repeated stress in relatively large. A significant zone of material is in a yield condition and the plastic strains accumulate rapidly with failure occurring relatively quickly.

2.3.5. Resilient Modulus. Resilient modulus (\(M_r\)) has been used to describe the behavior of railroad ballast subjected to repeated loading. Resilient modulus is defined as the repeated deviator stress divided by recoverable portion of the axial strain. A depiction of these measurements can be seen in Figure 2.3 titled Measurement of resilient modulus after Raad (1992). Resilient modulus has received more study than has permanent strain, in no small part due to the relative ease in testing. While permanent strain is a destructive testing process that requires a new sample after each testing probe. If the stress ratios are kept low, the resilient characteristics of granular materials are basically insensitive to stress history. If sequential tests are ordered from lower to higher stresses, large numbers of resilient tests can be run sequentially on the same specimen (Brown and Hyde, 1975; Lekarp, Isacsson, and Dawson, 2000b).
Several methods of predicting the resilient modulus have been proposed and typically verified using laboratory testing involving repeated loading and unloading. Vuong (1992) presents a typical form of resilient modulus prediction as:

\[ M_r = M_1 \left( \frac{\sigma_m}{\sigma_{\text{ref}}} \right)^n \]  

(7)

Where \( \sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3 \), \( \sigma_{\text{ref}} \) is defined as 100 kPa, the reference stress, and \( n \) & \( M_1 \) are material properties to be determined experimentally.
Nair and Chang (1970) found resilient modulus to change non-linearly. This characteristic was modeled using an iterative technique of applying a general resilient modulus equation to linear sections of the overall non-linear curve.

Knutson (1976) finds the “[r]esilient response of granular materials cannot readily be linked to material properties. In addition, the resilient response is almost totally independent of gradation, load history, and density. Although some dependence of resilient response on material type can be shown, the effects are not consistent. None of the other variables is nearly so important a parameter in determining the resilient response of granular materials as is the stress level.”

Others find that resilient response is dependant on particle type and shape. Crushed aggregate, having angular to sub-angular particles generally exhibit a higher $M_r$ than more rounded particles (Hicks and Monismith, 1971; Thom, 1988). This is thought to be due to the load spreading properties of angular particles.

Marsal (1973), in a theoretical derivation of interparticle stresses, defines “active and idle” particles as those carrying load in the matrix and those idly standing by. Kolisoja (1997) explains the increased stiffness of granular samples containing larger particles as an effect of the major portion of load acting on a granular assemblage being transmitted through specific particle queues. Larger particles have fewer particle contacts over a given volume or length of the queue. The smaller number of particle contacts results in less total deformation upon loading, yielding higher stiffness.

2.3.6. Additional Factors Involved in Cyclical Behavior. Timmerman and Wu (1969) cyclically tested sand specimens at frequencies between 2.5 and 25 Hz. The frequency of the loading appeared to affect the rate of strain but not the final strain of the specimens. Strain accumulated faster for the low frequency tests. It was inferred that the strain in the slower tests may be attributed to the longer load pulse, thereby allowing more strain to occur during the individual loading. High strains were not observed to occur until the cyclical stress ratio exceeded three quarters of the principal stress ratio at failure.

Hicks and Monismith (1973) found that for radial strains, a softening pattern was always observed in cyclical triaxial testing. A slight softening was observed for axial strains at low axial stresses and stiffening observed at higher axial stresses. Additionally,
it was noted that reasonable data could be gathered from a cyclical test after 100 load cycles were performed.

Brown and Hyde (1975) conclude that similar values of both resilient modulus $M_r$ and plastic strain were found from the cycling of the confining pressure and maintaining a constant cell pressure at the median of the cycled confining values. Constant and cycled confining stress tests found similar volumetric and shear stress-strain relations except when there was dilation occurring in the sample. Loading history has very little effect on resilient modulus below failure levels, but considerable effect on permanent strain.

Thom and Brown (1987) found when water is added to crushed rock aggregate, sizable increases in both elastic and permanent strain were observed. Permanent deformation accumulation rate was observed to increase ten fold when moisture was introduced to a sample. Additionally, no appreciable pore pressures accompanied the water addition at lower moisture contents ($S < 0.85\%$) indicating that the water acts as a lubricant on the particles.

Principal stress reorientation due to vehicular traffic was considered to “significantly” increase the amount of plastic strain in granular material (Lekarp, 2000).

2.4. PARTICLE SHAPE ANALYSIS

Particle shape can be described using three primary measures: aspect ratio; roundness; and surface texture. Aspect ratio and roundness have typically been accepted as significant indicators of particle shape. Due to a high degree in difficulty in assessment, surface texture has historically been neglected. More recently, measurement of particle shape has become more automated, with image based measurement becoming more reliable and common.

2.4.1. Sphericity and Aspect Ratio. Several authors have assessed the shape of particles using the concept of sphericity. Wendell (1933) defines sphericity as the cube root of the ratio of the volume of the particle to the volume of the circumscribing sphere. Lees (1964) defines sphericity as the surface area of a sphere of the same volume as the particle divided by the surface area of the particle.
Possibly aspect ratio can be more easily visualized as a particle fitting into a three-dimensional box of dimensions of length, width and height. Aschenbrenner (1956) more exactly terms this box a “tetrakaidekahedron” defined as “three mutually perpendicular parameters derived from tridimensional intercept measurements of grains.” These three mutually perpendicular dimensions are then used to describe the aspect ratio for a given particle. Lees (1964) gives elongation (q) and flatness ratios (p), based on these three dimensional orthogonal lengths. The flatness ratio (p) is the shortest length, divided by the intermediate length. The elongation ratio (q) is the intermediate length divided by the greatest length. The three mutually orthogonal dimensions of a particle are thereby used to define the aspect ratio of the particle.

2.4.2. Angularity. While no single definition of angularity exists, angularity can be generally described as the shape feature which measures how sharp the corners of a particle are (Chandan et al., 2004). Barksdale & Itani (1989) define roundness as the measure of the curvature of the corners of a particle as a ratio of the average curvature of the particle. In this study angularity is used to describe the wear of edges, with heavily worn particles exhibiting generally rounded corners.

2.4.3. Image Based Shape Assessment. Shape analysis has historically been assessed using manual methods each individual particle is measured and data recorded. This method is considered both cumbersome and subjective (Molinaro, 2003; Maerz, 2004; Maerz & Lusher, 2001; Swift, 2007). Therefore, considerable recent effort has been focused on image based shape analysis.

Barksdale, et al. (1991) investigated the possibility of using modern data acquisition procedures for measuring individual aggregate particles. While a procedure was not presented, conclusions of this study identified the possibility of acquiring large amounts of particle shape data at a relatively low cost using AutoCad and a spreadsheet program. Frost, et al. (1996) and Kuo, et al. (1996) developed three-dimensional methods to analyze the morphological characteristics of aggregates. Methods of measuring flatness and elongation of aggregate particles were demonstrated. These methods still required considerable time to load samples into plexiglass frames for imaging.
Brzezicki and Kasperkiewicz (1999) used a method of measuring the shadows along with the particle edge at perpendicular angles of the same particle. This method allows three-dimensional shape characteristics of the particles to be measured, namely length, width and height.

A later system developed by Fletcher, et al. (2002) separates aggregate into fine and coarse particles. The fine particles are analyzed for shape and angularity, while coarse particle analysis also includes surface texture. Methods for measuring particle shape have also been developed using laser scanner by Kim, et al. (2002) at the University of Texas-Austin. Using this method a laser scanner passes over an aggregate sample placed evenly on a flat surface. The three-dimensional scanner data is then used to calculate shape, angularity, and surface texture parameters.

An imaging system marketed as WipShape has been developed by Dr. Maerz of the Missouri University of Science and Technology. This system uses a contrasting colored conveyor belt to carry particles in front of two orthogonal cameras (Maerz, 1998 and 2001). Images from these cameras are then used to calculate three-dimensional shape parameters of the particles.

Several rules to be considered when using image based measurement techniques for assessing particle shape have been found useful. Chanden, et al. (2004) recommends when using digital imagery, a pixel should be less than 1% of the average particle diameter for shape analysis images. Maerz (2004) notes that uniform colored particles greatly assist in the image reading process. Additionally, angularity can be best assessed using the minimum curve radii of the corners of a particle projection (Swift, 2007; Maerz, 2004).

2.5. ATTRITION

The particle size distribution of granular materials changes continuously during the loading process due to the degradation, or attrition of particles. The degree of breakage is dependant primarily on the gradation of the granular material, the crushing strength of the material and the level of stress applied to the material. This particle breakdown typically begins with the crushing of angular corners as particles attempt to
rearrange to form a more stable matrix. As stresses increase, fracture of relatively large and angular particles is expected. A result of this degradation process is that particles become smaller and less angular. The reduced angularity contributes to a reduction in shear strength. Additionally, the attrition is the primary source of ballast contamination (Selig and Waters, 1994; Ionescu et al., 1996). The subsequent clogging of ballast voids with the fines created by particle breakage account for up to 40% of the “fouled” ballast material. Particle breakage changes the grainsize distribution of a granular material during loading. Several authors have presented methods for measuring this attrition.

Perhaps the most direct method of measuring particle breakage can be performed by comparing the grainsize distribution curves of the material before and after stress have been applied. The differences in the particle size distribution curves tends to be slight; generally understating the level of breakage in a sample. Additionally, this method presents attrition qualitatively. Further efforts have focused on assessing a quantitative measurement of the particle breakage. An example of attrition measurement using a grainsize distribution curve can be seen in Figure 2.4.

A variation of the comparison of initial and final grainsize distribution curves has been presented by Indraratna et al., (2005) as the Ballast Breakage Index (BBI). The BBI is assessed by graphing the initial and final particle size distributions with a line of maximum breakage on the grainsize distribution curve. The line of maximum breakage is defined by the minimum available sieve and extends to D95 of the largest sieve used. The area under the initial and final gradation curves is then used in conjunction with this line of maximum breakage to calculate the BBI. This method is relatively well suited for ballast materials with a limited range of particle sizes that can be plotted on an arithmetic grainsize scale. A typical plot using log scale for grain sizes does present a problem using this technique.

Indraratna et al., (2005) note that there have been several successfully applied breakage indices based on surface area of the particles. One such study performed by Miura and O’Hara (1979), used this surface area concept. Attrition was assessed by finding the differences in weights of material retained on the specific sieves before and after loading. Each grainsize, as determined by sieve analysis, was assumed to be the
same diameter, density, and of spherical shape. Using this method good correlation was found between stress levels applied to samples and attrition.

![Grain size distribution curves](image)

Figure 2.4. Example of attrition measurement using grainsize distribution curves (Indraratna et al., 1998)

Surface area calculations are generally limited by the fact that they have to assume a particle shape. This assumption has been proven useful with rounded particles, while this method of assessing attrition has been found to be greatly limited when highly angular material, such as ballast, is tested.

Lee and Farhoomand (1967) performed a laboratory investigation on particle breakage testing granitic gravels. After mining and crushing of the material, the particles
were very angular. A portion of this crushed material was then tumbled for several
weeks, in a mill, creating sub-rounded particles. They produced different sizes of the
original angular material and separately sub-rounded particles from 0.75” to the #100
sieve. Loads were applied monotonically and held for two hours before final readings
were taken. This method of holding the maximum loads was previously suggested by
Lee and Seed (1966). They found there to be a time dependency of strain where the
compression and particle breaking continue at an ever decreasing rate. This holding of
the maximum load allows the significant amount of compression and particle breakage to
occur. To measure the particle breakage, Lee introduced “relative crushing” as the ratio
of the initial D15 to the final D15 after the test was run. This study was intended to
investigate the crushing of sand drain particles under the relatively high confining
stresses typical of an earthen dam environment. The 15% grainsize was selected because
it is the key criterion used in the design of drains and filters. Compression is noted to
usually be accompanied by a certain amount of particle breakage, and the two phenomena
seem to be somewhat related. Coarse grained soils were found to compress and break
more than small grained soils. Uniformly graded soils compressed more than well graded
soils for the same maximum grain size. Also, angular particles were found to compress
and break more than rounded particles.

