Cyclic Behaviors of Railroad Ballast within the Parallel Gradation Scaling Framework

Adam Sevi[1] and Louis Ge, M.ASCE[2]

Abstract: Because of the large grainsizes typical of railroad ballast, large triaxial samples are required to assess the reactions of these materials. The parallel gradation modeling technique was originally developed by John Lowe in 1964 to allow assessment of large grain-size geomaterial properties in smaller, more typical testing facilities. Emphasis has focused on monotonic loading, in which the material is progressively loaded to failure. Cyclic testing of this model has been absent. This paper presents an investigation of the possibility of using the parallel gradation modeling technique in a cyclic triaxial testing framework. Three separate gradations of ballast material were used in this research. The largest gradation contains a top particle size of 63.5 mm (2.5 in.) and is marketed as #3 modified railroad ballast. The second two gradations contained a top size of 38 mm (1.5 in.) and 19 mm (3/4 in.), respectively. Up to 10,000 load cycles were applied for each test. Resilient modulus, permanent axial, volumetric strain, and particle shape were determined from the test results. It is concluded that applying parallel gradation technique to cyclic behavior characterization should be cautious. If particle shape is not consistent throughout the particle sizes used in the parallel gradation model, the model is invalid in the cyclic triaxial framework. **DOI:** 10.1061/(ASCE)MT.1943-5533.0000460.

CE Database subject headings: Railroad ballast; Triaxial tests; Cyclic strength.

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Introduction

The movement of freight and persons is a critical component of a modern transportation system. 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 both goods and people. Serviceability of railway tracks requires the alignment 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 (railroad ties) 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 because of its granular composition. Additionally, the substructure typically requires a considerable percentage of the maintenance attention for a given section of railroad.

Railroad ballast material functions to support the superstructure and traveling loads of the railway. 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 breaking, a process known as attrition (Selig 1994). Ballast is also intended to absorb energy (work) from traveling loads, prohibit vegetation growth, and provide large voids to allow the free drainage of water and the movement of fine fouling materials produced by attrition of the ballast material. The ballast also needs to readily facilitate railway realignment maintenance activities, such as tamping and cleaning. Understanding the stress-strain characteristics of ballast material in an environment of many loadings is paramount to the assessment of ballast quality and performance estimates.

This paper presents an investigation of the possibility of using the parallel gradation modeling technique in a cyclic triaxial testing framework. Three separate gradations of ballast material were used. The largest gradation contains a top particle size of 63.5 mm (2.5 in.) and is marketed as #3 modified railroad ballast. The second two gradations contained a top size of 38 mm (1.5 in.) and 19 mm (3/4 in.), respectively. These gradations were manufactured to have a grain-size distribution curve, parallel to the 63.5 mm prototype gradation.

Background

Parallel Gradation Modeling Scheme

Two of the most important characteristics in the design of roadbeds, railroad beds, and rock fill structures are shear strength and compressibility of the granular material. Testing of these properties is typically performed in the geotechnical engineering discipline by using the triaxial testing apparatus. This testing apparatus allows the closest simulation of field conditions in the laboratory, by allowing a confining pressure to be applied through a flexible membrane surrounding the sample during axial loading. This simulates, in the laboratory, the situation underground in which the ballast is surrounded and supported by adjacent ballast.

[1]Assistant Professor, Dept. of Civil and Environmental Engineering, Norwich Univ., Northfield, VT 05663. E-mail: asevi@norwich.edu

[2]Associate Professor, Dept. of Civil Engineering, National Taiwan Univ., Taipei, Taiwan 10617 (corresponding author). E-mail: louisge@ntu.edu.tw

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Because of the scale of triaxial specimens necessary for ballast materials testing, the number of facilities that are capable of testing these large grain-size materials is few. Therefore, a method of assessing shear strength and deformation characteristics of larger granular materials using more typical grainsizes (and equipment) is of great interest.

