

Adam F. Sevi,¹ Louis Ge,² and W. Andy Take³

A Large-Scale Triaxial Apparatus for Prototype Railroad Ballast Testing

ABSTRACT: Shear strength and compressibility of large grain-size materials are critical parameters for the geotechnical design of road bases, rock fill embankments, and railroad sub-base. However, due to the correspondingly large scale of triaxial specimens necessary for rock-fill and railroad ballast material testing, the numbers of facilities that are capable of testing these materials are few. In this paper, a cost effective design is documented for a triaxial apparatus capable of testing prototype railroad ballast material containing particle sizes up to 63.5 mm (2.5 in.). Unique to this testing apparatus is the use of vacuum as confinement to allow an unobstructed digital image measurement of specimen volume change during testing. The specimen preparation methodology, manufacture of latex membrane, and instrumentation are also discussed. Finally, the results of a cyclical triaxial test are presented to demonstrate the quality of the testing data from this triaxial apparatus.

KEYWORDS: triaxial testing, railroad ballast, PIV

Introduction

Two of the most important characteristics in the design of roadbeds, rock-fill embankments, and railroad structures are shear strength and compressibility of the granular material. Testing of these properties is typically performed using the triaxial testing apparatus. The triaxial test configuration allows a confining pressure to be applied through a flexible membrane surrounding the sample during axial loading. It has been demonstrated that the largest grain size that can be accurately examined in the triaxial apparatus must be one-sixth the diameter of the testing specimen. Additionally, a sample height to diameter ratio of two is necessary to alleviate end plate confinement of the specimen during testing (ASTM D5311-92).

It is not uncommon for railway ballast materials to contain individual particles of sizes up to 63.5 mm (2.5 in.). One such railway ballast, a dark fine-grained igneous rock mined and cone crushed by Iron Mountain Trap Rock (a subsidiary of Fred Webber Inc., MO), was chosen to evaluate the performance of the prototype large grain-size triaxial apparatus. This ballast material is considered a very strong railroad sub-base material with a Los Angeles abrasion value of 15. The gradation of the ballast material contains a maximum particle size of 63.5 mm (2.5 in.) and is marketed as #3 modified railroad ballast (63.5 mm to 9.5 mm (2.5 in. to 3/8 in.)) as shown in Fig. 1.

If the 1 to 6 maximum particle size to sample diameter ratio is met, the minimum diameter of a triaxial specimen of this material should be approximately 381 mm (15 in.). Therefore, due to the

large scale of triaxial specimens necessary for rock-fill and ballast material testing, the numbers of facilities that are capable of testing these large grain-size materials are few (Marachi et al. 1969; Raymond and Davis 1978; Indraratna et al. 1998; Varadarajan et al. 2003). Shear strength and compressibility of large grain-size materials are critical parameters regardless of grain size; therefore a cost effective technique for estimating these quantities for large grain-size materials is necessary.

Triaxial Testing Facility

A prototype large grain-size triaxial testing apparatus has been developed at the Missouri Institute of Science and Technology (Missouri S&T) which is capable of testing specimen diameters of up to 419.1 mm (16.5 in.). In a traditional triaxial test apparatus, the confining pressure is provided by a fluid contained within the triaxial cell. Due to the sample size requirements for railway ballast, the adoption of a similar approach would require a triaxial cell that would be sufficiently heavy to require mechanical assistance

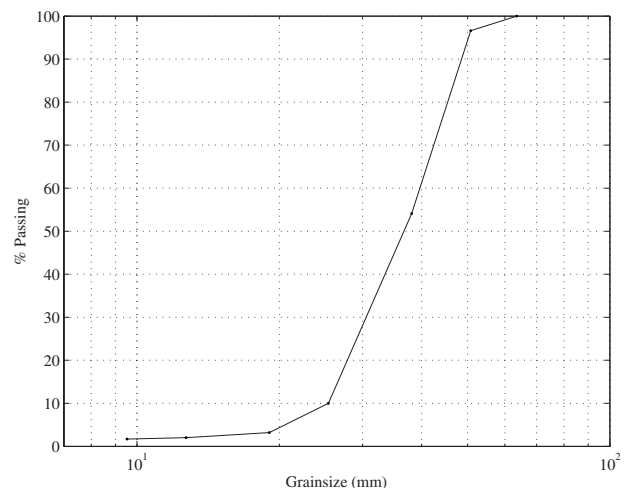


FIG. 1—Gradation curve of #3 modified railroad ballast.