As a refinement of this attrition measuring method, a particle breakage factor was
introduced by Marsal (1973). The breakage factor, Bg, is calculated by first finding the
difference between the percentages of the total sample contained in each size fraction
before and after loading, ΔWk. The algebraic sum of ΔWk must equal zero for a given
sample. The breakage factor is then calculated as the sum of the positive ΔWk values
expressed in percent. Therefore, Bg is calculated from the gradation before and after
loading and is the percent by weight of the particles that has undergone breakage. ΔWk
can be plotted against the opening of the upper sieve corresponding to that fraction for
comparison with other attrition data. The breakage factor, Bg, as defined by Marsal is
considered an improvement over Lee’s relative crushing value as it accounts for breakage
throughout the grain sizes tested (Indraratna and Christie, 1998; Varadarajan et al., 2003).
Generally it is noted that the breakage factor increases with the size of the particles and
the confining pressure.
Marachi et al. (1969) cite Griffith’s crack theory to explain the increase in particle breakage as a result of an increase in particle size. Griffith (1920) offers a theoretical criterion of rupture based on the theorem of minimum energy. He supports this criterion with a rigorous proof and experimental verification using a “hard English glass”. Glass was selected because of its obeying of Hooke’s law at all stresses and whose surface tension at ordinary temperatures could be estimated. It was found that the theoretical maximum tensile strength is attainable for small diameter wires while larger wires are found to carry lower tensile stresses. This discrepancy was attributed to slight imperfections on the surface of the glass (scratches).

Four other factors that seem to be the most common contributors to the particle breakage of ballast include hardness, toughness, particle shape and weathering resistance (Chrismer, 1985).

2.6. ANGLE OF REPOSE

The majority of significant work regarding the angle of repose has been associated with the powders industry (Nelson, 1955; Train, 1958; Cartensen & Chan, 1965; Carstensen & Chan, 1976; Pilpel, 1964; ASTM 2001). Train (1958) identifies four methods of measuring the angle of repose: fixed funnel and free standing cone; fixed bed size cone; tilting box; and revolving cylinder. Several notes from his testing program using glass balls, lead shot and silver sand, include “(w)ith the heaped cone techniques, the magnitude of the final ratio of height to base depends on reducing the momentum of the particles (otherwise the stability of the existing heap is upset and general slip takes place)…..” Methods presented for measuring the angle of repose are presented in Figure 2.5.

Carstensen & Chan (1976) present a geometry based derivation of the angle of repose based on heaps of spheres. The maximum angle of repose for monodisperse spheres (all one size) is found to be 30 degrees. Additionally, it is found that polydisperse particles, containing fines in the voids, higher angles of repose are possible.
Generally, the repose angle decreases with increasing particle diameter for powders.

\[ \phi = \left( \frac{q}{d} \right) + s \]  \hspace{1cm} (8)

or,

\[ \log \phi = -n \log d \]  \hspace{1cm} (9)

Where \( q \) and \( s \) are parameters related to specific powder and \( d \) is the particle diameter, and \( n \) is specific to the powder and “need not be unity” (Pilpel, 1964). These two equations have been found to be useful in the powders industry. Using the above equation, the issue does arise that, as \( \phi \) approaches infinity, \( d \) approaches 0. Physically \( \phi \) should approach something shy of 90 degrees as \( d \) increases. The first equation holds
well for material above 100\(\mu\)m for magnesium oxide. Both of these equations are obviously empirical with no apparent connection to the physical dynamics of heaps.

Taylor (1948) and others have separated internal friction into at least two components: The internal frictional component, which is a combination of rolling and sliding friction and the component of shearing that acts against interlocking particles, often referred to as dilatancy. As angularity increases, the energy required for dilation increases. Therefore, the angle of internal friction increases due to particle interlocking.

More recently, interest in the angle of repose test has increased outside of the powders field. Frette et al. (1996) tested avalanche dynamics of rice grains. In this study it is found that for elongated rice grains the rice moved slowly and coherently while holding a solid like coherency between grains. The more round rice grains tended to roll down the outside. In this case, there wasn’t much or any of the movement of a coherent semisolid bunch moving together.

Baxter et al. (1998) found when pouring inhomogeneous granular materials, stratification was almost eliminated when pouring is performed quickly (1.76 lb/s). The same materials were found to stratify significantly when poured slowly (0.015 lb/s). Stratifications occur even when all particles are of similar angularity. If the fill rate is sufficiently slow, stratification was found to occur even if the angle of repose of the fines was lower than the large particles. It is explained that due to the lower probability of a large grain finding a good embedment in a pile of finer particles that the large particles tend to roll down to the bottom of the heap. Interestingly, it is not the differences in angularity between large and small particles that was attributed to stratification. Stratification is found to occur when the size ratios of the material are sufficiently high (D_{50} ratio of 2:1). The elimination of stratification is considered due to the impact of the fast loading rate where all particles are embedded in the pile and not free to move.

Vallejo (2001) investigated two sizes of beads poured through a funnel into free standing piles. By varying the percentage of different sized beads it was found that when the coarse percentage is relatively high (70%) the large particles are responsible for carrying the load, and thereby define the slope of the pile. Once only 40% of the mixture is coarse material the structure is supported on the fines and their strength governs. A transition phase is noted between these percentages.
Lee (1993) defines three different angles of repose that are then used in a theoretical study with laboratory testing accompanying. (θ<sub>R</sub>) the finite angle of repose is defined as the slope of the pile, which is strongly dependent on the friction coefficient. Finite angle of tilting (θ<sub>T</sub>) is then a little steeper than the slope of the pile, and is obtained after the pile is poured it is then tilted until the surface again slides. The angle of marginal stability (θ<sub>MS</sub>) is then defined as the maximum angle that can be measured by adding grains “laboriously” to a stable pile, θ<sub>MS</sub> > θ<sub>T</sub>.

2.7. INDEX TESTING OF LARGE GRANULAR MATERIALS

McDowell (2003) investigated the assessment of granular material strength using index testing. In this study, he argues that “unconstrained comminution” degradation is exhibited in the LA abrasion test while wear under the track is “constrained comminution”. Strengths of granular materials could be better assessed using the aggregate crushing value (ACV) test. This test incorporates the crushing of 10-14mm diameter compacted aggregate in a 154mm diameter mold. The height to diameter ratio of this mold is 0.65. The specimen is compacted and then a uniaxial stress of 21 MPa is applied over 10 minutes. The ACV is calculated as the percentage of mass passing the 2.36mm sieve after the stress is applied.

Raymond (1985) studied index testing as applied to railroad ballast specifications. In this study it is concluded that an Aggregate Index (AI) may be more reliable for the assessment of granular materials than simply the Los Angeles abrasion (LAA). Impacts of LAA steel ball charge increases slightly with increasing hardness, resulting in higher LAA values for harder materials. However, the field breakdown for harder rock is lower because of less powdering of the corners. Therefore, it is concluded that the Mill Abrasion (MA) test is better suited for assessing ballast materials than LAA. The Mill Abrasion test involves revolving 3 kg of a specific gradation of material about a longitudinal axis of a 9 inch diameter ceramic jar containing water for 10,000 revolutions at 34 rpm. The Aggregate Index (AI) is then defined as:
Aggregate Index (AI) = LAA + 5* MA  \hspace{1cm} (10)

This work formed the basis for improved material needed at railroad curves and inclines. Improvements were realized using a broader ballast gradation yielding higher strength. One example in the Canadian Rockies found maintenance cycles went from 3 months to 2 years by changing from a typical railroad ballast specification at the time (AREA 4) to this broader gradation (AREA 24).

Boucher and Selig (1987) investigated the performance of ballast materials finding that ballast performance is a function of field conditions, particle shape, and grading as well as factors that can be identified by petrographic analysis.
3. PROCEDURE

3.1 MISSOURI TRIAXIAL TESTING APPARATUS DESIGN

In order to test a prototype gradation of railroad ballast, a triaxial testing apparatus was needed that could test particle sizes typical of railroad ballast. Railroad ballast contains particles up to 2.5 inches (63.5 mm) in diameter. Dimensions of the Missouri railroad ballast triaxial testing apparatus was based on generally accepted requirements that a triaxial specimen diameter must be six times the length of the largest particles nominal diameter. Prototype railroad ballast is comprised of a steep grainsize distribution curve with the largest particle passing the 2.5 inch (63.5 mm) screen. Therefore, a specimen diameter of 16.5 inches (419 mm) was necessary for triaxial testing of these large particles. The Missouri railroad ballast testing apparatus incorporates a top cap and bottom cap with the specimen surrounded by a latex membrane only. For specimen preparation a special sample mold was designed to allow assembly and densification of the sample while protecting the membrane from puncture. Confinement during testing is provided by vacuum routed inside the sample. A photograph of this testing apparatus can be viewed in Figure 3.1.

This design has several advantages and disadvantages. Because confinement is provided by vacuum inside the sample, this design allows testing of porous unsaturated samples only. Advantages over a typical triaxial testing apparatus include the lack of a chamber encompassing the sample to hold the confinement fluid or air. This simplification allows unobstructed and direct visual (and photographic) viewing of the sample during testing. In the case of photographic strain analysis this simplification avoids geometric corrections necessary for light traveling through a cylindrical chamber of fluid or air and the glass of the chamber itself. The physical simplifications of not requiring a confining cell are magnified by the sheer scale of the sample as well.

Both the top and bottom caps were machined from one inch thick aluminum plate. Each cap was fitted with two port holes, drilled and tapped for standard pipe thread. These ports can be used for access to the inside of the specimen for regulating vacuum
and/or vacuum measurement. Around the perimeter of both caps a 3/8-inch (9.5 mm) groove was machined centered at 1/3-inch (8.5 mm) from the exterior surface. This groove was designed to hold an o-ring in place around the entire diameter coupling the latex membrane to the cap. While this groove was instrumental in keeping the o-rings from rolling off the top and bottom of the caps, additional o-rings helped maintain a tight seal between the latex and the cap circumference.

The top cap was fitted with six bolts in a circular pattern 12.5-inches (318 mm) in diameter. These were placed to surround the load platen of the MTS 880 load frame used in this testing program. The six bolts were necessary to maintaining alignment of the load platen with the top cap during testing. Hollow plastic rods were placed over the bolts to protect the top cap. In addition, the MTS 880 load frame uses a spherical seat at the top platen to allow free tilting, thereby avoiding stress concentrations along the top cap. The two port holes of the top platen were fitted with a ¼-inch and a 3/8-inch standard pipe thread tapped into the aluminum plate. Attached to these ports are ball
valves that allow vacuum/vacuum measurement at both ports. The two ports were useful in times when the membrane leaked. A large volume of vacuum could be applied to the specimen using the two ports, until it was stabilized through patching and/or sealing of the membrane.

The bottom cap was fitted with an aluminum table attached to the bottom surface of the bottom platen. This table was fitted with four steel angles bolted to the bottom and directed straight down from the bottom of the cap. On the vertical face of these angles a hole was centered at 2.5 inches down from the bottom cap to allow the bottom cap to be bolted to the MTS 880 bottom load platen. This table was useful when moving the specimen throughout the laboratory. The table was of a width that a forklift could be used to lift and move the specimen one constructed. The two ports drilled and tapped into the bottom platen were not used in this testing program as they tended to accumulate fine debris caused by specimen attrition. They would be useful in the case that water was to be drained out of the specimen if saturated surface dry conditions were of interest. However, for the current testing, these ports were plugged and not used. A photo of the two platens can be seen in Figure 3.2 Triaxial cell end platens photo. A diagram of the top and bottom platen design can be seen in Figure 3.3 and Figure 3.4.

![Figure 3.2. Missouri triaxial cell end platens photo](image-url)
Figure 3.3 Bottom platten schematic

Figure 3.4 Top platten schematic
Due to concern of puncturing the latex membrane surrounding the ballast sample during sample building and densification a unique sample mold was designed. The mold consisted of a PVC tube 18-inches in diameter and cut to 35-inches tall with a sheet of rubber placed inside. The latex membrane was then placed inside the rubber sheet and ballast placed inside of this membrane. The PVC tube was cut in half lengthwise creating two halves each standing 35-inches tall and semicircular. Inside the rigid PVC tube the sheet of 3/8-inch rubber was cut to fully cover the inside walls of the rigid PVC mold. Both the PVC half tubes and the rubber lining sheet were fitted with matching columns of port holes drilled into each component. These holes were used as ports for applying vacuum to pull the membrane tight against the mold during sample building. The lining sheet of rubber was intended to avoid pinching of the latex membrane between particle corners and the rigid PVC mold during sample construction. The specimen mold with rubber liner is depicted in Figure 3.5 below.