The parallel gradation modeling technique was originally developed and tested by Lowe (1964). The parallel gradation model states that a smaller grain-size distribution model rock fill, composed of the same material as the prototype material, can be used for triaxial testing at a scaled down grain-size, if the model material's grainsize is parallel to the prototype material. Therefore, a model granular material composed of smaller but parallel grain-size distribution can be used to predict shear and compressive properties of a larger (prototype) rock fill material. Numerous researchers have tested materials on the basis of this model since then. Emphasis has been focused on monotonic loading, in which the material is loaded progressively to failure. Railroad ballast is loaded and unloaded repeatedly when trains pass by. Therefore, cyclic loading of railroad ballast is of paramount importance in the railroad industry. Cyclic testing of this model parallel gradation modeling scheme has been absent.

Cyclic Behaviors of Railroad Ballast

Large size aggregates including railroad ballast and rock fill materials have been tested for decades (e.g., Lowe 1964; Morgan 1966; Marachi et al. 1969; Hicks and Monismith 1971; Marsal 1973; Brown and Hyde 1975; Raymond and Davies 1978; Knutson 1976; Janardhanam and Desai 1983; Thom and Brown 1987, 1988, 1989; Selig and Boucher 1990; Raad et al. 1992; Vuong 1992; Kolisoja et al. 1998; Indraratna et al. 1998, 2005; McDowell et al. 2003; Varadarajan et al. 2003; Kaya 2004; Indraratna and Salim 2005). Generally, researchers have shied away from permanent strain studies, preferring resilient behavior, largely because of 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; Lekarp et al. 2000a).

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 (e.g., Morgan 1966), number of load applications (e.g., Barksdale 1972; Paute et al. 1996; Selig and Waters 1994; Vuong 1992; Kolisoja 1998; Lekarp et al. 2000b; and the concept of shakedown Werkmeister et al. 2001). Stress condition modeling schemes attempt to relate the repeated stress loading magnitude and static load testing results to predict plastic strains. Predictions on the basis of the number of load applications estimate the plastic strain by separating loading into situations in which the repeated load can be considered small or large in magnitude. This approach leads to the concept of shakedown. 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 cyclic stresses, the shakedown concept predicts a ratcheting effect in which plastics strain persists and the sample is soon destroyed.

Resilient modulus has been used to describe the behavior of railroad ballast subjected to repeated loading. It has received more study than has permanent strain, because of the relative ease in testing. Although 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 (Marsal 1973; Brown and Hyde 1975; Knutson 1976; Vuong 1992; (Lekarp et al. 2000b). Resilient response is also dependent on particle type and shape. Crushed aggregate, having angular to subangular particles, generally exhibit a higher resilient modulus than more rounded particles (Hicks and Monismith 1971; Thom and Brown 1988) This is thought to be caused by the load spreading properties of angular particles.

Digital Image Particle Shape Analysis

While investigating the parallel gradation model, variation on particle shape throughout the range of particles tested is of interest. Particle shape can be described by using three primary measures: aspect ratio, roundness, and surface texture. Aspect ratio and roundness have typically been accepted as significant indicators of particle shape. Because of a high degree in difficulty in assessment, surface texture has historically been neglected. More recently, because of the cumbersome nature of measuring shape parameters manually, efforts have been put forth to assess particle shape in an automated fashion. Digital image based measurement presents huge advantages for mining industries and is becoming more reliable and common (Maerz and Lusher 2001).

Aspect ratio can be visualized as a particle fitting into a three-dimensional box with dimensions of length, width, and height. These three mutually perpendicular dimensions are then used to describe the aspect ratios for a given particle. 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 (Lee 1964).

Although no single definition of angularity exists, angularity can be generally described as the shape feature that measures how sharp the corners of a particle are. Inscribed circles fitted into the corners of two-dimensional particle projections can be used to describe and compare the angularity of particles (Maerz 2004). This inscribed circle method is used in this study.

As previously mentioned, shape analysis performed manually is typically considered cumbersome and subjective. Therefore, efforts have been focused on image-based shape analysis. By using this method, a digital photograph is taken of particles. A computer analysis of these images is then used to assess the shape parameters of the photographed particles. For reliable results, each pixel of the image should be less than 1% of the average particle diameter. Additionally, to avoid unequal pixel intensity the particle size to width of image ratio must be maintained equal throughout the particle sizes photographed and analyzed (Maerz 2004).