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¹Assistant Professor, Department of Civil Engineering, Norwich University, 158 Harmon Drive, Northfield, VT 05663, E-mail: asevi@norwich.edu. Formerly, Ph.D. Student, Missouri University of Science and Technology, Rolla, MO 65409.

²Assistant Professor, Department of Civil, Architectural, and Environmental Engineering, Missouri University of Science and Technology, 1401 North Pine Street, Rolla, MO 65409, E-mail: geyun@mst.edu

³Assistant Professor, Department of Civil Engineering, Queen's University, Kingston, ON K7L 3N6, E-mail: andy.take@civil.queensu.ca

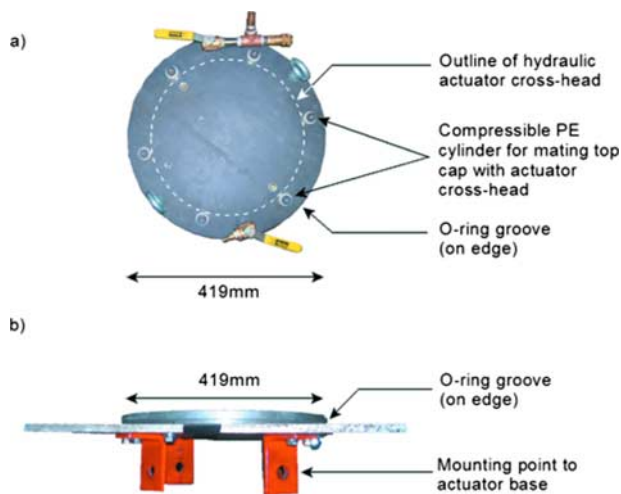


FIG. 2—Top and bottom platen details.

for assembly. This fact, combined with the acceptability of the relatively low confining stresses, in the range of 20–80 kPa (2.9–12 psi) for testing railway ballast, led to the adoption of vacuum backpressure applied inside the specimen as an alternative means of apply confining pressure for the large grain-size triaxial testing apparatus. This method of confinement is only sufficient for materials relatively close to the surface, and therefore under relatively low confinement. The maximum confinement available using vacuum is 101 kPa (1 atmosphere).

Both the top and bottom caps, as shown in Fig. 2, were machined from 1-in. thick aluminum plate. Each cap has 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 vacuum measurement. Around the perimeter of both caps a 9.5 mm (3/8-in.) groove was machined centered at 8.5 mm (1/3 in.) from the exterior surface. This groove was placed to hold an o-ring in place around the entire diameter sealing 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 placed outside the groove helped maintain a tight seal between the latex and the cap circumference.

Figure 2(a) shows the design of the top platen, which was fitted with six bolts in a circular pattern 317.5 mm (12.5 in.) in diameter. These were placed to surround the load platen of the MTS load frame, 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 6.4-mm (1/4-in.) and a 9.5-mm (3/8-in.) standard pipe thread tapped into the aluminum plate. Attached to these ports are ball valves that allow vacuum and 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 the sample was stabilized through patching of the membrane.

The design of the bottom cap is given in Fig. 2(b). The bottom cap 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 63.5 mm (2.5 in.) down from the bottom cap to allow the bottom cap to be bolted to the MTS 880 bottom load platen. An aluminum table 13 mm (1/2-in.)

thick was bolted to the bottom of the bottom platen allowing the sample to be lifted using a fork lift. 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.

Although vacuum confinement greatly simplifies the triaxial testing system, it does lead to measurement difficulties; in particular, the measurement of sample volume change. In a traditional triaxial test apparatus, volume change is recorded by controlling or measuring the volume of flow in or out of the triaxial sample. In the case of vacuum confinement, no such measurement is possible. To overcome this limitation, two methods of calculating volume change have been adopted: on-sample local radial strain transducers and digital image analysis.

Building a 419 mm (16.5-in.) Diameter Specimen

Once the material was delivered to the Missouri S&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. A 419 mm (16.5-in.) diameter and 864 mm (34-in.) tall triaxial specimen yields a volume of 0.12 cubic meter (4.21 cubic ft). At a density of 1571 kg/m³ (98 pcf) this is a specimen of almost 190 kg (420 lb). 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 609.6 mm by 762 mm (24 in. by 30 in.) screens. The sieve system used was capable of taking approximately 23 kg (50 lb) of material at a time. In general, the specimens were broken into ten equal parts of approximately 18 kg (40 lb) 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 37 kg (82.5 lb) each.

