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Evaluation of Factors Affecting Ballast Performance

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Summary

To evaluate ballast performance under heavy axle loads (HAL) (39 tons per axle), both field tests and numerical simulations were conducted by Transportation Technology Center, Inc. and the University of Illinois at Urbana-Champaign (UIUC).

Two of three key ballast performance requirements were evaluated. Over the first 90 MGT of HAL traffic, the ballast with the most rounded particles performed best in vertical settlement. The rounded particles, indicated by a lower angularity index, allow the ballast to consolidate more efficiently during surfacing. The ballast with the most vertical settlement had a high angularity index. In addition, this ballast had a higher flat and elongated ratio, indicating a higher likelihood of particle breakage under loading. In the lateral plane, the high angularity ballast performed best, with higher resistance to lateral movement. While all ballasts tested were of the same nominal AREMA gradation, the best lateral performer had the most uniform distribution of particle sizes. The drainage capability of each ballast was not measured. Because all have a minimum of fine material, they should be free draining.

Results from the dynamic, repeated train loading simulations indicate that the ballast discrete element method (DEM) model can reasonably predict magnitudes of the field ballast settlements over 100 million gross ton performance trends. The ballast settlement predictions are sensitive to both aggregate shape and gradation. The aggregate image-aided ballast DEM model has been successfully validated using the field settlement data for predicting ballast deformation behavior under realistic train loading. The DEM model has the potential use as a tool for engineering ballasted track designs and addressing critical substructure concerns such as those related to variable track stiffness and track transition zones.

The field performance evaluations considered four different ballast materials provided by Association of American Railroads members and installed as new ballast layers on a 5-degree curve at the Facility for Accelerated Service Testing for HAL applications at Transportation Technology Center, Pueblo, Colorado.

Numerical simulations of settlement were conducted using a ballast performance model developed at UIUC based on image analyses of individual aggregate particles for shape, texture and angularity indices, and the DEM model generating the corresponding ballast particles and performing the track repeated loading simulations. This model represents a significant improvement in granular material layer design. Traditional methods treat the ballast as a continuous layer and do not allow the effects of ballast aggregate gradation, aggregate shape, texture and angularity, and field compaction to be included.

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INTRODUCTION

An evaluation of the performance of ballast designs currently used by members of the Association of American Railroads (AAR) for HAL applications was conducted at the Facility for Accelerated Service Testing (FAST), Pueblo, Colorado. In the field test study, the following performance measures in particular were of interest: permanent deformation of the ballast layer, track surface degradation, and ballast breakdown. A second objective of the testing was to demonstrate the capabilities of the aggregate image-aided ballast model based on the DEM model developed at UIUC under the AAR Affiliated Laboratory Technology Scanning Program. The ballast DEM model was used to predict settlement trends of four different ballast materials having different size and shape properties.

TEST SECTIONS AND MATERIALS

The field test was conducted in Section 3 of the High Tonnage Loop at FAST. There were four test zones constructed with different ballast materials donated by AAR members: BNSF Railway, Union Pacific Railroad, CSX Transportation, and Norfolk Southern Railway, respectively. There was a transition zone installed between each pair of adjacent test zones to minimize the potential for one test zone to affect the other.

Figure 1 shows the weight percentages of aggregate materials retained on each sieve for each ballast section. Figure 1 shows ballast donated by railroad 4 (RR 4) has a large proportion of the total sample as 1½-inch size particles. It has fewer particles smaller than 1½-inch size than required for an AREMA No. 24 gradation. This ballast gradation is closest to being a single size. On the other hand, the ballast material donated by railroad 2 (RR 2) has the smallest proportion of 1½- inch particles and a wider distribution of particle sizes.