Materials and Testing Procedures

The railroad ballast tested in the current research was a dark fine-grained igneous rock mined, marketed, and cone crushed by Iron Mountain Trap Rock (a subsidiary of Fred Webber Inc.) in Iron Mountain, Missouri. This ballast material is considered a very strong railroad ballast material with a Los Angeles abrasion value of 17, MOHS hardness of 7 (same as quartz), and a compressive strength of 324.3 MPa (47,000 psi). The most common ballast product used by the North American rail industry is #3 modified gradation. This gradation of ballast contains a maximum particle size of 63.5 mm (2.5 in.) and is cleaned of all material below 9.5 mm (3/4 in.). Fig. 1 shows the gradation of the prototype and model materials for the cyclic tests in the current study.

A prototype large grain-size triaxial testing apparatus, as shown in Fig. 2, was developed at the Missouri Institute of Science and

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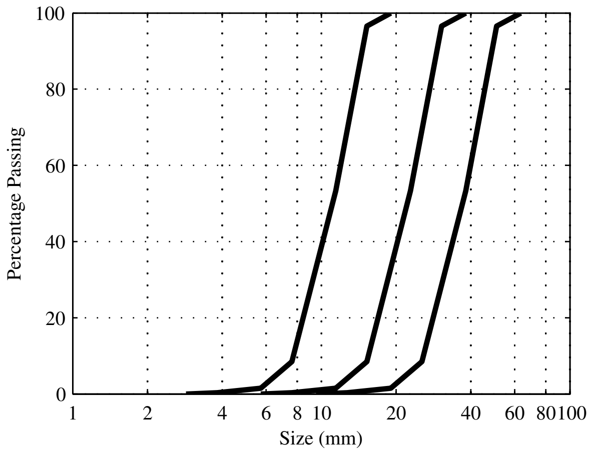

Fig. 1. Grain-size distributions of prototype and model gradations

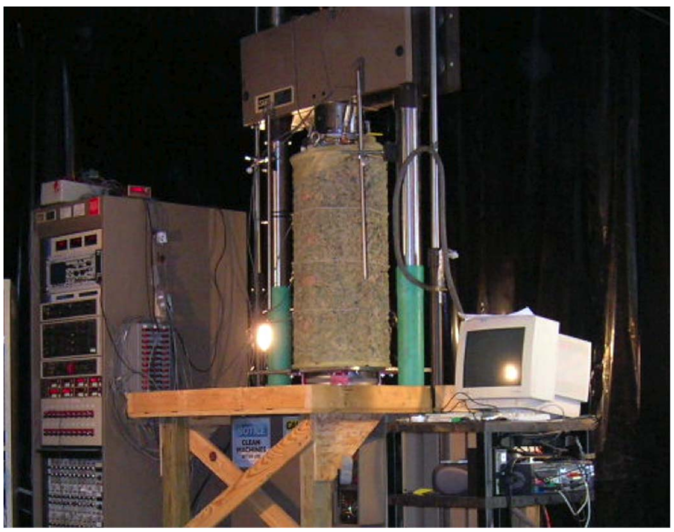

Fig. 2. Missouri S&T ballast testing apparatus (adapted from Sevi et al. 2009)

Technology (Missouri S&T), which is capable of testing triaxial specimens up to 419 mm (16.5 in.) in diameter. One of the unique features of this apparatus is the use of vacuum, applied inside the sample, for confinement. This greatly simplifies the apparatus by avoiding a surrounding vessel to apply the confinement from outside the sample membrane. A detailed discussion of the design of this apparatus and specimen preparation is available in Sevi et al. (2009).

Cyclic Triaxial Testing

Monotonic triaxial testing was performed on all three gradations to assess the peak deviator stress capacity of these materials. Attrition, or particle breakage, was assessed after each triaxial test, and the gradations were brought back to the exact gradation before further testing. All triaxial testing was performed using a confining stress of 20 kPa (3 psi), typical of railroad ballast in the field. Initial testing density was carefully controlled, with a target of all samples compacted to 14.2 kN/m^3 (98 lb/ft^3) before testing. Cyclic triaxial testing was then performed on all three gradations of model and prototype railroad ballast material with stresses applied in cycles to three stress ratios (n), based on the monotonic triaxial testing results. Separate samples were prepared for each monotonic and cyclic test.

$$\text{Cyclic Stress Ratio} = n = \frac{(\sigma_1 - \sigma_3)_{\text{cyclical}}}{(\sigma_1 - \sigma_3)_{\text{failure}}}$$

The cyclic triaxial testing program is summarized in Table 1. Cyclic triaxial testing was analyzed for resilient modulus, permanent axial strain, and permanent volumetric strain.