Figure 3.5. Sample mold including PVC rigid mold with rubber liner inside
The mold was designed to be one-inch taller than the sample. One-inch was included at the base of the mold allowing it to be hose-clamped around the one-inch tall bottom cap. In this fashion a sample 34-inches tall was constructed.

3.2. MANUFACTURE OF THE THREE PARALLEL GRADATIONS

Manufacture of the gradations to be tested was performed by super imposing the prototype #3 Main Line railroad ballast gradation curve over a graph of available sieve sizes. #3 Main Line railroad ballast is marketed by Fred Webber Inc. for use as railroad ballast throughout North America. From this graph, depicted in Figure 3.6, the gradation curves and the amounts of material required from specific sieves were found. This portion of this study was performed by David Baugher as an OURE undergraduate research project at the MS&T. These model material curves were then mixed from the Iron Mountain material that had been retained on specific sieves.

![Figure 3.6. Parallel gradation manufacturing curves](image-url)
3.3. THE BUILDING OF A 16.5-INCH DIAMETER SAMPLE

The original material included in this testing program was obtained from Iron Mountain Trap Rock of Iron Mountain, Missouri. At the quarry, the ballast material was poured into 55 gallon drums and transported to the Missouri University of Science and Technology materials lab. Several different gradations were obtained from the quarry. Gradations ranged from prototype railroad ballast, marketed as #3 railroad ballast (2.5” to 3/8”), down to a manufactured sand (3/8” to #200). The manufactured sand material is marketed most commonly as a floor hardener. These grainsizes were then used to manufacture all testing gradations.

Once the material was delivered to the MS&T civil engineering laboratory the barrels were emptied into drying trays, oven dried and then sieved. All testing gradations were mixed from this sieved fresh material. These gradations, namely the 2.5-inch (63.5 mm) prototype, 1.5-inch (38 mm) model and ¾-inch (19 mm) model, were kept as separate specimens throughout the testing. In this manner separate material was maintained for the three different size gradations. This greatly simplified the tracking of samples throughout the testing and the attrition analysis portion of this study.

A 16.5-inch diameter and 34-inches tall triaxial specimen yields a volume of 4.21 cubic feet. At a density of 98 pcf (1570 kg/m³) this is a specimen of almost 420 pounds (190 kg). The gradation of the specimens was important, therefore sieving and remixing of each sample before and after triaxial testing was performed. Sieving was performed using Gilson shakers with 24 x 30 inch screens. The sieve system used was capable to taking approximately 50 pounds (23 kg) of material at a time. In general, the specimens were broken into ten equal parts of approximately 40 lbs (18 kg) each. In this fashion, two buckets comprised a fifth of the sample. This was useful as the sample was built using five equal lifts of 82.5 pounds (37 kg). Table 3.1. depicts the gradations used in this testing program.

After a specimen was triaxially tested, the sample was dumped into a slurry tray. This steel tray was accompanied by a wooden pallet for ease of movement around the lab. The tray was raised to the bottom platen after testing. The vacuum in the sample was then allowed to dissipate and the sample pushed into the tray. The tray was then placed on a stack of pallets and tilted to approximately 45 degrees. Five-gallon buckets were
then placed under the low end of the tray and the material shoveled/ funneled into the buckets. This can be seen in Figure 3.7. While the buckets were not weighed during this step, approximately 40 lbs of material was placed in each bucket. In this fashion ten buckets were used. This allowed a consistent number of buckets to be used for transporting the sample throughout the sample preparation process.

The buckets were then poured into the sieve machine with the proper sieve stack for the specific gradation. The material captured on the different sieves was then placed in delineated buckets. After sieving the entire sample, the material captured on the respective sieves was weighed for attrition measurements. To bring the gradation back to the specified testing gradation, material typically needed to be either added or removed from some or all of the sieves. In the case of adding material to a sieve, fresh material

<table>
<thead>
<tr>
<th>Table 3.1. Sieve sizes for gradations tested</th>
</tr>
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<tbody>
<tr>
<td>2.5” Prototype Gradation</td>
</tr>
<tr>
<td>Sieve</td>
</tr>
<tr>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>1.5</td>
</tr>
<tr>
<td>1.25</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>3/4</td>
</tr>
<tr>
<td>1/2</td>
</tr>
<tr>
<td>3/8</td>
</tr>
</tbody>
</table>
was always added. In the case that more material was on a sieve than needed material was removed from the sample material and wasted. In this process some fresh material was added to the sample each test. Typically no more than five pounds of material was added or removed from any sieve during this process.

With the proper weights of material at the different sieve sizes obtained, the material was then thoroughly mixed. Mixing was performed by pouring the different sizes of material into a 4 cubic foot (0.11 cubic meters) concrete drum mixer. Mixing was performed at 12 rpm while adjusting the tilt of the mixing bucket several times to insure proper mixing. Leaving the tilt at one setting did not mix the material. The mixed gradation was then poured into the steel tray and again tilted on top of several pallets to be poured into buckets. Pouring of the sample from the mixer into the steel transport tray is depicted in Figure 3.8. The ten buckets were filled to exactly 41.25 pounds (18.7 kg) each. In this manner two buckets comprised one 82.5 pounds (37.4 kg) sample lift, once compacted to 98 pcf (1570 kg/m³).
3.3.1. Obtaining Uniform Initial Density. Cyclical loading of railroad ballast is generally thought to “condition” the ballast material during the first several loading cycles. In this manner, meaningful data is considered to be obtained only after this initial conditioning has occurred. This initial conditioning is typically considered to occur during the initial 100 load cycles. In this manner, the initial density of the sample is relatively unimportant during cyclical triaxial testing. However, during monotonic loading density is known to greatly affect load capacity.

In order to construct a uniform sample for triaxial testing, the density must be controlled throughout the sample. Several strategies for obtaining uniform density throughout the sample were tested in preparation for this triaxial testing program. The most effective method will be described here. A uniform initial testing density of 98 pcf (1570 kg/m³) was established as the target density based on initial densities of materials placed in the field.
Relative density is not typically determined for materials containing particles of the size included in railroad ballast. This is primarily due to large particles edge effects on void ratio along the walls of a containing mold. However, in order to assess the apparent relative density of the different gradations of railroad ballast the following method was executed. Using the 16.5-inch (419 mm) sample mold built for triaxial testing, ballast material was poured in from the top of the mold. This was a distance of 34-inches (864 mm) from the top of the mold to the bottom platen for the bottom lift. Each lift comprised a fifth of the sample and weighed 82.5 pounds (37.4 kg). A measurement was then taken from the top of the mold down to the surface of the material at four locations around the perimeter of the sample. Using this measurement and the weight of material added, the initial density of the material was found. The maximum density was defined as the density of the material comprising the first lift stabilized to when horizontally shaken using a sine wave amplitude of 0.05-inches (1.27 mm) and 30 Hz. Stabilization was generally observed after 40 seconds of shaking. These amplitude and frequency levels were found to be most expedient during preliminary testing.

Minimum density was determined using the fourth lift in a sample. The density of the fourth lift, as poured into the mold was considered the “minimum” density for the gradation. Minimum density was calculated for all samples built. A reduction in the initial density, as poured into the sample was observed as subsequent lifts were added. This is likely an effect of the reduction in energy imparted on the lift during the drop of the ballast from the top of the mold.

All samples for triaxial testing were prepared to an initial target density of 98 pcf. This density was achievable for all the gradations and considered stable after the sample had been constructed. During preliminary density control investigations magnets were placed in the sample at the interface of respective lifts to monitor density during sample building. These magnets were ring shaped light weight magnets (bonded neodymium-iron-boron). By covering the hole of the ring, using sheet metal, the unit weight of the magnet was made close to the unit weight of an intact ballast particle. Magnets were placed at the interface of the lifts during sample construction. These magnets could then be monitored during densification of subsequent lifts. This monitoring was achieved by using a high power magnet outside the sample mold. By running the high power magnet
along the mold the location of the magnets at the respective lift interfaces could be monitored. It was found that five lifts was effective for controlling sample density throughout. Magnets were not used during the building of samples that were used as triaxial samples, however, two painted ballast particles were used to mark lift interfaces. These painted ballast particles could be found visually through the membrane after the sample mold was removed. Measuring the location of the bottom of the painted rocks allowed an estimate of the final density of the individual lifts.

Preliminary sample construction and compaction revealed that once a lift was densified to 95 to 100 pcf (1522 to 1602 kg/m$^3$) the lift would not appreciably further compact during the placement and densification of subsequent lifts. All densification was performed with the sample attached onto a horizontal shake table. The shake table used was a Kimball K-3396 table assembly with an MTS 204 actuator and operated by a MTS 407 controller. This piece of equipment is more customarily used for earthquake loading simulation, however it was found to be quite satisfactory for the densification of railroad ballast. A sample being constructed on the horizontal shake table can be seen in Figure 3.9.

Figure 3.9. Sample preparation on the shake table
3.3.2. Construction of 16.5-inch (419 mm) Diameter Latex Membrane.

Typical latex membranes used in triaxial testing are made by dipping a wire hoop oriented horizontally into a pan of molten latex. The hoop is then removed from the molten creating a cylinder of latex. This latex cylinder is then allowed to cure and subsequently redipped until the proper thickness of the membrane is achieved. There was no latex company willing to custom build membranes 16.5 inches (419 mm) diameter and 34 inches (864 mm) in length. Therefore, latex membranes for this testing were constructed in house. Rolls of latex of dimensions 0.025” x 42” x 69’ (0.635 mm x 1067 mm x 21 m) were purchased. These rolls were then cut into 53.3 inch (1354 mm) sections ($\pi \times 16.5” + 1.5’’$). The extra 1.5 inch (38 mm) was used to form an overlapping glue seam. The 1.5-inch wide seam was found to adequately seal the sample at the low confinements used in this testing. Sandpaper was used to scratch the two 1.5-inch overlapping seam portions of the membrane before gluing the seam together.

In order to glue the seam together, the latex was thoroughly cleaned of all powders that are used during shipping. These powders keep the latex from sticking to itself while in a roll. Cleaning of this dust was performed using a clean wet rag. It was found that latex tended to curl once glue was applied and started to cure. In order to allow the glue to be applied before the latex curled onto itself a method of temporarily adhering the latex to metal channels was developed. The channels served to both hold the membrane flat during glue application and serve as flat surfaces to sandwich the membrane seam between while the glue was allowed to cure. The channels were first cleaned of all debris including any fine powder or leftover glue from previous seam building. Both the latex and metal were then wetted and the latex was laid flat on the channel. All air bubbles were squeezed out from between the two surfaces. The system is then allowed to dry overnight allowing the latex to lightly adhere to the metal channel.

At this point Scotch-Grip contact adhesive 1357 from 3M was applied to both 1.5-inch (38 mm) wide scratched latex surfaces. The best method of applying the glue was found to be placing a heavy bead on one surface and brushing this bead uniformly across the 1.5 inch seam. Two light beads were run the length of the adjoining seam. Several seconds were allowed to let the glue cure initially before the seams are joined by placing one channel on top of the other. Several weights were placed on the top channel at this
point to maintain contact. If the glue was not allowed to dry before contact or too much weight applied to hold the seam together the result was that the glue was pushed out of the seam resulting in poor seam bonding. The glue was then allowed to cure for at least an hour. At this point the latex was peeled off the channels and the seam inspected. If there were areas that did not adhere for the full width of 1.5-inches, more glue was applied to the voids and the latex seam again pressed together between the flat channel surfaces. At this point the membrane was structurally complete and visual texturing was applied for assistance in the photographic strain analysis. The process of building a latex membrane is depicted in Figure 3.10. below.

Figure 3.10. Assembling the seam of the latex membrane
a) Heavy bead of glue applied to one side of seam
b) Evening the glue on the heavy side of the seam
c) Thin beads of glue on the second side of the seam
d) Final weights applied as the glue is allowed to cure
3.4. MONOTONIC TRIAXIAL TESTING

Monotonic strain controlled triaxial compressive testing was performed on the three parallel gradations of railroad ballast. These gradations included the prototype railroad ballast gradation, the 1.5-inch (38 mm) top size parallel gradation, and ¾-inch (19 mm) top size parallel gradation. Three monotonic loading tests were performed on each of the three gradations. Axial load, axial strain, volumetric strain, confining pressure were continually monitored during testing. All monotonic testing was carried out at a deformation rate of one inch per 150 seconds (25.4 mm/s) or 0.4 inches per minute (10.2 mm). All samples were built to a density of 98 pcf (1570 kg/m$^3$). Confining pressure was held at 3 psi (20.7 kPa) throughout the monotonic testing.