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 throughout the lab. The tray was raised to the bottom platen after triaxial testing using a fork lift. The vacuum in the sample was then allowed to dissipate and the sample was 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. While the buckets were not weighed during this step, approximately 18 kg (40 lb) of material was placed in each bucket. In this fashion ten buckets were used to contain the entire sample. 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 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 in each test.

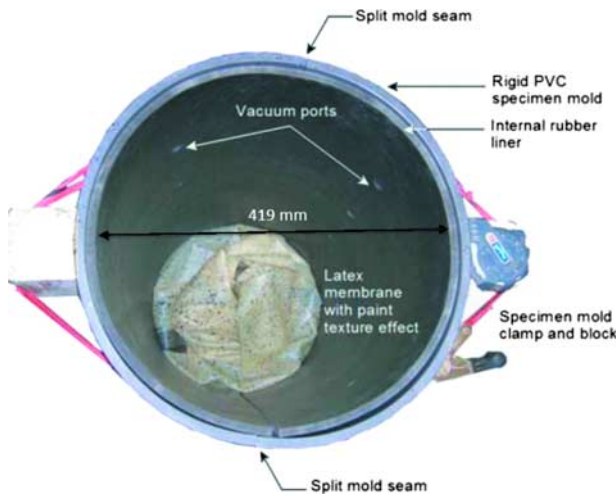


FIG. 3—Specimen mold including PVC rigid mold outside, rubber liner inside, and latex membrane laying at bottom of sample mold.

Typically, no more than 1 % of the original 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 concrete drum mixer. Mixing was performed at 12 r/min while adjusting the tilt of the mixing bucket several times to ensure proper mixing. Leaving the tilt at one setting did not mix the material. The mixed gradation was again poured into the steel tray and again tilted on top of several pallets to be poured into buckets. The ten buckets were filled to exactly 18.7 kg (41.3 lb) each. In this manner two buckets comprised one 37.4 kg (82.5 lb) sample lift, once compacted to 1570 kg/m³ (98 pcf).

Specimen Mold

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 457 mm (18 in.) outside diameter and cut to 889 mm (35 in.) 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 889 mm (35 in.) tall and semicircular. Inside the rigid PVC tube a sheet of 9.5 mm (3/8-in.) rubber BUNNEAU 60A was cut to fully cover the inside walls of the rigid PVC mold as shown in Fig. 3. 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/punching of the latex membrane between particle corners and the rigid PVC mold during sample construction.

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 25.4 mm (1 in.) tall bottom cap. In this fashion a sample 864 mm (34 in.) tall was constructed.

Constructing 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. For thicker membranes a slower rate of extraction from the pan of molten latex is used. There was no latex company willing to custom build membranes 419 mm (16.5 in.) in diameter and 889 mm (35 in.) in length. Therefore, latex membranes for this testing were constructed in house. Rolls of latex of dimensions 0.635 mm by 1067 mm by 21 m (0.025 in. by 42 in. by 69 ft) were purchased. These rolls were then cut into 1358.9 mm (53.3 in.) sections (π by 16.5 in. + 1.5 in.). The extra 38.1 mm (1.5 in.) was used to form an overlapping glue seam. The 38.1 mm (1.5-in.) wide seam was found to adequately seal the sample at the low confinements used in this testing. Sandpaper was used to prepare the two 38.1 mm (1.5-in.) 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 adhering 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. This additional step was found sufficient to properly apply the glue and join the two edges of the membrane forming an air tight seam.

At this point Scotch-Grip contact adhesive 1357 from 3M was applied to both 38.1-mm (1.5-in.) 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 38.1 mm (1.5-in.) 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 was 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 38.1 mm (1.5 in.), more glue was applied to the voids and the latex seam was again pressed together between the flat channel surfaces. At this point the membrane was structurally complete. The assembling of the seam of the latex membrane is displayed Fig. 4.

Visual texturing was applied in order to provide texture for the digital image PIV strain analysis. A flat black oil-based paint was used for applying texture to the latex. This paint was flicked onto the membrane using a paint brush. The best method for applying many small nonuniform dots of paint was running a finger through the bristles and allowing the bristles to then flick the paint onto the membrane. The paint was then allowed to dry and the other side of the membrane was painted after being allowed to dry overnight.