Once the sample was set up, cyclic loading was performed by using a MTS function generator in conjunction with a MTS 880 loading system maintained at Missouri S&T. The loading system was run at the 10% capacity setting allowing 44 kN (11,000 lbs) of capacity from a system with a maximum capacity of 490 kN (110,000 lbs). This allowed more accurate control of the system for the loads required for this testing. Loads required for this testing ranged from a seating load of 1.3 to 17.9 kN (250 to 4,000 lbs).

An extensive explanation of the techniques used to perform the cyclic triaxial testing is included in Sevi et al. (2009) and is summarized here for convenience. Cyclic triaxial testing was performed by using two different loading frequencies. A relatively fast loading was used for the vast majority of the loadings between readings, whereas a slower loading was used during data gathering events.

Loading cycles were controlled by the function generator by using sinusoidal load control as defined by a midpoint and a span function. Both of these controls were dialed in by using analog 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 s per cycle), whereas 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, and 500 cycles and then every 1000 cycles thereafter. Each cyclic test was performed for 10,000 cycles. Data readings taken during the cyclic load testing included axial load, axial deformation, circumferential deformation, and confining pressure. All of these parameters were monitored at a rate of 100 data points per s. The slower loading during data readings was used to allow digital cameras placed at three different angles around the sample to operate taking a picture every 2 s. This allowed 10 pictures per cycle and is the focus of an ongoing Particle Image Velocimetry (PIV) stress-strain study.

The material tended to stiffen and plastic deformation continued to accumulate during testing. Because of these sample characteristics, monitoring of the median load and span was required

Table 1. Cyclic Triaxial Testing Program Summary

Test #	Gradation	Maximum capacity from monotonic testing (kN)	Peak load capacity to cyclic testing (kN)	Stress ration
1	2.5	16.2	12.2	0.75
2			13.6	0.84
3			15.2	0.94
4	1.5	16.8	11.3	0.67
5			14.1	0.84
6			15.1	0.90
7	3/4	18.6	12.1	0.65
8			15.1	0.81
9			16.7	0.90

throughout testing. 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 the data gathering loading rate of 0.05 Hz. Once this slower loading span was set, it was fine tuned at the beginning of each data recording period. In this fashion, the fifth loading of the 10 slower data recording loadings was close to a perfect loading. The fifth loading, of the respective recorded load cycles, was taken as the data for the respective load cycle number (e.g., 100, 200, 500, 1000, and 2000).

Shape Analysis

At the conclusion of triaxial testing, particle shape was assessed for both fresh ballast material and material that had been included in the triaxial testing program. Representative samples of particles from samples of both fresh ballast material and material that was used in the accompanying triaxial testing program were assembled. Shape analysis focused on particle aspect ratio (length to width ratio) and angularity, as assessed by using minimum inscribed circles. All shape analysis was performed by using digital image analysis of individual particles. Digital image shape analysis was performed on over 1,100 particles. Images were obtained by laying particles flat on a contrasting colored sheet.

The nominal size (sieve number) of particles to be analyzed was selected to have three particle 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, whereas the number of particles necessary to fill this requirement for the smaller particles posed a considerable photo imaging challenge.

The ratio of nominal particle size to width of the image was maintained constant for all particle sizes. In this manner, the pixel intensity across particle sizes could be maintained equal, and all particles appear the same size in the respective images. Samples from the individual particle sizes were placed on a white cardstock sheet including 25 particles per picture.

The shape analysis was performed to assess both the length to width ratio and angularity of the individual particles. Both analyses were performed by using a single two-dimensional image of the particles. 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 because the particles lay flat on the cardstock under the lens.