Monotonic loading was performed using a MTS 880 load frame. The load frame is controlled by an analogue MTS 448.85 Test Controller and the load rate is dialed into a MTS 410.80 Function Generator. The 880 load frame was operated using the 10% of full load capacity setting yielding an 11,000 lbs scale (10% of the 110,000 lbs full capacity of the system). This allowed satisfactory control at the relatively small loads used in this testing.

After the sample was placed on the MTS 880 loading platen, a confining vacuum was maintained at all times to prevent sample collapse. Vacuum was maintained during sample preparation using the laboratory vacuum system. If there was a membrane leak suspected before removing the sample mold, a second vacuum system was connected to the sample. This second portable vacuum pump had a large volume capacity. This large volume capacity allowed the patching of the membrane in all but one occasion. Once a stable vacuum was attained, the sample mold was removed and wire extensionometers placed. Wire extensionometers were placed surrounding the samples circumference at 1/4H, 1/2H and 3/4H. Two LVDT’s were placed at opposite sides of the specimen as a redundant measurement of total deflection. The specimen with wire extensionometers affixed is depicted in Figure 3.11 below.

Occasionally the latex membrane surrounding the sample was found to leak after construction of the sample. Only four punctures during the entire testing program were due to holes apparently punched in the membrane during sample building. In these cases
the hole was a relatively small and located on the membrane outside the vicinity of the glued seam. These holes were patched using a round piece of latex, cut from a previous membrane, and glued into place on the sample. This method worked very well and it is considered likely this success was in no small part due to the fact that the confinement was provided by vacuum. The vacuum effectively pulled the glue and patch into the sample maintaining a good seal with minimal effort. The second form of leak was the delamination of the seam of the latex membrane. This problem was found more likely when larger particles were tested. The inside ply at the seam would tend to be pulled into the sample void while the outside ply did not have the vacuum acting on it. In this manner the two latex sheets tended to separate in areas where a weak glue bond encountered a large void in the railroad ballast sample. These leaks were considerably more serious due to the size of the hole that could occur. Placing abundant glue in the

Figure 3.11. Top cap and wire extensionometers positioned on a railroad ballast sample
seam and applying pressure by hand worked to stabilize the situation in all but one case. Improvements to the membrane manufacturing process incorporated during this study included sandpaper scratching of the latex along the seam before gluing and only applying a maximum vacuum to the sample during sample preparation of 5 psi (34.5 kPa). The delaminations were due to pulling excessive vacuum during sample preparation. This controlled vacuum prevented the excessive pulling of the membrane into the voids of the sample. The combination of these improvements eliminated leaking at the seam of the membrane quite well.

3.5. CYCLICAL TRIAXIAL TESTING

Cyclical triaxial testing was performed on the three parallel gradations including the prototype railroad ballast material (top particle size of 2.5-inches (63.5 mm)), the 1.5-inch (38 mm) top size model gradation, and the ¾-inch (19 mm) top size model gradation. Stress ratios that the material was cyclically loaded to were calculated based on the monotonic testing previously discussed. Stress ratios tested are summarized in Table 3.2. Cyclical triaxial testing schedule.

Once the sample was set up, cyclical loading was performed using the MTS function generator in conjunction with the MTS 880 loading system maintained by the Civil Engineering department at MS&T. The loading system was again run at the 10% capacity setting allowing 11,000 lbs (4990 kg) of capacity from a system with an 110,000 lbs (49900 kg) capacity. This allowed more accurate control of the system for the loads required for this testing. Loads required for this testing ranged from 250 lbs. to 4,000 lbs.

The following procedure was used to perform the cyclical loading of railroad ballast samples using the analogue system available. At the beginning of the test the control of the load was performed by manually dialing the load using the MTS test controller in load control. In this manner the seating load (250 lbs for all cyclical tests) was dialed in. At this point the data acquisition was started. The load was then increased
Table 3.2 Cyclical triaxial testing schedule

<table>
<thead>
<tr>
<th>Gradation from Monotonic Testing</th>
<th>Maximum Capacity lbs.</th>
<th>Peak Load Capacity lbs.</th>
<th>Stress Ratio n</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>3644</td>
<td>2745.9</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3061</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3431.9</td>
<td>0.94</td>
</tr>
<tr>
<td>1.5</td>
<td>3783.8</td>
<td>2541</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3180</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3405.4</td>
<td>0.90</td>
</tr>
<tr>
<td>3/4</td>
<td>4172</td>
<td>2750</td>
<td>0.65</td>
</tr>
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</tr>
<tr>
<td></td>
<td></td>
<td>3755</td>
<td>0.90</td>
</tr>
</tbody>
</table>

To the median load. The median load is the load that defines the midpoint for the cyclical loading using this MTS system. The first cycle was continued manually up to the maximum load and then decreased to the seating load. During this load, the span was set for subsequent cycles. In some cases it was necessary to manually control another cycle in this fashion in order to get the proper midpoint and span dialed in. The load was then returned to the median load in preparation for the function generator controlled cycles. All cycles controlled by the function generator were sinusoidal load controlled as defined by midpoint and a function span. Both of these controls were dialed in using analogue dials controlling the load exerted at the platen of the load frame.

Preliminary testing concluded that there were no differences in the ballast reaction to loadings performed from 0.05 to 3 Hz. Therefore, all measurement readings were taken at 0.05 Hz (20 seconds per cycle), while all loadings between readings would be
performed at 1 Hz for expedience. Readings were taken for the initial 12 cycles and then for 10 cycles at 100, 200, 500 cycles and then every 1000 cycles thereafter. Data readings taken during the cyclical load testing included axial load, axial deformation, circumferential deformation, and confining pressure. An additional data channel was dedicated to attach a time stamp to digital photographs captured during testing. All of these parameters were monitored at a rate of 100 points per second. The slower loading during data readings allowed digital cameras placed at three different angles around the sample to operate taking a picture every 2 seconds. This allowed 10 pictures per cycle. Digital image strain analysis will be performed at a future date in conjunction with Dr. Andy Take of Queens University, Kingston, Ontario, Canada.

The material tended to stiffen but plastic deformation continued to accumulate during testing. Due to these sample characteristics monitoring of the median load and span was required. Data readings were taken while loadings continued at 1 Hz and the midpoint and span adjusted accordingly. A separate span setting was needed to achieve proper loading at a loading rate of 0.05 Hz. Once this slower loading span was set it was fine tuned at the beginning of each data recording. In this fashion the fifth loading of the ten loadings recorded would be close to a perfect loading.

### 3.6. ATTRITION MEASUREMENT

Attrition measurements were performed after each triaxial test. The exact gradation of each individual sample was recorded before the sample was sent to be mixed and placed into the triaxial sample. After the respective triaxial test, the ballast material was again sieved on the exact sieve stack as before sample manufacture. Again the weight of material captured on each sieve was recorded. All sieving was performed using a dry sieve technique. The changes in the gradations curve were recorded. After these measurements were taken, material was added or subtracted from the individual grainsizes as needed to build the proper gradation for future testing as outlined above.
3.7. DIGITAL IMAGE PARTICLE SHAPE ANALYSIS

Shape, surface roughness, gradation and level of compaction have been identified as primary characteristics affecting the load bearing capacity of granular materials. Digital photo images were taken in order to assess particle shape of the materials used in this study. These images were then analyzed for shape parameters using Matlab. This computer code was designed to assess both the length to width ratio and minimum curve radius of individual particles in a digital photograph containing 25 particles. The length to width ratio and angularity is calculated for each particle and then averaged for the 25 particles contained in an image. The average of all particles of a specific gradation were then taken as the shape parameters for that grainsize.

Representative samples of particles from samples of both fresh ballast material and material that was used in the accompanying triaxial testing program were assembled. Particles were taken from a randomly selected single bucket of the desired size material. For fresh material these buckets were filled after sieving the material from barrels of the fresh material as obtained from the mine. In the case of used material the particles were taken after sieving a triaxial sample at the end of the triaxial testing program. These buckets were then quartered, and requartered as needed, to get a number of particles that was suitable for the shape assessment study.

The nominal size (sieve number) of particles to be analyzed was selected in order to have three sizes from each of the gradation curves used in triaxial testing. In this manner, six gradations of particles were selected from the plethora of particles sizes used in the triaxial testing program. For comparative analysis, representative particle samples were assembled from gradations that had previously been used in triaxial testing (used) and fresh railroad ballast material (fresh). A goal of analyzing 1% of the particles included in the triaxial testing was attainable for larger particles while the number of particles necessary to fill this requirement for the smaller particles posed a considerable photo imaging challenge. A summary of the particles used in the shape analysis portion of this study can be seen Table 3.3 Shape analysis sample summary.

The capturing of digital images for the particle shape analysis portion of this study was performed using equipment owned and maintained by Dr. Norbert Maerz of MS&T. The ratio of nominal particle size to width of the image was maintained constant.
Table 3.3. Shape analysis sample summary

Prototype 2.5" Curve

<table>
<thead>
<tr>
<th>Sieve #</th>
<th>Lbs. used in triaxial sample</th>
<th>Grams in triaxial sample</th>
<th>Grams of material used on photo shape analysis</th>
<th>Number of particles used in photo shape analysis</th>
<th>% of triaxial sample analyzed for shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>14.42</td>
<td>6542</td>
<td></td>
<td></td>
<td>7.9%</td>
</tr>
<tr>
<td>1.5</td>
<td>182.77</td>
<td>82902</td>
<td>6556.8</td>
<td>50</td>
<td>13.8%</td>
</tr>
<tr>
<td>1.25</td>
<td>81.42</td>
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<td>5107.0</td>
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<td>49351</td>
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<td></td>
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<tr>
<td>3/4</td>
<td>28.80</td>
<td>13065</td>
<td>1798.6</td>
<td>100</td>
<td>13.8%</td>
</tr>
<tr>
<td>1/2</td>
<td>5.08</td>
<td>2304</td>
<td>594.2</td>
<td>100</td>
<td>25.8%</td>
</tr>
<tr>
<td>3/8</td>
<td>1.85</td>
<td>840</td>
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<td></td>
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</table>

Model 1.5" Curve

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<th>Sieve #</th>
<th>Lbs. used in triaxial sample</th>
<th>Total grams in triaxial sample</th>
<th>Grams of material used on photo shape analysis</th>
<th>Number of particles used in photo shape analysis</th>
<th>% of triaxial sample analyzed for shape</th>
</tr>
</thead>
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<td>1.25</td>
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<td>70203</td>
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<td>2.6%</td>
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<td>5886</td>
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Model 3/4" Curve

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<th>Lbs. used in triaxial sample</th>
<th>Total grams in triaxial sample</th>
<th>Grams of material used on photo shape analysis</th>
<th>Number of particles used in photo shape analysis</th>
<th>% of triaxial sample analyzed for shape</th>
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</thead>
<tbody>
<tr>
<td>3/4&quot;</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>1/2&quot;</td>
<td>126.21</td>
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<td></td>
<td></td>
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<tr>
<td>#4</td>
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<td>150</td>
<td>1.6%</td>
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</tbody>
</table>
for all particle sizes. In this manner, the pixel intensity across particle sizes could be maintained equal. Samples from the individual particle sizes were placed on a white cardstock sheet including 25 particles per picture. These 25 particles were placed in five rows of 5 columns each. The rows were carefully placed such that each particle’s uppermost edge was slightly below the preceding particle in the row. This alignment allowed individual particles to be identified in the data stream after image processing.

The shape analysis was performed to assess both the length to width ratio and angularity of the individual particles. This was performed using a single 2 dimensional image. In this manner, the smallest dimension of the particle is assumed to be in the vertical plane and therefore not measured in this analysis. Similarly, angularity is assessed along the projected perimeter of the middle and longest dimension of the particle only.