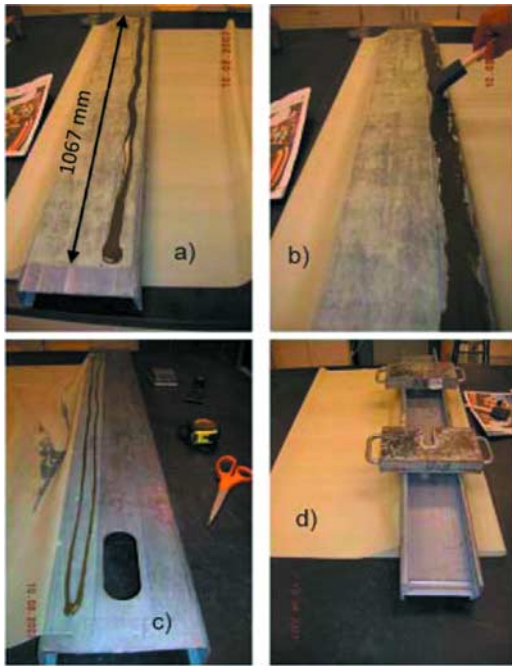


FIG. 4—Assembling the seam of the latex membrane.

Obtaining Uniform Initial Density

Compaction of granular material to a uniform initial density 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).

In order to construct a quality 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 the triaxial testing program. The most effective method found will be described here. A uniform initial testing density of 1571 kg/m^3 (98 pcf) 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 particle edge effects on void ratio along the walls of a containing mold. All samples for triaxial testing were prepared to an initial density of 1571 kg/m^3 (98 pcf). This density was achievable for all the gradations and considered stable after the sample had been constructed. To assess the density of the sample during construction, magnets were placed in the sample at the interface of respective lifts for monitoring. These magnets were ring-shaped lightweight magnets (bonded neodymium-iron-boron). By covering the hole of the ring, using thin sheet metal, the unit weight of the magnet was made close to the unit weight of an intact ballast particle. 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 lifts could be monitored. It was found that five lifts were effective for controlling sample density throughout. Magnets were not used during the building of samples that were used for triaxial testing; however, painted ballast particles were used to monitor lift interfaces.

During preliminary sample compaction it was found that once a lift was densified to 1522 to 1602 kg/m^3 (95 to 100 pcf) the lift would not appreciably further compact during the placement and densification of subsequent lifts. All densification was performed by attaching the sample onto a horizontal shake table. The shake table, as shown in Fig. 5, 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.

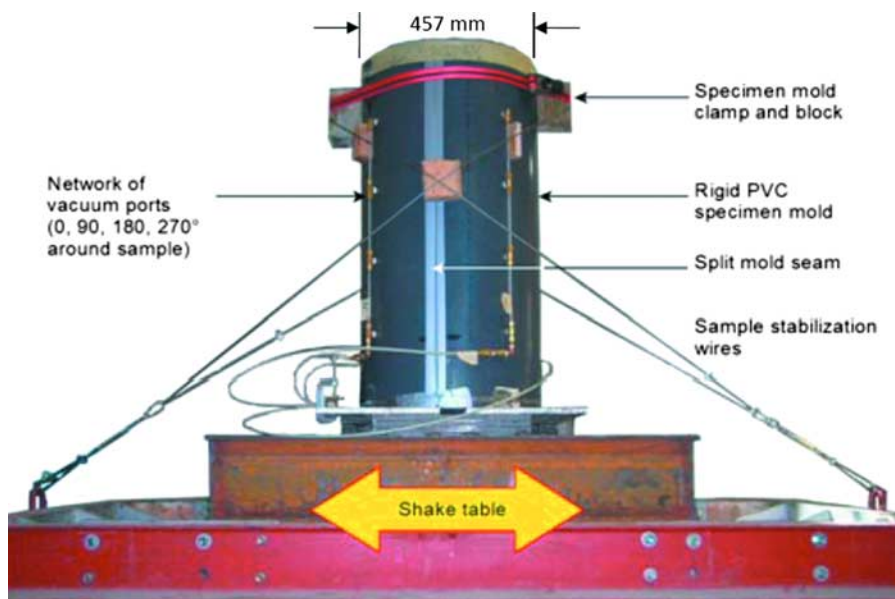


FIG. 5—Sample mold on the shake table.