Shape analysis was performed by using a Matlab script to analyze digital images containing 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 in a systematic image search, from left to right and top to bottom. Once a particle was encountered, a perimeter walk was performed, and a log of the pixel coordinates was 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 for this particle.

With the outline of each individual particle contained in a x, y coordinate file, the shape parameters were 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. In this manner, one section of the width line is above the length line, and the other is below. A schematic of the shape assessment is contained in Fig. 3 below.

The calculation of angularity is based on the size of inscribed circles fitting along the projected perimeter of each 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 as the minimum inscribed radius of the particle.

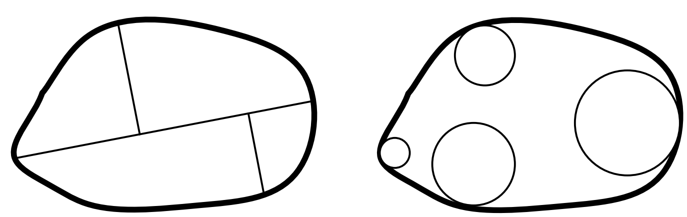

Fig. 3. Shape parameter calculation schematic

Test Findings and Analysis

Data were recorded periodically throughout the 10,000 load cycles. Typical stress-strain curves are shown in the Fig. 4, in which data is presented corresponding to the 100, 500, and 1,000 load cycle, and the every 1,000 load cycles until the completion of the test.

All deviatoric stress-strain curves exhibit a hysteretic loop for each loading and unloading cycle. This loop indicates work absorbed 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 Figs. 5–7 in which the resilient moduli versus number of loading cycles were presented.

Resilient Modulus, Permanent Axial Strain, and Permanent Volumetric Strain

To assess the usefulness of the parallel gradation modeling scheme in a cyclic triaxial environment, Figs. 5–7 show a direct comparison of the different gradations at the specific stress ratios. Starting with the lowest stress ratio, ~0.67, resilient modulus is shown to compare quite closely for the 38-mm (1.5-in.) and 19-mm (3/4 in.) gradations. The cyclic loading of the 63.5-mm (2.5-in.) prototype at a stress ratio $n = 0.75$ unfortunately discounted this test from this comparison. Regarding the permanent strain data for the