Shape analysis was performed using a Matlab script assembled with considerable assistance from Mr. Josh McNiff, a computer science graduate student at MS&T. The analysis of particle shape was performed on the digital images including 25 particles per image as follows. The raw image was first converted to a black and white binary image and a salt and pepper cleanup performed to eliminate stray pixels. The code then identified particles starting in the top left hand corner and worked across to the right. At the end of each pixel row the search would continue to the next row down. Once a particle was encountered, a perimeter walk was performed and a log of the pixel coordinates of each particle taken and stored. At the completion of the perimeter walk for an individual particle the left to right and top to bottom search was continued. When another particle perimeter was encountered with coordinates that are not already contained in a previous particle perimeter file a perimeter walk was performed of this particle. In this manner the uppermost tip of each particle defines this particles position for all further calculations and output.

With the outline of each individual particle contained in a x,y coordinate file, the shape parameters are assessed. To calculate length, each point on the outline of an individual particle is checked for distance to every other point of the outline. Once this is completed, the longest distance is taken as the length of the particle. This line across the particle is also retained as the “length line” of the particle. This line of longest distance
from point to point of the outline of the particle is then used as a dividing line for finding the width. The width is calculated as the total of the two longest distances from the length line extending perpendicular to the perimeter of the particle. The length and width of a particle are depicted in Figure 3.12. below.

The calculation of angularity is based on the size of inscribed circles fitting along the perimeter of the individual particle. A smaller inscribed circle represents a sharper corner of the particle. To assess the radius of an inscribed circle for a given point on the perimeter of a particle the following procedure was used. Starting at the point of interest two pixels are skipped and the third pixel from the starting point on the perimeter of the particle is taken. A line is then drawn between these two points and a perpendicular line is drawn from the midpoint of this line extending into the particle. The circle is then defined as that which passes through these two points and has a center along the perpendicular line. This process is then carried out for each point on the perimeter of the particle. The average radius of the four smallest corners of a particle are taken to quantify the angularity of the particle.

Figure 3.12. Shape parameter schematic.
3.8. ANGLE OF REPOSE MEASUREMENT

An angle of repose measurement was taken of the three gradations of railroad ballast tested in the triaxial testing program as a measure of the loose frictional characteristics of the material. Due to the large particle size of the railroad ballast material, pouring the material from a funnel was not practical or reliable. Therefore, a tilting method was performed in the following manner. The mixed gradation was poured into the steel tray and the top surface leveled. The tray was then tilted until the free surface of the material fully moved. This occurred as loose particles rolled down the free surface. The angle of the free surface 6-inches (152 mm) from each side of the tray and directly in the middle of the slope was then measured. Measurements were performed using a Starrett angle meter, commonly used in the machining trade, attached to a straight metal channel 2.5-feet (762 mm) in length. In this manner the slope was measured over a 2.5-foot section of the slope. The measurement of the angle of repose is depicted in Figure 3.13.

Figure 3.13. Measurement of the angle of repose
3.9. LOS ANGELES ABRASION

Los Angeles abrasion testing was performed on all three gradations of railroad ballast material. Los Angeles abrasion testing was performed in general conformance with ASTM C 535 – Standard Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine and C131 – Standard Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine. The weight of the impact balls was confirmed before running the tests. The 2.5-inch (63.5 mm) prototype and 1.5-inch (38 mm) model gradations required the C535, large size test using 10,000 grams of material, while the ¾-inch (19 mm) model gradation was run using C131 small size specification requiring 5,000 grams of material. Again, all sieving was performed using a dry sieve method.
4. TEST FINDINGS AND ANALYSIS

4.1 MONOTONIC TRIAXIAL COMPRESSION TESTING

Deformation controlled monotonic triaxial tests were performed on three samples of each railroad ballast gradation. Load, deformation, circumferential elongation, and confining pressure were recorded at a data sampling rate of 100 data points per second. The monotonic loading tests were performed to large deformations, up to six-inches (152 mm) at a rate of 0.4 inches per minute (10.2 mm/min). The intent of the monotonic load testing was to establish the peak load capacity of the different gradations. Using these peak loads, the cyclical load ratios for the cyclical triaxial testing portion of this study could then be calculated.

4.1.1. Sample Construction and Density Control. All samples were prepared to a target initial density of 98 pcf (1570 kg/m³). This initial density was established based on initial densities of railroad ballast placed in the field. Relative density is typically not measured for materials with particle sizes ranging up to two-inches. Due to the initial densification of granular materials in a cyclical triaxial framework, initial density of a specimen is of relatively little concern. However, relative density was measured for the three gradations tested. Minimum density as defined in the procedure of this report was measured during the construction of all triaxial samples. The minimum density as reported here represents the average minimum density for the specific gradation throughout all testing. This minimum density is the density of the material after it was poured into the fourth lift (of five). The first particle of this lift was poured 13.6-inches (345 mm) from the top of the mold to the top surface of lift three. The final lift was considered unreliable, as placement of this lift required shaking and reshaking as further material was added to the mold. The maximum density was measured three times for each gradation, the average of these three measurements is reported here as the maximum density. Table 4.1 presents the relative densities for the three ballast gradations used in this study.
Table 4.1. Relative density

<table>
<thead>
<tr>
<th>Sample</th>
<th>Minimum density</th>
<th>Maximum density</th>
<th>Relative density at 98 pcf</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/4&quot;</td>
<td>90</td>
<td>102</td>
<td>0.66</td>
</tr>
<tr>
<td>1.5&quot;</td>
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<td>106</td>
<td>0.31</td>
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<tr>
<td>2.5&quot;</td>
<td>97</td>
<td>108</td>
<td>0.09</td>
</tr>
</tbody>
</table>

While relative density estimations are useful for comparative analysis between the different gradations tested the initial target density of samples was used to control initial sample preparation. After each lift was poured into the sample mold, shaking was performed to densify the lift. The distance from the top of the mold to the top of the lift was measured in four locations. Based on the location of the previous lift interface the density of the lift was calculated. If the lift was found to be at a lower density than required, further shaking was performed and measurements again taken until proper density was achieved. With the lift at the proper density two painted ballast particles were placed along the outside edge of the sample before material for subsequent lifts was added. The location of the bottom of these two locator particles was then measured, for each lift, after the sample mold was removed. In this manner, a relatively coarse measurement of the final density of the individual lifts was found. The initial sample density data for representative samples is presented in Table 4.2.

4.1.2. Monotonic Loading. The MTS 880 load frame was operated using deformation control for monotonic loading. In this manner the post peak behavior could be observed. The peak load capacity of a gradation was used to calculate cyclical stress ratios. By holding the confinement pressure constant throughout both monotonic and cyclical triaxial testing these peak load capacities provided a method to carry out the cyclical triaxial testing, portion of this study. This was considered the most reliable
Table 4.2. Initial sample density data

<table>
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<th>Sample #</th>
<th>6</th>
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<th>9</th>
<th>10</th>
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<th>12</th>
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<td></td>
<td></td>
</tr>
<tr>
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<td>97.0</td>
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<td>98.3</td>
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<td>105.2</td>
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<td>97.0</td>
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<td>93.9</td>
<td>101.1</td>
<td>100.9</td>
<td>102.6</td>
<td>98.3</td>
<td>94.0</td>
<td>95.7</td>
<td>100.9</td>
</tr>
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<td>97.6</td>
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<td>95.9</td>
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<td>93.9</td>
<td>98.3</td>
<td>99.2</td>
<td>94.2</td>
<td>98.1</td>
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</table>

Average Sample Density: 98.1

Initial density of lift measured after densification of individual lift (pcf)

<table>
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<th></th>
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<th></th>
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<td>96.6</td>
<td>92.1</td>
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</tr>
<tr>
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<td>93.0</td>
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<td>96.6</td>
<td>94.5</td>
<td>101.5</td>
<td>98.4</td>
<td>88.0</td>
<td>94.3</td>
<td>89.0</td>
<td>103.6</td>
<td>107.0</td>
<td>104.2</td>
<td>100.4</td>
</tr>
</tbody>
</table>

Average Sample Density: 98.4

Initial density of lift as measured by red rock position after complete sample was built (pcf)
method for assessing and controlling cyclical stress ratio. The MTS 880 used with this testing program did not allow control of specimen loading in terms of deviatoric stress, more modern equipment may.

The different load capacity characteristics between the prototype and model gradations are apparent when reviewing the load capacity versus deformation plots. As can been seen in Figure 4.1, the 2.5-inch (63.5 mm) prototype material fluctuations in load were on the order of 30% of the median load reading at and near the peak load capacity of the material. For the 1.5-inch (38 mm) model these fluctuations were typically around 17% while fluctuation in load capacity for the ¾-inch (19 mm) model gradation were on the order of 5% at and around the peak load capacity of the material. These fluctuations in measured load were generally observed to coincide with snapping sounds often accompanied with a rapid reorientation of the material. This reorientation was sometimes visible through the latex membrane. At this point the load would fall off. With further deformation, the load would again pick up to near the original load reading. The larger particles of the prototype material are thought to magnify this effect while the smaller, model gradation particles, tended to minimize this effect. Figure 4.1 shows an example of load versus deformation data with all curves included. Figure 4.2 depicts the three different gradations with the chosen curve only.

The absolute peak load carried by a gradation at any point in the monotonic deformation controlled environment generally represents an unstable configuration for the material. If this peak load were to be applied to the material in a load controlled environment rapid deformation leading to complete destruction of the sample was observed. Therefore, a method for evaluating the peak load capacity of the material was needed to determine the peak load capacity of the material for use in assigning the cyclical stress ratios, n, for cyclical triaxial testing.

Due to this spiking of the load capacity in deformation controlled testing, the peak load of the material was assigned using a polynomial curve fit to the data. In this manner fourth, fifth, sixth, and seventh order polynomials were fit to the load versus deformation data for each monotonic test. While these curves tended to diverge from the data at low deformations the peak capacity section of the curve was quite well represented. The most
A representative polynomial fit line was picked from the group of polynomial fit lines when plotted with the raw load-deformation data. The peak load capacity and corresponding strain was then found using the equation of this polynomial line. Preference was given to lower deformation peaks in order to avoid excessive strain and bulging associated with large sample deformations. In this manner the peak load capacity was assessed for each monotonic triaxial test. The monotonic test results were then averaged to assign the peak load capacity for the specific gradation as seen in Table 4.3.

These peak load capacities do not account for the cross-sectional expansion that occurs to the specimen during triaxial compression. Deviatoric stress results are more
Figure 4.2. Representative load versus deformation data for 2.5-inch prototype, 1.5-inch model, and \( \frac{3}{4} \)-inch model gradations.
Table 4.3 Peak load capacities from monotonic load testing

<table>
<thead>
<tr>
<th>Test #</th>
<th>Sample gradation</th>
<th>Peak Load</th>
<th>Deflection at peak load</th>
<th>Order of curve fit</th>
<th>Average peak load capacity</th>
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</tbody>
</table>

useful in properly assessing the capacity of the railroad ballast material. In this manner the effects of cross-sectional expansion and variations in confinement pressure are taken into account. Figures 4.3 through 4.5 depict the deviatoric stress versus axial strain for the 2.5-inch (63.5 mm) prototype material. Figures 4.6 through 4.8 similarly depict these parameters for the 1.5-inch (38 mm) model gradation, and Figures 4.9 through 4.11 depict the ¾-inch (19 mm) specimen deviator stress versus strain curves. Table 4.4 presents a summary of the maximum monotonic deviator stresses.
Figure 4.3. Sample #5 2.5-inch prototype gradation

Figure 4.4. Sample #7 2.5-inch prototype gradation
Figure 4.5. Sample #12 2.5-inch prototype gradation

Figure 4.6. Sample #11 1.5-inch model gradation
Figure 4.7. Sample #13 1.5-inch model gradation

Figure 4.8. Sample #14 1.5-inch model gradation
Figure 4.9. Sample #6 3/4-inch model gradation

Figure 4.10. Sample #9 3/4-inch model gradation
The peak stress carried by the ¾-inch (19 mm) gradation is higher than the larger two specimens. Another general trend that can be seen in both the peak load and deviatoric load data is that the monotonic capacity of the different gradations is found to generally decrease with each test performed. This is particularly dramatic for the smaller, 1.5-inch (38 mm) and ¾-inch (19 mm) gradations. Initial density of all samples was carefully controlled and confinement was consistently held to 3 +/- 0.2 psi. This loss in capacity of the material as further tests were performed on the same material could be due to changes in the particle shape. Again, the particles from one test were then sieved and remixed to additional samples. In this manner, the rounding of the corners of the particles, observed in the particle shape image analysis portion of this study, could be responsible for the decreasing load and deviatoric stress capacity of the materials throughout the testing program. A summary of monotonic testing can be seen in Table 4.4.
Table 4.4. Monotonic maximum deviator stress summary