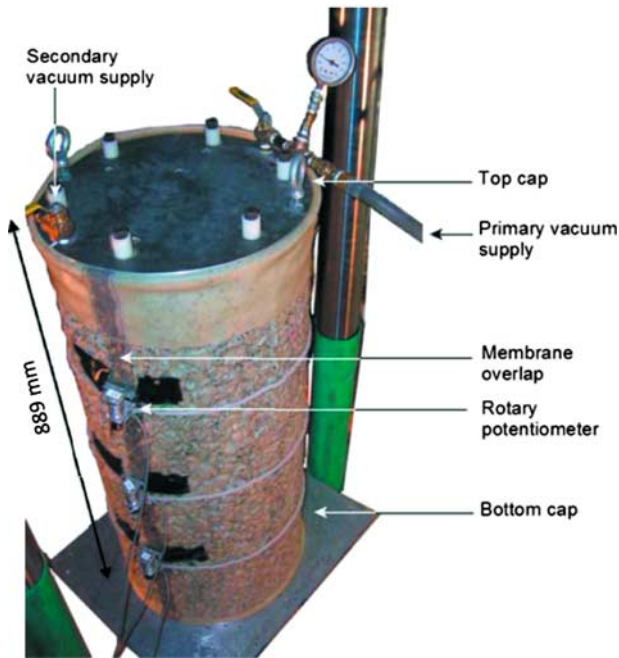


FIG. 6—Triaxial specimen fitted for testing.

Instrumentation

Monotonic Testing

Monotonic strain controlled triaxial compression testing was performed on the prototype railroad ballast. Axial load, axial strain, volumetric strain, and confining pressure were continually monitored during testing. The monotonic testing was carried out at a displacement rate of 0.17 mm/s (1 in. per 150 s) or 10.2 mm per minute (0.4 in. per min). Confining pressure was held at 20.7 kPa (3 psi) throughout the monotonic testing.

Monotonic loading was performed on a MTS 880 load frame. The load frame is controlled on an analogue MTS 448.85 Test Controller and the load rate is dialed into a MTS 410.80 Function Generator. 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. As shown in Fig. 6, wire extensionometers were placed surrounding the samples circumference at 1/4H, 1/2H, and 3/4H. This positioning was used to allow calibration between the wire extensionometers and digital image radial strain measurements throughout the sample. The wire extensionometers used in this study were loaned by Raymond Frenkel of the University of Massachusetts-Amherst and are the same extensionometers used in the Suiker et al. (2005) study. Two LVDTs were placed at opposite sides of the specimen as a redundant measurement of total vertical deflection.

For photographic strain analysis three digital cameras were set up surrounding the sample 120 degrees from each other. The camera shutter was controlled by sending a voltage to the remote shutter control on the individual camera. All three cameras were operated from the same voltage output allowing all three cameras to shoot at the exact same time. Each camera stored images from each data gathering event on local memory. These memory cards were then downloaded to an independent computer after testing was complete. The elimination of the confining cell of the prototype large grain-size triaxial testing apparatus, allowed unobstructed and direct visual (and photographic) viewing of the specimen during testing. In the case of digital image strain analysis this simplification avoids geometric corrections necessary for light traveling through a cylindrical chamber of fluid or air and the glass of the