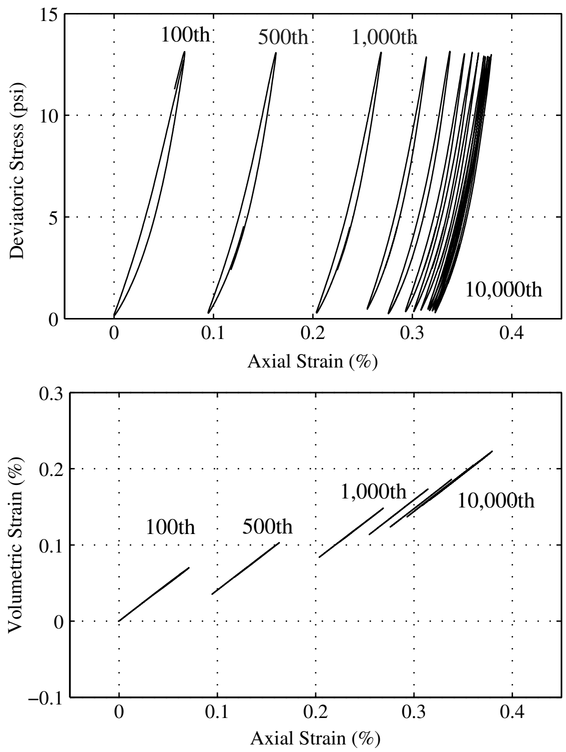

Fig. 4. Typical cyclic stress-strain response

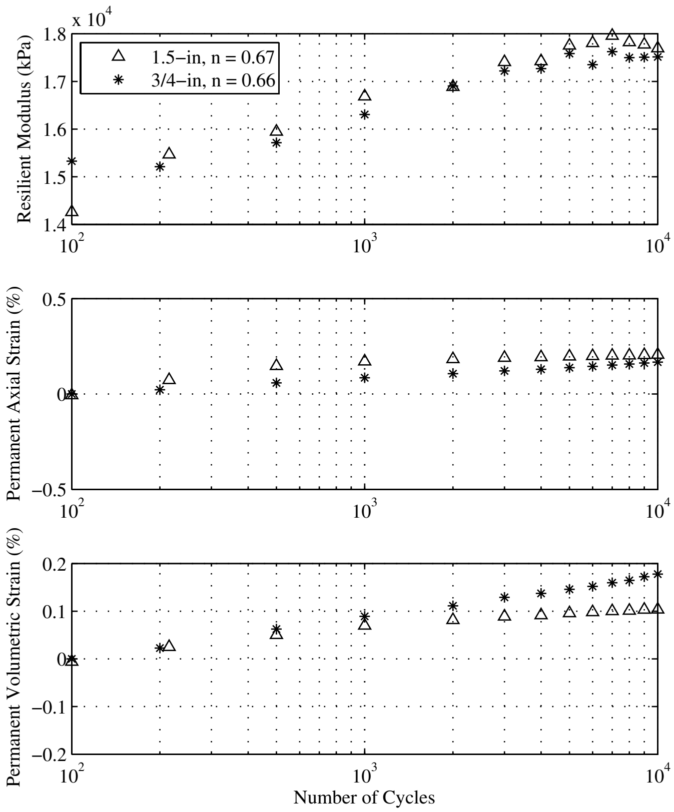

Fig. 5. $n = 0.67$ resilient modulus, permanent axial strain, and permanent volumetric strain comparison

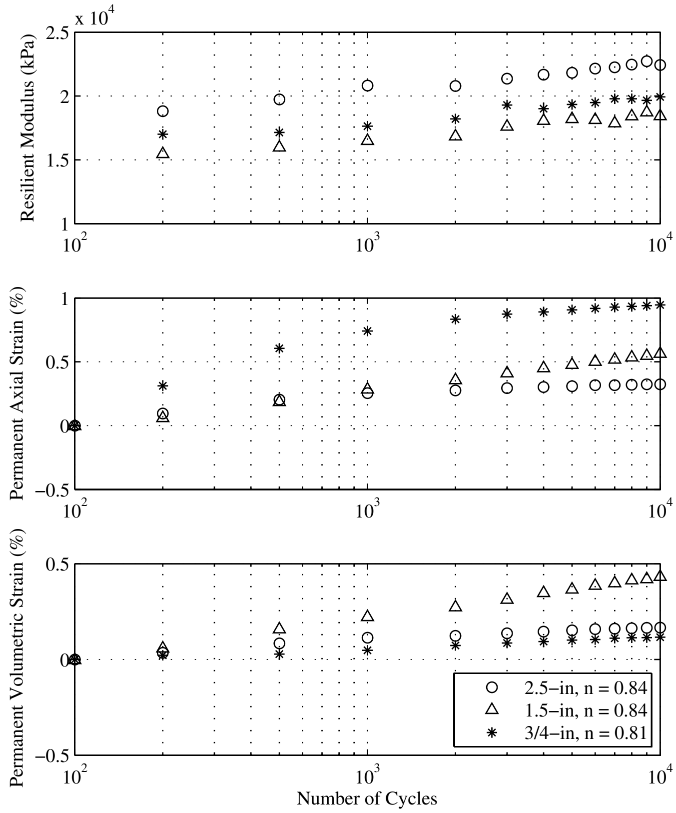

Fig. 6. $n = 0.84$ resilient modulus, permanent axial strain, and permanent volumetric strain comparison