<table>
<thead>
<tr>
<th>Test #</th>
<th>Sample gradation</th>
<th>Maximum Deviator Stress</th>
<th>Strain at peak deviator stress</th>
<th>Order of deviator stress curve fit</th>
<th>Average deviator stress psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2.5</td>
<td>17.3</td>
<td>0.09</td>
<td>5</td>
<td>17.3</td>
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<tr>
<td>7</td>
<td>2.5</td>
<td>17.3</td>
<td>0.06</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>2.5</td>
<td>17.3</td>
<td>0.04</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>1.5</td>
<td>18.4</td>
<td>0.03</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>1.5</td>
<td>17.6</td>
<td>0.04</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>1.5</td>
<td>17.0</td>
<td>0.04</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>3/4</td>
<td>20.6</td>
<td>0.06</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>3/4</td>
<td>19.9</td>
<td>0.04</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>3/4</td>
<td>17.8</td>
<td>0.05</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

4.2. CYCLICAL TRIAXIAL TESTING

All cyclical triaxial testing was performed using the MTS 880 load frame. Cyclical triaxial testing was performed on the three railroad ballast gradations at three different stress ratios as outlined in Table 4.5. Each cyclical test was performed for 10,000 cycles. At the end of each test the material was removed from the sample and remixed to the original gradation for further testing. In this manner vast majority of the material was reused in each progressive sample throughout the testing program.
### Table 4.5 Cyclical triaxial testing schedule

<table>
<thead>
<tr>
<th>Gradation</th>
<th>Maximum capacity</th>
<th>Peak cyclical load</th>
<th>Stress ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lbs.</td>
<td>lbs.</td>
<td>n</td>
</tr>
<tr>
<td>2.5</td>
<td>3644</td>
<td>2746</td>
<td>0.75</td>
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<tr>
<td></td>
<td></td>
<td>3061</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3432</td>
<td>0.94</td>
</tr>
<tr>
<td>1.5</td>
<td>3783.8</td>
<td>2541</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3180</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3405</td>
<td>0.90</td>
</tr>
<tr>
<td>3/4</td>
<td>4172</td>
<td>2750</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3365</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3755</td>
<td>0.90</td>
</tr>
</tbody>
</table>

Data was recorded periodically throughout the 10,000 load cycles. Data is presented in the following figures corresponding to the 100, 500, and 1,000th load cycle, and then every 1000 load cycles until completion of the test. The final data stream corresponds to the 10,000th load cycle. Figures 4.12 presents the sign convention used for axial and volumetric strains. Figures 4.13 and 4.14 present a key to the deviatoric stress versus axial strain and volumetric strain versus axial strain plots respectively. Figures 4.15 through 4.38 contain the cyclical loading data for all cyclical tests.
Figure 4.12. Contraction and dilation sign convention key
Figure 4.13. Deviator stress versus axial strain key

Figure 4.14. Volumetric strain versus axial strain key
Figure 4.15. Sample #16 2.5-inch n = 0.75 resilient modulus, permanent axial strain, and permanent volumetric strain
Figure 4.16. Sample #16 2.5-inch n = 0.75 stress and volumetric strain
Figure 4.17. Sample #24 2.5-inch $n = 0.84$ resilient modulus, permanent axial strain, and permanent volumetric strain
Figure 4.18. Sample #24 2.5-inch \( n = 0.84 \) stress and volumetric strain
Figure 4.19. Sample #19 2.5-inch $n = 0.94$ resilient modulus, permanent axial strain, and permanent volumetric strain
Figure 4.20. Sample #19 2.5-inch n = 0.94 stress and volumetric strain
Figure 4.21. Sample #17 1.5-inch n = 0.67 resilient modulus, permanent axial strain, and permanent volumetric strain
Figure 4.22. Sample #17 1.5-inch n = 0.67 stress and volumetric strain
Figure 4.23. Sample #20 1.5-inch n = 0.84 resilient modulus, permanent axial strain, and permanent volumetric strain.
Figure 4.24. Sample #20 1.5-inch n = 0.84 stress and volumetric strain
Figure 4.25. Sample #23 1.5-inch n = 0.90 resilient modulus, permanent axial strain, and permanent volumetric strain
Figure 4.26. Sample #23 1.5-inch \( n = 0.90 \) stress and volumetric strain
Figure 4.27. Sample #15 3/4-inch n = 0.66 resilient modulus, permanent axial strain, and permanent volumetric strain
Figure 4.28. Sample #15 3/4-inch n = 0.66 stress and volumetric strain
Figure 4.29. Sample #18 3/4-inch n = 0.81 resilient modulus, permanent axial strain, and permanent volumetric strain
Figure 4.30. Sample #18 3/4-inch n = 0.81 stress and volumetric strain
Figure 4.31. Sample #25 3/4-inch n = 0.90 resilient modulus, permanent axial strain, and permanent volumetric strain
Figure 4.32. Sample #25 3/4-inch n = 0.90 stress and volumetric strain
Figure 4.33. $n = 0.67$ resilient modulus, permanent axial strain, and permanent volumetric strain comparison
Figure 4.34. $n = 0.84$ resilient modulus, permanent axial strain, and permanent volumetric strain comparison
Figure 4.35. $n = 0.90$ resilient modulus, permanent axial strain, and permanent volumetric strain comparison
Figure 4.36. 2.5-inch prototype gradation comprehensive resilient modulus, permanent axial strain, and permanent volumetric strain
Figure 4.37. 1.5-inch model gradation comprehensive resilient modulus, permanent axial strain, and permanent volumetric strain
Figure 4.38. 3/4-inch model gradation comprehensive resilient modulus, permanent axial strain, and permanent volumetric strain.
All deviatoric stress strain curves exhibit a hysteretic loop for each loading and unloading cycle. This loop indicates work adsorbed by the ballast. Work generally decreased with further loading. Additionally, these stress strain loops became closer together with further loading but did not reach an overlapping situation. This indicates that “shakedown” was not attained even at the lower stress ratios within the 10,000 cycles tested. The steepening of the stress strain loops indicates an increase in resilient modulus with further loading as would be expected. This can also be seen in the resilient modulus versus number of loading plots.

Several interesting observations can be made from Figures 4.36 through 4.38 comparing the three materials tested at similar stress ratios. While the resilient modulus readings tended to fluctuate, a general trend of higher stresses lead to higher resilient modulus can be observed. This was observed for all gradations except the ¾-inch (19 mm) model. In this case, the 0.81 stress ratio exceeds the 0.90 stress ratio in resilient modulus. This stands out as a result that would not be expected based on current knowledge. However, the 2.5-inch (63.5 mm) prototype and 1.5-inch (38 mm) model gradations demonstrated the expected increase in resilient modulus with increased stress. Increased permanent axial strains were observed for all gradations corresponding to greater stress. Asymptotic leveling off of permanent strain can be observed to be imminent for the lowest stress ratio within 10,000 cycles performed, indicating shakedown may soon be attained.

Most interesting, however, are the stress ratio comparison graphics, Figures 4.33 through 4.35, depicting a direct comparison of the different gradations at the specific stress ratios. These plots form the basis for assessing the usefulness of the parallel gradation modeling scheme in a cyclical triaxial environment. Starting with the 0.67 stress ratio resilient modulus can be seen to compare quite closely for the 1.5-inch (38 mm) and ¾-inch (19 mm) gradations. The cyclical loading of the 2.5-inch (63.5 mm) prototype at n = 0.75 unfortunately discounted this test from this comparison. Regarding the permanent strain data for the 1.5-inch (38 mm) and ¾-inch (19 mm) gradations at n = 0.67, this is the only case where the larger material was observed to exhibit larger permanent strain than the smaller gradation. It is likely that the relatively large strain between the 100th cycle and 500th cycle for the 1.5-inch (38 mm) gradation resulted in
this discrepancy. If these two readings were to be disregarded the axial and volumetric strains of the larger 1.5-inch (38 mm) gradation would be lower than the smaller gradation. This would be consistent with the other stress ratio data.

The higher stress ratios, 0.84 and 0.90, comparing all three gradations cyclically testing at similar stress ratios the following observations regarding resilient modulus can be made. While the resilient modulus data is not entirely conclusive, larger gradations exhibited larger resilient modulus readings throughout the cyclical testing. This is clearly exhibited at the 0.90 stress ratio. Higher stiffness would be expected of the larger grainsizes as fewer particle contacts are expected in a load carrying queue extending the height of the sample (Kolisoja, 1997). Fewer particle contacts would be expected to yield more rigid behavior.

Several observations can be made of the permanent axial strain response at the higher stress ratios as well. Without exception, the smaller the gradation the larger the permanent axial strain. This can be clearly seen for the two higher stress ratios. It should be noted that the 2.5-inch prototype gradation was run at a stress ratio of 0.94. Even with this increased stress ratio this gradation consistently exhibited the lowest permanent strain.

The volumetric strain response of the three gradations poses the largest discrepancy in the parallel gradation modeling scheme. At the lowest stress ratio the smaller grainsize material exhibited the largest level of contraction. At the middle stress ratio, n = 0.84, no trend is evident, with the middle sized material exhibiting the largest volumetric contraction and the ¾-inch material contracting the least. The prototype material exhibited a level of contraction between the smallest and median grainsize material. At the highest stress ratio the prototype material was observed to again contract, however, the two smaller gradations exhibited some volumetric dilation. Small levels of dilation were observed on the 1.5-inch gradation, with a higher level of dilation exhibited by the smallest, ¾-inch material. A definite trend of larger permanent axial strains can be seen for the smaller materials. The increased axial deformation exhibited by the smaller gradations at high cyclical stress levels appears to have compacted the material to such an extent that caused volumetric dilation. This discrepancy in
4.3. PARTICLE SHAPE ANALYSIS

Samples of particles were taken both before and after the triaxial testing program to be included in the digital image shape analysis program. Digital image shape analysis was then performed on over 1100 particles consisting of both fresh and previously triaxially tested ballast material. Material that was included in the triaxial testing program is denoted as “used” material in this portion of the study. Image analysis was performed to assess the length width ratio and angularity of particles of different sizes. Angularity was assessed as the average inscribed curve radius of the four sharpest corners of the 2-dimentional projection of a given particle. Particles are delineated by the sieve they were captured on. In this fashion the particles used in the angularity analysis are those passing the next larger sieve used in the testing program and retained on the sieve corresponding to their name.

Particles were place laying flat on a contrasting colored sheet to obtain images for shape analysis. When placing particles on a flat sheet the natural tendency of the particle is to rest with the larger two axes visible from overhead. In this fashion the shortest dimension of the particle is oriented parallel to the supporting surface, and perpendicular to the overhead camera lens. Therefore, the smallest dimension of a particle is not accounted for in this two dimensional shape analysis. The shape analysis is based on a projected image of the median and largest dimensions of the particles.

4.3.1. Length to Width Ratio. The method for analysis of the length to width was outlined previously. Essentially, a line is established between the two furthest points of the particle image outline. This line of longest dimension represents the length of the particle. This line is then used as a dividing line for the width measurement to be made. The width is then the sum of the two lines of maximum dimension extending to the perimeter of the image on both sides of the length line. The calculation of the ratio for a specific particle is then recorded. The length to width ratio for a size of material is then taken as the average of all the particles of the group. This shape measurement, being a

volumetric strain response presents the most troubling challenge in applying the parallel gradation modeling scheme in a cyclical triaxial environment.
ratio, renders the actual size of the particle irrelevant. Length to width ratio data can be seen in Figure 4.39 below.

![Graph showing length to width ratios of fresh and used particles](image)

**Figure 4.39.** Length to width ratios of fresh and used particles

While definitive conclusions from the length to width ratio data is not supported by the data, one trend is apparent. Generally, smaller particle sizes correspond with a higher length to width ratio for the railroad ballast materials included in this study.