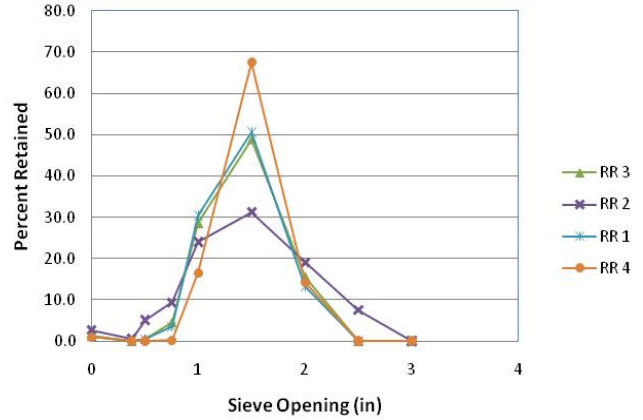

Figure 1. Weight Percentages of Material Retained on Each Sieve for Each Ballast Material

Table 1 lists the shape properties details of each granite type ballast material used in this field test study. These are the particle shape or morphological indices, the flat and elongated (F&E) ratio, the angularity index (AI), and the surface texture (ST) index, quantified for each ballast material using the UIUC Aggregate Image Analyzer (AIA).[1,2] The ballast materials donated by RR 1 and RR 4 had both high angularity (AI) and high surface texture (ST). Ballast material from RR 3 had more rounded particles (lower AI) and high surface texture (ST). Ballast material donated by RR 2, had both high AI and ST; however, this material had the largest flat and elongated (F&E) ratio.

Table 1. Ballast Material Characteristics

Test Section	Angularity Index	Surface Texture Index	Flat & Elongated Ratio	AREMA Gradation
RR 1	584	2.3	2.2	No. 24
RR 2	590	2.5	3.5	No. 24
RR 3	461	2.2	2.6	No. 24
RR 4	509	1.8	2.3	No. 24*

*** Does not meet all gradation requirements**

The level of field compaction or achieved density influences ballast deformation behavior significantly. It is a required input and establishes initial conditions for the ballast DEM model used in any full-scale track loading simulations. However, an appropriate and convenient method to quantify the ballast compaction level or density in the field is not readily available. To evaluate the compaction level of the ballast layers constructed in the field tests, an open metal box was placed in the ballast layer of RR 1 test section to determine the initial void ratio (or density). Next, a similar compactive effort was then replicated and the compaction energy was quantified in the laboratory for achieving the same target field density. Using this approach, the other three ballast materials were compacted in the laboratory at the same compaction energy to determine the initial void ratios of the RR 2, RR 3, and RR 4 ballast materials in the field test sections. Table 2 lists the initial void ratios of the constructed ballast layers essentially used as required inputs in the full-scale track DEM simulations.

Table 2. Ballast Field Compaction Levels

Test Zone	Initial Void Ratio
Zone 1 RR 1	37%
Zone 2 RR 2	32%
Zone 3 RR 3	37%
Zone 4 RR 4	45%

SUMMARY OF BALLAST PERFORMANCE

During the ballast layer construction, settlement plates were installed on top of subgrade in the middle and outside rail locations to measure deformations within the ballast. In particular, the following performance measures were of interest: permanent deformation of the ballast layer, track surface degradation, track stiffness, and ballast breakdown. Vertical settlement trend of each test section was measured over time. Settlements were measured at two locations in each test section. Figure 2 shows the average total settlement accumulated with increased tonnage for each ballast section for up to 90 million gross tons (MGT). Note that the ballast material donated by RR 2, showing the highest settlements in Figure 2, also had the most flat and elongated particles, which are prone to particle breakage.

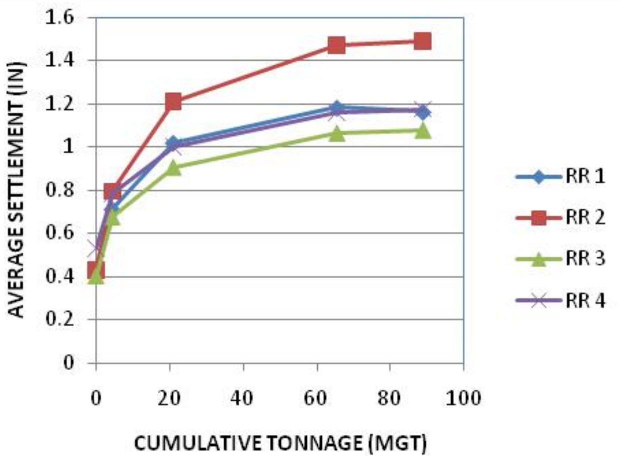

Figure 2. Ballast Settlement versus Cumulative Tonnage

Settlement plates installed on top of the subgrade were used to determine how much settlement was occurring in the foundation below the ballast layer, and, accordingly, the settlement within the ballast could be computed from the top of rail measurements. Figure 3 indicates that the major contribution of the track settlement was in fact from the ballast layer. In this field test, the subgrade accounted for about 10 percent of the total settlement, as Figure 3 shows.