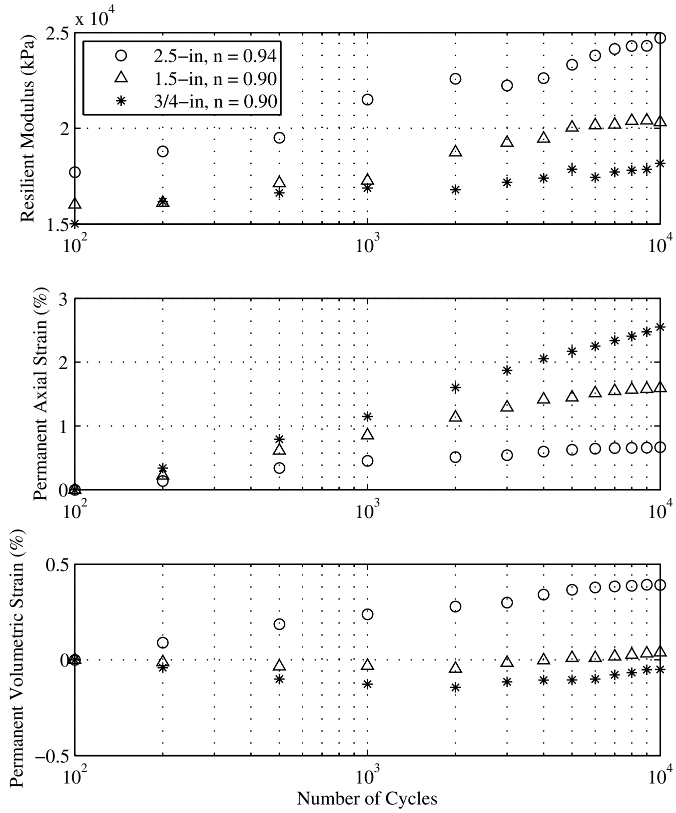

Fig. 7. $n = 0.90$ resilient modulus, permanent axial strain, and permanent volumetric strain comparison

38-mm (1.5-in.) and 19-mm (3/4 in.) gradations at stress $n = 0.67$, this is the only case in which 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 38-mm (1.5-in.) gradation resulted in this discrepancy. If these two readings were to be disregarded, the axial and volumetric strains of the larger 38-mm (1.5-in.) gradation would be lower than the smaller gradation. This would be consistent with the other stress ratio data.

For the higher stress ratios, 0.84 and 0.90, comparing all three gradations cyclicly tested at similar stress ratios, the following observations regarding resilient modulus can be made. Although the resilient modulus data is not entirely conclusive, larger gradations exhibited larger resilient modulus readings throughout the cyclic testing. This is clearly exhibited at the 0.90 stress ratio. Higher stiffness would be expected of the larger grainsizes because 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 for 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. The 63.5-mm (2.5-in.) prototype gradation was run at a stress ratio of 0.94 (versus 0.90 for the smaller gradations). 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 grain-size 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 19-mm (3/4 in.) material contracting the least. The prototype material exhibited a level of contraction between the smallest and the median grain-size material. At the highest stress ratio tested, 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 38-mm (1.5-in.) gradation, with a higher level of dilation exhibited by the smallest 19-mm (3/4 in.) material. Because a definite trend of larger permanent axial strains is shown for the smaller materials, the increased axial deformation exhibited by the smaller gradation at high cyclic stress levels appears to have compacted the material to such an extent that caused volumetric dilation. This discrepancy in volumetric strain response presents the most troubling challenge in applying the parallel gradation modeling scheme in a cyclic triaxial environment.

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 perpendicular to the supporting surface, and parallel to the overhead camera lens field of view. Therefore, the smallest dimension of a particle is not accounted for in this two-dimensional shape analysis. Therefore, the shape parameter calculated here is the intermediate and longest dimensions of the box that the particle would fit in. Additionally, this shape measurement, a ratio, renders the actual size of the particle irrelevant. Although definitive conclusions from the length to width ratio data are 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. This finding indicates that smaller particles were more elongated than larger prototype particles. Trends in aspect ratios are shown in Fig. 8 below.

Angularity was assessed as the average of the four smallest inscribed curve radii for a specific particle. These smallest inscribed curve radii were then averaged for all particles of a specific particle size. 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 in the average minimum curve radius data is that larger particles generally measured larger inscribed curves. Again, all images were normalized with the same particle diameter to image width ratio. This allows a direct comparison of the angularity data between particle sizes.