### 4.3.2. Angularity.

Angularity was assessed as the average of the four smallest inscribed curve radii for a specific particle. This smallest inscribed curve radius was then averaged for all particles of a specific particle size. All particle sizes were photographed using the same image width to nominal particle diameter ratio. In this manner the effects
of pixel intensity were eliminated from the shape analysis. This allows minimum inscribed curve radii to be reported in pixels for comparison between the different particle sizes. The average minimum curve radius can be more intuitively thought of as the measurement of the sharpness of the corners of a particle. A lower minimum curve radius can be inscribed within a tighter corner. Variations of inscribed curve radii are summarized in Figure 4.40.

![Graph showing corner sharpness as measured by minimum inscribed curve radii of fresh and used particles.](image)

Figure 4.40 Corner sharpness as measured by minimum inscribed curve radii of fresh and used particles

Two trends are apparent from the variation in average minimum curve radius measurements. First, the material that had previously undergone triaxial testing consistently measured larger inscribed curve radii than fresh material. The second
evident trend from the sharpness of corners data is that larger particles generally exhibited less sharp corners, or larger inscribed curves.

Minimum inscribed curve radii of the fresh ballast material consistently averaged smaller than those of the ballast material that had previously undergone triaxial testing. Again, the triaxial samples consisted of ballast material that had been “recycled” from previous tests of the specific gradation. The used ballast material has undergone at least three monotonic loading to failure and three cyclical triaxial tests including 10,000 cycles. This triaxial testing also included pouring the material into buckets twice, sieving, mixing and a concrete mixer and placement in the sample mold as outlined in the procedure section of this document. It appears, based on the average minimum inscribed curve radius data that the triaxial testing program effectively rounded the corners of particles. Fresh ballast material is found to exhibited sharper corners than ballast material that had previously undergone triaxial testing.

4.4. ATTRITION ANALYSIS

Attrition was measured after each monotonic and cyclical triaxial test. All sieving was performed using dry material. While the grainsize distribution of the material before and after testing are consistently different, comparing grainsize distribution curves is difficult due to the slight changes in these curves. A depiction of a grainsize distribution both before and after cyclical triaxial testing can be seen in Figure 4.41 below. In order to quantify the breakage of particles during testing the breakage factor, as introduced by Marsal (1973), was used. This method uses the deviations in the amount of material retained on specific sieves to calculate the breakage factor. The percentage difference in weight retained on each sieve is termed $\Delta W_k$. The sum of $\Delta W_k$ values for a sample should be zero. In cases where this sum is not zero, there was some loss or gain of sample during the testing process. Positive values of $\Delta W_k$ are then added up for the entire sample. The sum of the positive values of $\Delta W_k$ is the breakage factor, $B_g$. 
Attrition for a specific material has been noted to be primarily affected most by stress level. All tests performed in this testing program were at the same confinement of 3 psi (20.7 kPa). Variations in axial stresses used in this testing program were quite small. For example, the variation in stress from a stress ratio of $n = 0.66$ to $n = 0.90$ is 4.7 psi (32 kPa). Therefore, stresses were similar for all tests performed. Attrition measurements were also influenced by the size of particles sieved. Several cases were noted where more material was captured on the largest sieve of a gradation after testing than before. With the large particles included in this testing, particularly in the larger gradations, the retention of a single particle could influence the weight of material retained quite significantly. A summary of attrition results can be seen in Table 4.6.
Table 4.6. Attrition summary

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Curve</th>
<th>Test Run</th>
<th>$\Delta W_k$</th>
<th>Bg (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2.5</td>
<td>Monotonic</td>
<td>0.000</td>
<td>4.31</td>
</tr>
<tr>
<td>7</td>
<td>2.5</td>
<td>&quot;</td>
<td>0.079</td>
<td>3.67</td>
</tr>
<tr>
<td>8</td>
<td>2.5</td>
<td>&quot;</td>
<td>-0.100</td>
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</tr>
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<td>3/4</td>
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<td>0.95</td>
</tr>
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<td>1.5</td>
<td>&quot;</td>
<td>-0.025</td>
<td>2.15</td>
</tr>
<tr>
<td>13</td>
<td>1.5</td>
<td>&quot;</td>
<td>0.011</td>
<td>1.88</td>
</tr>
<tr>
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<td>&quot;</td>
<td>0.000</td>
<td>1.64</td>
</tr>
<tr>
<td>16</td>
<td>2.5</td>
<td>n = 0.75</td>
<td>0.000</td>
<td>4.99</td>
</tr>
<tr>
<td>19</td>
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<td>n = 0.94</td>
<td>0.000</td>
<td>2.11</td>
</tr>
<tr>
<td>21</td>
<td>2.5</td>
<td>Monotonic</td>
<td>0.000</td>
<td>1.74</td>
</tr>
<tr>
<td>24</td>
<td>2.5</td>
<td>n = 0.84</td>
<td>0.000</td>
<td>1.57</td>
</tr>
<tr>
<td>17</td>
<td>1.5</td>
<td>n = 0.67</td>
<td>0.000</td>
<td>0.85</td>
</tr>
<tr>
<td>20</td>
<td>1.5</td>
<td>n = 0.84</td>
<td>-0.201</td>
<td>2.11</td>
</tr>
<tr>
<td>23</td>
<td>1.5</td>
<td>n = 0.90</td>
<td>-0.039</td>
<td>1.73</td>
</tr>
<tr>
<td>15</td>
<td>3/4</td>
<td>n = 0.66</td>
<td>-0.017</td>
<td>9.58</td>
</tr>
<tr>
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<td>3/4</td>
<td>n = 0.81</td>
<td>0.192</td>
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</tr>
<tr>
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<td>n = 0.79</td>
<td>0.000</td>
<td>1.72</td>
</tr>
<tr>
<td>25</td>
<td>3/4</td>
<td>n = 0.90</td>
<td>0.000</td>
<td>1.13</td>
</tr>
</tbody>
</table>

The majority of attrition measurements were performed using only the sieves used in building the specific sample. In this manner, assessment of the smaller grainsizes created by attrition was quantified as the pan mass. The pan mass in this case was the
weight of material passing the smallest sieve used for manufacturing the sample. Most pan measurements were below a pound of material (> 0.2% of the original sample). The highest pan collected, by a significant margin, was 17 lbs of sample representing 4% of the original sample. Assessment of attrition of two samples included sieving the pan material using sieves ranging down to the #200 sieve. As can be seen in table 4.7, the levels of particle breakage down into smaller particles is relatively small. However, these small amounts of finer particles represent the portion of attrition that is of most concern to the railroad industry. Table 4.7 presents two triaxial samples that a full set of sieves was used to investigate attrition throughout the particle size spectrum.

4.5. ANGLE OF REPOSE

The angle of repose for the three gradations was measured using a tilting method. With the material in a tray, the tray was then tilted until the entire exposed face of the material moved. The slope of this face was then measured using a Starrett angle meter, commonly used in the machining trade, attached to a three-foot long metal channel. Six tilting events were performed for each gradation with three measurements taken per tilt. While this trend is not statistically supported, the angle of repose is found to trend toward lower values as the particle sizes reduced. Average angles of repose measured are presented in Table 4.8.

4.6. LOS ANGELES ABRASION RESISTANCE

Three Los Angeles abrasion (LAA) tests were performed, one for each gradation. Results from these tests are summarized in Table 4.9. The LAA results are central in the 10-17% range given for basalt aggregate in Barksdale’s aggregate handbook (Barksdale, 1991). Additionally, the results are in close proximity of results quoted by Fred Webber Inc. The differences between these results are within the 4.5% coefficient of variation as specified in the ASTM testing specification (ASTM C131, 2006). These LAA results indicate that the Iron Mountain Trap Rock ballast material is among more abrasion resistant aggregates available.
<table>
<thead>
<tr>
<th>Sample #</th>
<th>Curve</th>
<th>Sieve #</th>
<th>Diameter mm</th>
<th>As Built Weight lbs</th>
<th>Post Testing Weight lbs</th>
<th>% Retained</th>
<th>% Retained</th>
<th>As Built Accumulated % Retained</th>
<th>Post Test Accumulated % Retained</th>
<th>% Passing</th>
<th>% Passing</th>
</tr>
</thead>
<tbody>
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<td>17</td>
<td>1.5</td>
<td>1.5</td>
<td>38.1</td>
<td>12.6</td>
<td>0.028</td>
<td>0.030</td>
<td>0.0282</td>
<td>0.03</td>
<td>0.972</td>
<td>0.970</td>
<td>0.970</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
<td></td>
<td></td>
<td>11.85</td>
<td>0.274</td>
<td>0.265</td>
<td>0.3027</td>
<td>0.30</td>
<td>0.697</td>
<td>0.705</td>
<td>0.705</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td>110.85</td>
<td>0.368</td>
<td>0.373</td>
<td>0.6711</td>
<td>0.67</td>
<td>0.329</td>
<td>0.332</td>
<td>0.332</td>
</tr>
<tr>
<td></td>
<td>3/4</td>
<td></td>
<td></td>
<td>154.75</td>
<td>0.298</td>
<td>0.298</td>
<td>0.9691</td>
<td>0.97</td>
<td>0.031</td>
<td>0.034</td>
<td>0.034</td>
</tr>
<tr>
<td></td>
<td>1/2</td>
<td></td>
<td></td>
<td>125.15</td>
<td>0.031</td>
<td>0.031</td>
<td>1.0000</td>
<td>1.00</td>
<td>0.000</td>
<td>0.003</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>3/8</td>
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| 21       | 2.5   | 2.5     | 63.5        | 0.012              | 0.011                  | 0.0122     | 0.01        | 0.988                          | 0.993                           | 0.993     | 0.993     |
|          | 2     |         |             | 4.65               | 0.454                  | 0.448      | 0.4660     | 0.46                          | 0.534                           | 0.54     | 0.54     |
|          | 1.5   |         |             | 189.2              | 0.192                  | 0.182      | 0.5855     | 0.64                          | 0.342                           | 0.39     | 0.39     |
|          | 1     |         |             | 168.8              | 0.257                  | 0.261      | 0.9156     | 0.90                          | 0.004                           | 0.008     | 0.008     |
|          | 1.25  |         |             | 110.15             | 0.068                  | 0.075      | 0.5836     | 0.98                          | 0.016                           | 0.023     | 0.023     |
|          | 3/4   |         |             | 31.55              | 0.012                  | 0.013      | 0.9956     | 0.99                          | 0.004                           | 0.010     | 0.010     |
|          | 1/2   |         |             | 5.65               | 0.004                  | 0.006      | 1.0000     | 1.00                          | 0.000                           | 0.004     | 0.004     |
|          | 3/8   |         |             | 2.65               | 0.000                  | 0.000      | 1.0000     | 1.00                          | 0.000                           | 0.000     | 0.000     |
|          | 5/16  |         |             | 0.51               | 0.000                  | 0.001      | 1.0000     | 1.00                          | 0.000                           | 0.003     | 0.003     |
|          | #4    |         |             | 0.30               | 0.000                  | 0.001      | 1.0000     | 1.00                          | 0.000                           | 0.002     | 0.002     |
|          | #10   |         |             | 0.26               | 0.000                  | 0.001      | 1.0000     | 1.00                          | 0.000                           | 0.001     | 0.001     |
|          | #40   |         |             | 0.20               | 0.000                  | 0.000      | 1.0000     | 1.00                          | 0.000                           | 0.000     | 0.000     |
|          | #100  |         |             | 0.10               | 0.000                  | 0.000      | 1.0000     | 1.00                          | 0.000                           | 0.000     | 0.000     |
|          | #200  |         |             | 0.07               | 0.000                  | 0.000      | 1.0000     | 1.00                          | 0.000                           | 0.000     | 0.000     |
|          | Pan   |         |             | 0.17               | 0.000                  | 0.000      | 1.0000     | 1.00                          | 0.000                           | 0.000     | 0.000     |
|          |       | Total:   |             | 423.18             | 422.35                 |            |            |                               |                                 |           |           |

Table 4.7. Full sieve set attrition measurements.
Table 4.8. Angle of repose measurements

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<thead>
<tr>
<th>Gradation</th>
<th>Average angle of repose</th>
<th>Standard deviation</th>
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<tr>
<td>2.5&quot; (63.5 mm)</td>
<td>39.8</td>
<td>1.6</td>
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<td>1.5&quot; (38 mm)</td>
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<td>1.7</td>
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<tr>
<td>3/4&quot; (19 mm)</td>
<td>37.2</td>
<td>1.0</td>
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Table 4.9. Los Angeles abrasion results

<table>
<thead>
<tr>
<th>Sample</th>
<th>Weight of material tested (g)</th>
<th>Los Angeles abrasion measured</th>
<th>Los Angeles abrasion reported by Fred Webber Inc.</th>
</tr>
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<tr>
<td>2.5&quot;</td>
<td>10000</td>
<td>13.9%</td>
<td>15.1%</td>
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<tr>
<td>1.5&quot;</td>
<td>10000</td>
<td>15.8%</td>
<td>17.0%</td>
</tr>
<tr>
<td>3/4&quot;</td>
<td>5000</td>
<td>17.3%</td>
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5. SUMMARY

5.1 PROCEDURE SUMMARY

An assessment of the parallel gradations modeling scheme within the cyclical triaxial framework has been performed. Model gradations were built using particles of the same parent material as the prototype Iron Mountain Trap Rock ballast material. Shape analysis, attrition, angle of repose, and Los Angeles abrasion testing was performed in support of the cyclical triaxial testing program. The three parallel gradations of railroad ballast were first loaded monotonically in a custom designed and constructed triaxial cell measuring 16.5-inches (419 mm) in diameter and 34-inches (864 mm) tall. Monotonic loading results were then used to calculate stress ratios for cyclical triaxial testing. Cyclical triaxial loading of the three parallel gradations was then performed, loading the samples to three different stress ratios. In all 25 triaxial tests were performed on samples weighing approximately 420 lbs (190 kg) each.