Additionally, the lateral stability performance of each test zone was assessed using a single tie push test. This test gives a measure of the lateral stiffness of the track panel. It measures the lateral force needed to move a crosstie through the ballast. The average of two ties is reported for each test section. Figure 4 shows a summary of the test results. The zone having the RR 2 donated ballast had the largest lateral strength despite the largest settlement (see Figure 3).

BALLAST DISCRETE ELEMENT METHOD MODELING RESULTS AND ANALYSES

The DEM model studies the mechanical interactions of discrete elements displaced in a particulate system by explicitly accounting for the normal and shear dynamic loads acting at the particle contacts in a certain time step, as Figure 5 shows.

The UIUC ballast DEM model requires as input imaging based size and shape quantifications of scanned aggregate particles from three orthogonal views to quantify imaging based F&E ratio, AI, and ST morphological indices.

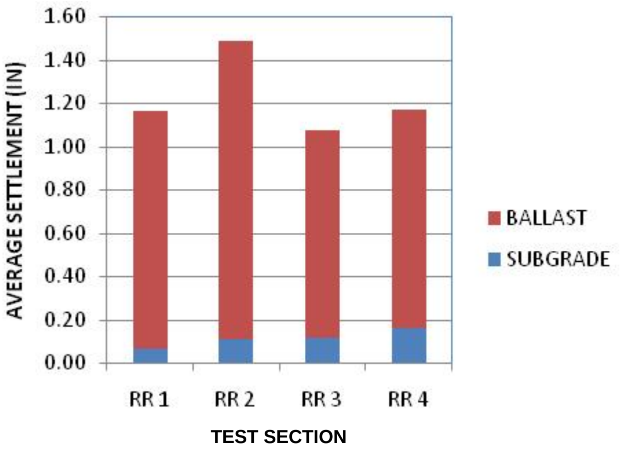

Figure 3. Settlements Accumulated after 90 MGT

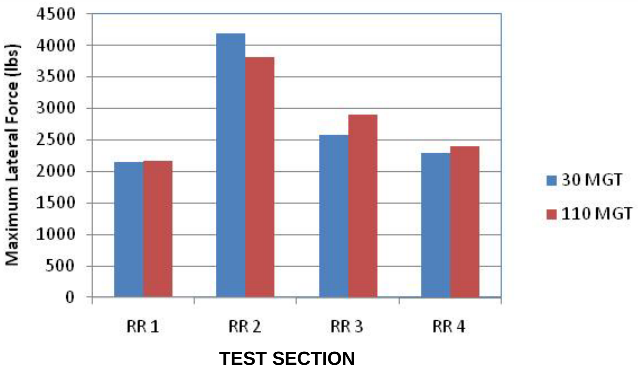

Figure 4. Lateral Strength Test Results

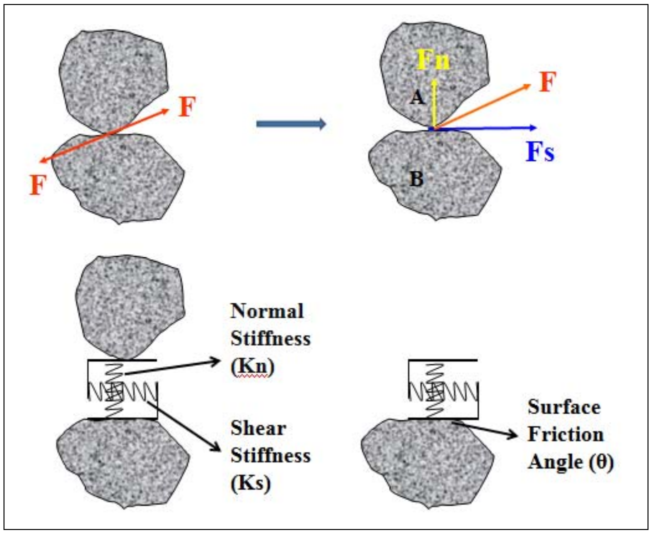

Figure 5. Discrete Particle Load Contacts in DEM

The image-aided DEM approach then recreates the 3D aggregate shapes as individual discrete elements based on the AIA scanned images.[3,4] For the four ballast materials with the various imaging based shape indices listed in Table 1 — 3D polyhedron type discrete elements having the same shape — indices were created to use in the DEM numerical simulations. Then, using these ballast particles, DEM simulations were established for the four full-scale test zones on the 5-degree curved track geometry, with the initial conditions as listed in Table 2 for different initial void ratios.

Due to the fact that nearly 13,000 ballast particles were used in these computationally intensive simulations, the actual train loading could only be applied for up to 2,000 car passes, which took approximately 5 months to complete. Figure 6 shows the ballast DEM model settlements predicted in each test zone with the number of car passes.

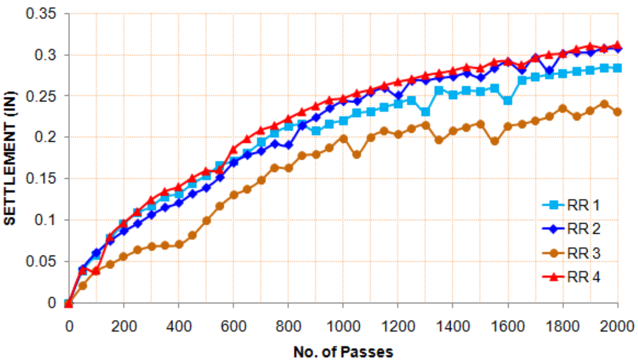

Figure 6. DEM Model Ballast Settlement Predictions for up to 2,000 Car Passes