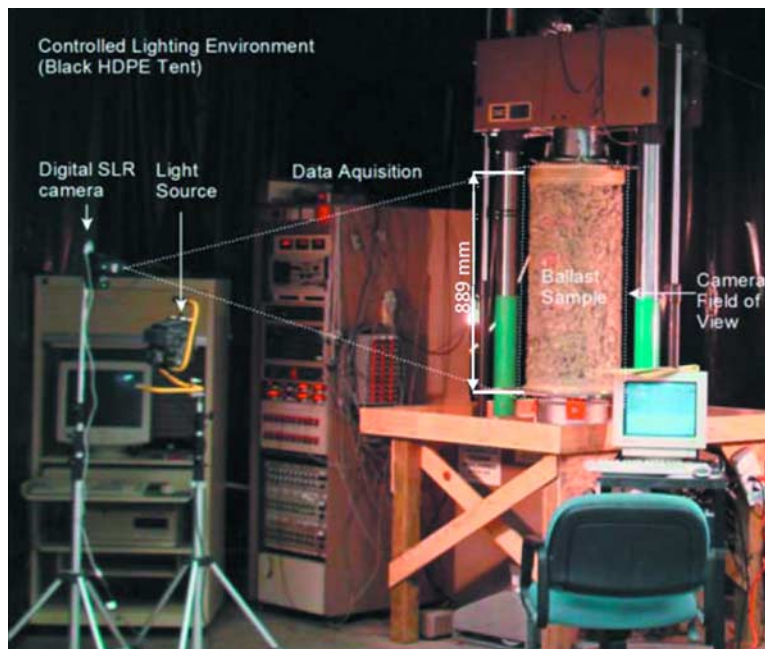


FIG. 7—Prototype large grain-size triaxial testing apparatus.

TABLE 1—Initial unit weights of prepared prototype ballast specimens.

Lift	Unit Weight (pcf)						
	Test #5	Test #7	Test #12	Test #16	Test #19	Test #21	Test #24
1	97.0	100.7	105.2	97.6	97.0	99.2	102.1
2	102.6	95.7	93.9	101.1	97.9	96.1	100.9
3	97.3	100.6	103.7	97.2	97.6	100.4	92.6
4	95.7	98.8	90.6	95.9	99.7	96.6	97.2
5	97.9	94.8	98.5	98.5	96.3	98.1	98.1
Average	98.1	98.1	98.4	98.1	98.1	98.1	98.2

chamber itself (Macari et al. 1997; Gachet et al. 2006). A sample being tested in a light controlled environment can be seen in Fig. 7.

Cyclic Testing

Stress ratios that the material was cyclically loaded to were calculated based on the monotonic testing previously discussed. Once the sample was prepared, cyclical loading was performed using the MTS function generator in conjunction with the MTS 880 loading system. The loading system was again run at the 10 % capacity setting allowing 49900 kg (11 000 lb) of capacity from a system with a 49 900 kg (110 000 lb) capacity. This allowed more accurate control of the system for the loads required for this testing. Loads required for this testing ranged from 113 kg (250 lb) to 1815 kg (4000 lb).

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 of 113 kg (250 lb) for all cyclical tests was dialed in. At this point the data acquisition was started. The load was then increased from the seating load 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 back to the seating load. During this initial load, the load 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 controls correct. 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 by function midpoint and span. Both of these functions were controlled using analogue dials adjusting the load exerted at the platen of the load frame.

Preliminary testing concluded that there was no difference in the ballast reaction to loadings performed between 0.05 to 3 Hz. Therefore, a testing program was established to both allow relatively slow loadings while data were being gathered, and accelerated between readings to expedite the testing. Therefore, all measurement readings were taken at 0.05 Hz (20 s per cycle), while loadings between readings were performed at 1 Hz for expedience. Data were gathered during the initial twelve cycles of a test and then for ten cycles at 100, 200, 500 cycles and then every 1000 cycles thereafter. The initial two cycles were recorded during the setting of the load span and midpoint load (1 to 2 cycles). Then a ten cycle data stream was recorded. All further data points consisted of ten cycle data streams. This ten cycle recording allowed fine tuning of the loading to be performed as these cycles continued. The fifth loading was then taken as the data readings for the specific loading number (100, 200, 500, 1000...). Data recorded

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 data 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 two seconds. This allowed ten pictures per cycle.

The ballast material tended to stiffen and plastic deformation continued to accumulate during testing. Due to these sample characteristics monitoring of the median load and span was required as load applications continued. 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 stresses 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 closest to a perfect loading. Therefore, the fifth loading provided the data assigned to the specific load cycle.