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. At the time of shape measurement the used ballast material has undergone at the least three monotonic loading to failure and three cyclic triaxial tests including 10,000 cycles. This triaxial testing program also included pouring the material into buckets twice, mechanical sieving, mixing in

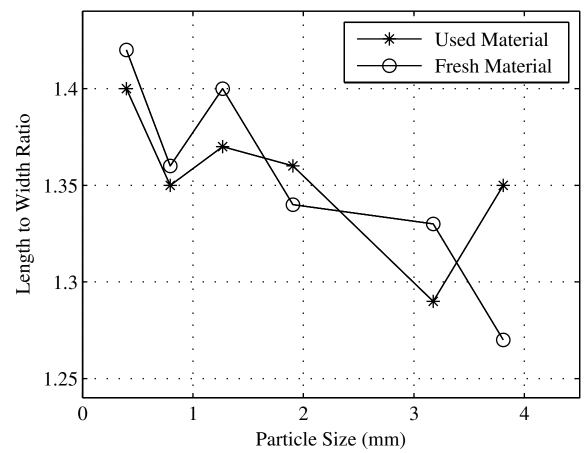

Fig. 8. Length to width ratios of fresh and used particles

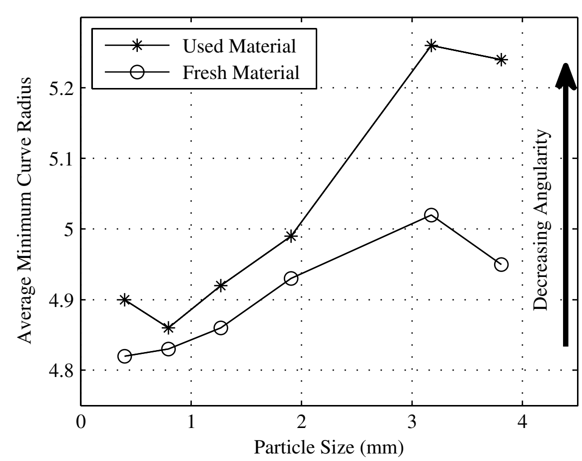

Fig. 9. Minimum inscribed curve radii of fresh and used particles

a concrete mixer, and placement in the sample mold. It appears, on the basis of the average minimum inscribed curve radius data, that the triaxial testing program effectively rounded the corners of particles. Trends in angularity can be seen in Fig. 9.

Summary and Conclusions

An assessment of the parallel gradations modeling scheme within the cyclic triaxial framework was performed. Model gradations were built by using particles of the same parent material as the prototype Iron Mountain Trap Rock ballast material. Shape analysis was performed in support of the triaxial testing program. The three parallel gradations of railroad ballast were loaded monotonically in a custom designed and constructed triaxial cell measuring 419 mm (16.5 in.) in diameter and 864 mm (34 in.) tall. Monotonic loading results were then used to calculate stress ratios for cyclic triaxial testing. Cyclic 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 190 kg (420 lbs) each.

Several conclusions can be drawn from the cyclic triaxial testing and shape parameter study. These conclusions form the basis of this evaluation of the validity of the parallel gradation modeling scheme in the cyclic triaxial environment.

1. Plastic strains increased as particle sizes decreased at the two higher cyclic stress ratios. Resilient modulus results generally indicate higher resilient modulus corresponding with larger grain sizes and higher stress. Generally, smaller particles were observed to exhibit a larger average length to width ratio than larger particles. The average minimum curve radius was observed to trend higher for the larger particles than the small particles tested.
2. Given the difficulty associated with the assessment of resilient modulus, the trend in resilient modulus is considered an observation. The selection of points of the stress-strain curve used to define the resilient modulus is problematic.
3. Smaller gradations did not model the prototype gradation in a cyclic triaxial framework. Poor modeling may be cause by different particle shape between grainsizes, as evidenced by particle shape measured in this paper. Particle shape influences relative density. Relative density is possibly the most important factor in coarse grained material behavior.
4. 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 indicated an initial 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 by 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 cyclic triaxial testing, the initial density of the sample is relatively unimportant because conditioning is considered to occur during the first several cycles. Only after these conditioning cycles is meaningful data obtained. Because the cyclic stress ratio is based on the monotonic peak stress, the critical state of a material is important in the cyclic triaxial environment.
5. 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.
6. The relative density of the gradations tested is important in assessing the cyclic behavior of granular materials. If particle shape for a given gradation is different, the minimum density of the material is likely to also be different. If particle shape is not consistent throughout the particle sizes used in the parallel gradation model, the model is invalid in the cyclic triaxial framework.

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