In conjunction with triaxial testing of the three gradations of railroad ballast, several supporting studies were conducted. Particle shape was assessed using digital image analysis on particles sizes throughout the range of gradations tested. Attrition was measured after each triaxial test, and a breakage factor assessed. Additionally, the angle of repose was measured using a tilting method for the three gradations. Finally, Los Angeles abrasion was assessed for the different gradations in order to place the investigated material into context with a common aggregate index parameter.

5.2 TEST FINDINGS SUMMARY

During sample building horizontal shaking of lifts comprising the triaxial sample was found to be an effective method for both controlling sample density and creating a uniform sample. Preliminary testing found no difference in material behavior between cyclical load application rates of 0.05 to 3 Hz. Monotonic triaxial testing of the parallel gradations of railroad ballast indicated a trend toward higher capacities for the smaller grainsize samples. Cyclical testing results revealed some consistent trends between
gradations as well as several trends that indicate a breakdown in the parallel gradation modeling scheme.

During cyclical triaxial testing plastic strains were observed to increase as particle sizes decreased at the two higher cyclical stress ratios. This trend was not found at the lower stress ratio, where permanent axial strain was observed to be lower for the smaller gradation. Resilient modulus results generally indicate a higher resilient modulus corresponding with larger grain sizes and higher stress. Permanent volumetric strain data presented the most problematic breakdown in the parallel modeling scheme. At the lowest stress level the smallest gradation exhibited the largest volumetric contraction. At the median stress level no trend regarding grainsize was evident. In this case the middle-sized gradation exhibited the largest contraction and the ¾-inch gradation the smallest level of contraction. At the highest cyclical stress ratio the prototype material was observed to contract throughout the 10,000 cycles. However, the two smaller, model gradations were observed to dilate during the cyclical loading. This difference in behavior presents the most glaring size effect when using the parallel gradation modeling scheme in a cyclical loading framework.

Observations from testing performed outside of the triaxial testing program include the following. Particle shape analysis indicated smaller particles exhibit a larger average length to width ratio than larger particles. Particle corners were observed to be more rounded for the larger particles than the smaller particles tested. Additionally, a consistent trend of sharper corners was observed for fresh ballast materials than for material that had undergone triaxial testing. Through angle of repose testing, a general trend of lower angle of repose for decreasing particle diameter was observed.

5.3 ANALYSIS SUMMARY

While all samples were constructed to the same initial density, relative density observations indicate the relative densities of the different gradations were different. The smaller gradations were likely at lower relative densities with all sample at the same bulk density. In this manner higher relative densities may have contributed to higher load capacities for the smaller gradations during monotonic loading.
Cyclical triaxial testing exposed several conflicts within the parallel gradation modeling scheme. Increased permanent axial and volumetric strains were exhibited by the smaller gradations at the higher stress ratios. This trend did not continue at the lowest stress ratio. These conflicts represent the largest discrepancy in material behavior between the three gradations cyclically tested in this program.

Resilient modulus was found to trend toward higher moduli for the larger particle gradations. This is likely a manifestation of larger particles requiring fewer contacts to form a sample than smaller gradations. Fewer particle contacts could contribute to higher material stiffness. Higher stiffness at increased stress is typical of granular materials, and was consistently observed in this testing. Given the inherent difficulty associated with assessment of resilient modulus, all trends in resilient modulus are considered observation. The primary difficulty being the selection of points of the stress strain curve used to define the resilient modulus.

Particle shape assessment was performed in support of the triaxial testing program by measuring both the length to width ratio and the sharpness of the corners of the particles. Larger particles were found to have a lower length to width ratio than the smaller particles, indicating more block particles at the larger grainsizes. Additionally, the smaller particles were found to have sharper corners than larger particles. Additionally, unused particles were found to exhibit sharper corners than used material after triaxial testing. While it is difficult to prove these trends statistically due to the large variability in these parameters the trends are seen as indicators of real particle characteristics.

Attrition was assessed after each triaxial test. Trends in attrition were not considered significant. This is likely due to all triaxial tests being performed at the same confinement and only slightly different stresses. Variations in attrition would be expected during a testing program covering a larger stress range.

Angle of repose was measured using a tilting method for the three parallel gradations included in this study. This trend may be due to an increased energy of dilatancy for larger particles. Larger particles require more energy to begin rolling down a slope when tilted.
Los Angeles abrasion (LAA) testing was performed on the three parallel gradations. LAA results indicate the material tested is a very abrasion resistant material as would be expected of a basaltic material such as trap rock.
6. CONCLUSIONS

Assessment of the parallel gradation modeling scheme was performed using a rigorous laboratory testing program. Monotonic triaxial, cyclical triaxial, attrition, particle shape, angle of repose and abrasion characteristics were investigated. Significant conclusions drawn from this testing program are summarized as:

- Horizontal shaking was found to be a suitable method for compacting granular material to a consistent and uniform density.
- Smaller gradations were observed to exhibit higher load capacity than the prototype railroad ballast material.
- During cyclical loading, axial plastic strains were observed to increase as particle sizes decreased at the two higher cyclical stress ratios.
- Resilient modulus results generally indicate a higher resilient modulus corresponding with larger grain sizes and higher stress.
- Permanent volumetric strain characteristics during cyclical loading indicate a breakdown in the parallel gradation modeling scheme.
- Generally, smaller particles were observed to exhibit a larger average length to width ratio than larger particles.
- Sharper particle corners, as assessed by the average minimum curve radius, were observed for the smaller particles than the larger particles tested.
- A consistent trend of sharper particle corners were observed in the fresh ballast materials as compared to the materials that had undergone triaxial testing. This trend indicates some rounding of corners occurred during triaxial testing.
- A general trend of lower angle of repose with decreasing particle diameter was observed.

In conclusion, smaller gradations did not consistently model prototype gradation in a cyclical triaxial framework as assessed by permanent axial strain, permanent
volumetric strain and resilient modulus. Smaller particles exhibited larger axial strain during cyclical loading than prototype material. Permanent volumetric response poses the largest challenge to the parallel modeling scheme. Observed volumetric strain response was found to exhibit different trends at different stress ratios. Most notably is at the highest stress ratio the prototype material was observed to contract volumetrically. The two smaller gradations exhibited some dilation at the highest stress level. Poor modeling may be due to different particle shape between grainsizes as evidenced by particle shape and relative density analysis. If the parallel gradation modeling scheme is to be improved upon, careful assessment and control of relative density of the different gradations appears to be paramount. Due to the influence on relative density, particle shape may prove to be a prominent indicator of the similarity in behavior that could be expected between gradations, of different sizes, within a cyclical loading framework.
7. FUTURE RESEARCH

7.1. SMALLER PARALLEL GRADATIONS

The intention of the parallel gradation modeling scheme is to reduce the particle size of large granular materials to sizes that can be more readily assessed for strength, deformation and durability characteristics. Triaxial machines are commonly available up to 6-inch diameter. Additionally, cyclical simple shear machines containing a specimen diameter of up to 4-inches are available.

The ¾-inch model gradation tested in this program is of suitable particle size to be tested in a common 6-inch triaxial machine. Testing of the ¾-inch model gradation and smaller gradations should be performed. These specimens are relatively small and would be considerably easier to build and test. Assessment of parallel gradation modeling of specimens that could be tested in the cyclical simple shear machine should be carried out. The cyclical simple shear testing apparatus represents the most readily available method of subjecting granular materials to the stress rotations exerted by a passing wheel.

7.2. RELATIVE DENSITY AND CRITICAL STATE ASSESSMENT FOR LARGE PARTICLES

It is likely the most difficult parameters associated with the parallel gradation modeling scheme are relative density and critical state of the granular materials. All specimens contracted during loading indicating a density condition below the critical state for the materials. The assessment of relative density for large particles is inherently difficult in the laboratory setting. The assessment of relative density can be performed in the laboratory using specific equipment and input energies. However, it is the density of the granular material relative to the critical state for the given confinement that is most important in assessing the strength and deformation characteristics of the material. In cyclical triaxial testing, the initial density of the sample is relatively unimportant as conditioning is considered to occur during the first several cycles. Only after these conditioning cycles is meaningful data obtained. Loading of the material will lead to
contraction or dilation during initial loadings depending on the initial density and confinement. This luxury is not afforded when monotonically loading a sample. Because the cyclical stress ratio is based on the monotonic peak stress, the critical state of a material is important in the cyclical triaxial environment. Assessment of the critical state characteristics of the different gradations before monotonic testing could assist in assessing the peak stress capacity of different sizes of materials. This in turn may lead to better comparisons between different scale parallel gradations.

7.3. MOISTURE EFFECTS ON BALLAST

The effects of moisture on railroad ballast could be investigated using the UMR triaxial railroad ballast testing apparatus. Granular materials exhibit different characteristics depending on whether they are wet or dry. Ballast is designed to drain rapidly, but wet particles have been found to exhibit different elastic and resilient modulus than dry ballast in the field. The MS&T triaxial railroad ballast apparatus contains two drain ports at the bottom of the sample. By taking an already built sample of railroad ballast with the mold still in place, the sample could then be filled with water. The water could then be drained out before applying the confining vacuum and removing the mold. In this manner ballast could be tested in a saturated surface dry condition, similar to wet ballast in the field.
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Adam Frederick Sevi was born in Charleston, South Carolina on February 23, 1973. He attended grade school in Roxbury, Vermont, a town of 500 people located in the Green Mountains of Vermont. He graduated from Northfield High School where he was a member of the Northfield state champion soccer and baseball teams. The day after graduating from Norwich University in 1995, he moved to Alaska and co-lead a successful summit expedition on Mt. McKinley (20,320ft). After working with the National Park Service he moved to Berkeley, California where he worked as an environmental engineer for several years. Employment was later primarily in Alaska until 1999. After working in Albania and Kosovo during 1999 he moved back state side to attend the Missouri University of Science and Technology. In 2002 he received a Master of Science in Civil Engineering under Dr. Richard Stephenson. This research was focused on sub-surface salt migration in Luxor, Egypt.

After receiving his master’s degree he moved back to Alaska where he worked with Peratrovich, Nottingham and Drage Inc. of Anchorage, Alaska. With this firm he worked primarily on offshore structures and arctic engineering. On June 21, 2003 he was married to Marcy Allen, a fellow Vermonter, in Cooper Landing, Alaska. In 2005 he re-enrolled at the University of Missouri-Rolla as a PhD candidate. One June 16, 2006 Sophia Sevi was born at Phelps County Hospital, where Marcy was working. In December 2007 he moved, with his family to Northfield, Vermont to teach at Norwich University. He then graduated from Missouri University of Science and Technology in December 2008, and continues to teach at Norwich University where he is also the faculty advisor of the cycling and mountaineering student organizations.