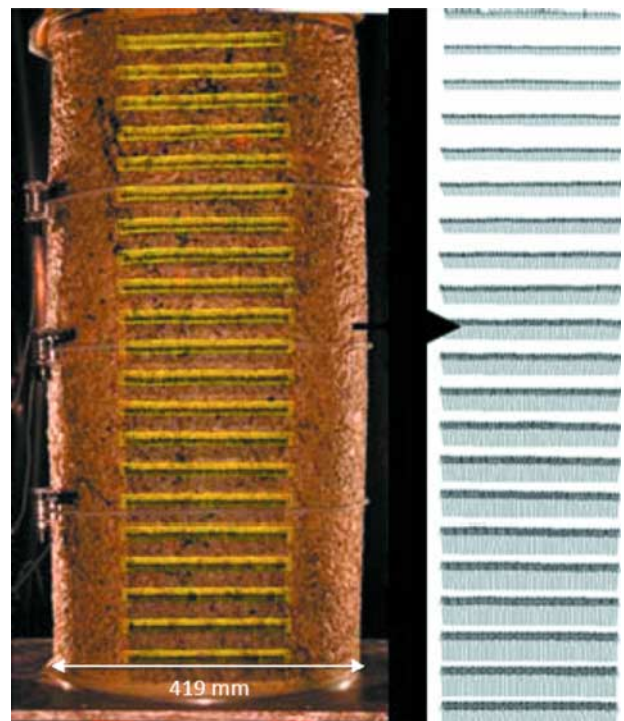


FIG. 8—PIV patches on triaxial specimen and corresponding strains.

Test Results

Initial unit weight measurements of each lift of prepared prototype ballast specimens is displayed in Table 1. Lift 1 represents the very bottom layer of compacted ballast after horizontal shaking. It shows that unit weights of specimens for Test #5, 7, 16, 19, and 21 were controlled within 5 % variation of average initial unit weight. Among them, unit weights of specimens for Test #19 and 21 were even down to 2.5 % variation. On the other hand, the specimen for Test #12 yields the most scattered unit weight distribution of all specimens prepared. It was up to 8 % variation of the average value. Based on the data displayed in Table 1, horizontal shaking is found to be an effective method to achieve the uniform distribution of initial unit weight for railroad ballast samples.

As indicated earlier, digital image technique was used to capture volumetric strain behavior during triaxial testing. Figure 8 shows a set of particle image velocity (PIV) patches on a triaxial specimen and corresponding strain measurements at different elevations on the sample as found using this technique. The PIV method uses the movement of “PIV patches” to calculate local strains at the surface of the sample. These strains are calculated by tracking these PIV patches from one image to the next, as testing continues. The pixel pattern within a PIV patch is established on the first image in time. As testing continues a second image is taken. The PIV algorithm searches the second image for a pattern similar to a patch in the first. Once this patch match is made between the two images, the distance this patch has moved in the image can be calculated. It is imperative that each patch have a unique pixel pattern and consistent lighting. A random pattern (in this case splatter paint) is needed on the sample membrane in order for the PIV algorithm to function. A regular pattern, or no pattern at all, on the sample membrane would create many patches that were similar. This would increase the likelihood of one patch being mistaken as another on a different region of the sample. This mismatching would lead to grossly erroneous strain calculations. A more technical and thorough explanation of the PIV analysis method can be found in White et al. (2003). Additionally, Take and Kemp (2006) and White et al. (2001) present applications of PIV strain analysis. Figure 9 displays the

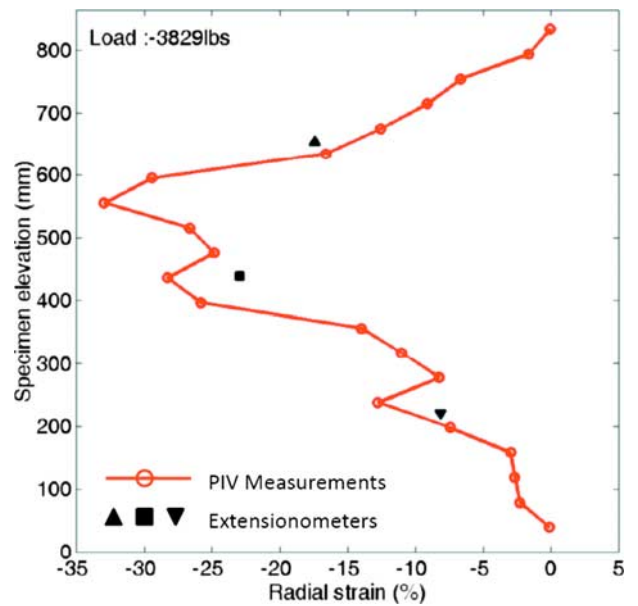


FIG. 9—PIV (line) and wire extensionometers (dots) measurements.

radial strain measurements by both wire extensionometers and the PIV technique at different elevations on the sample. The measurements from these two methods can be seen to be well matched.

Figure 10 presents the cyclic stress strain results for a prototype ballast gradation sample tested using a stress ratio 0.94. The stress ratio is defined as the ratio of the applied cyclical deviatoric load to the peak deviatoric load from the monotonic tests. The cyclical test was performed for 10 000 cycles under a constant confining pressure 20.7 kPa (3 psi). Data were recorded periodically throughout the 10 000 load cycles. Data are presented in Fig. 10 corresponding to the 100, 500, and 1000th load cycle, and then every 1000 load cycles until completion of the test. The final data stream corresponds to the 10 000th load cycle. Figure 11 shows the permanent or accumulated axial and volumetric strains at the se-

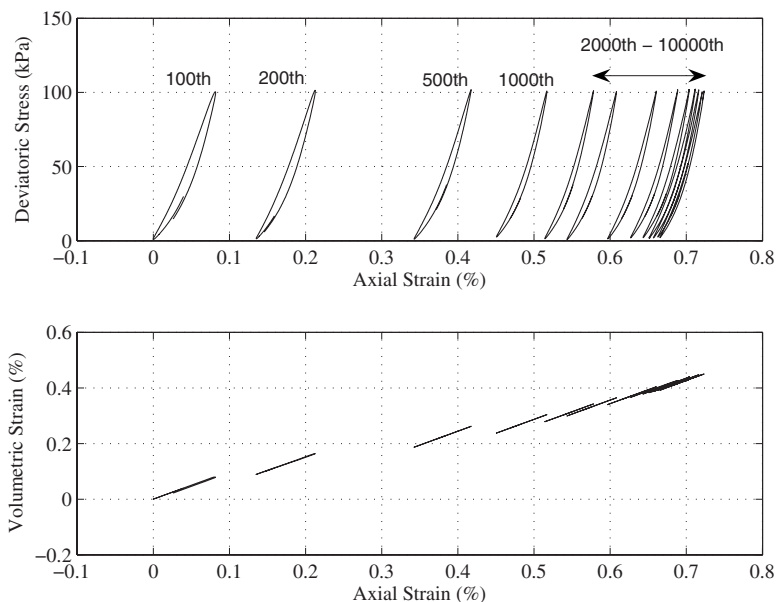


FIG. 10—Cyclic stress-strain curves at various number of cycles.

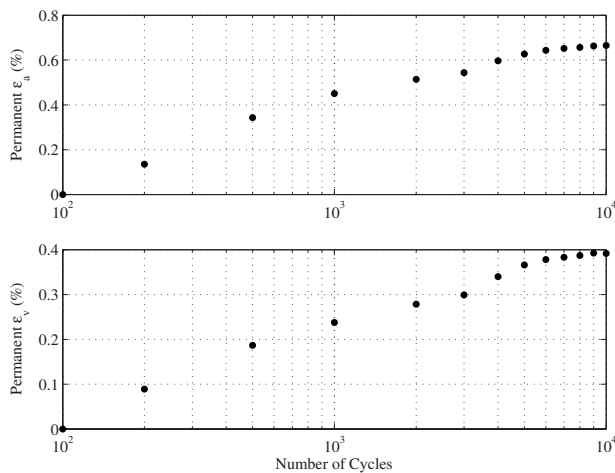


FIG. 11—Permanent axial and volumetric strains versus number of cycles.

lected number of cycles (100, 500, 1000, ..., 10 000).

The following observations can be made regarding the prototype cyclical test results. The specimen exhibited contraction upon axial cyclical loading. This indicates the material is below the critical void envelope at a confinement of 20.7 kPa (3 psi). 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. In this fashion “shake down” was not achieved, where the material ceases to accumulate plastic strain.

Summary and Conclusions

The development of a cost effective large-scale triaxial testing apparatus is presented. The apparatus can test prototype railroad ballast material with grain size up to 63.5 mm (2.5 in.). This configuration uses a vacuum routed inside the sample to provide confinement. This method of providing confinement allows direct visual (and photographic) contact with the triaxial sample, simplifying PIV strain assessment. This method of providing confinement is useful for testing of materials that are to be tested at relatively low confinements, below 101 kPa (1 atmosphere). The specimen preparation, instrumentation, and testing procedure are also discussed. The cyclical test data shown here demonstrate the quality results that are possible when using this apparatus. An attempt of incorporating a digital image technique to capture the volumetric strain during testing is also discussed. This possibly represents a great advantage of this triaxial configuration by removing the surrounding chamber and fluid, allowing unobstructed imaging during testing.

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