The DEM simulations predicted the track with the ballast material from RR 3 to have the lowest settlement, which is in agreement with the field observed trends. This can be primarily attributed to the more rounded (low AI) nature of the RR 3 ballast material having the least tendency to crush particles. A similar, more compact ballast layer packing by rounded particles was also observed to yield low settlements in an earlier modeling effort.[3] Note that the ballast DEM model so far cannot accommodate particle breakage in numerical simulations and therefore could not predict the much higher settlements observed for the RR 2 donated ballast material that had more flat and elongated particles.

Using the predicted settlement data for only up to 2,000 car passes (around 0.3 MGT), DEM settlement prediction models were developed based on regression analyses to extrapolate the settlement trends and predict the long-term performance of the ballast test zones. Table 3 lists the developed settlement prediction models and the DEM predicted long-term ballast settlements, which in general compare favourably to the field measurements at 90 MGT.

Table 3. DEM Settlement Prediction Results

	DEM Settlement (S) Prediction Models (N = No. of passes)	DEM Predicted at 90 MGTs (in.)	Field measured at 90 MGTs (in.)
RR 1	$S = 0.74N^{0.29}$ $R^2 = 0.93$ $e = 37\%$	1.395	1.446
RR 2	$S = 0.64N^{0.32}$ $R^2 = 0.91$ $e = 32\%$	1.566	1.768
RR 3	$S = 0.62N^{0.30}$ $R^2 = 0.92$ $e = 37\%$	1.430	1.251
RR 4	$S = 0.84N^{0.29}$ $R^2 = 0.88$ $e = 45\%$	1.505	1.466

SUMMARY AND CONCLUSIONS

The intent in this study has been to develop a better basic understanding of aggregate size, shape, texture and angularity, and surface texture properties influencing engineered ballast designs. To evaluate ballast performance under HAL, both field tests and numerical simulations were conducted. Four different ballast materials with varying aggregate shape, texture, and angularity properties were donated by AAR member railroads to construct ballast test zones at FAST. By capturing the shape properties of the ballast particles through image analyses and assessing adequately field compaction conditions, the UIUC ballast model based on the DEM model was used to generate numerical simulations of the full-scale curved track test zones under realistic heavy axle train loadings. The ballast DEM simulations closely predicted the lowest settlement performance of one of the ballast materials with only 2,000 car passes investigated. The test section with more flat and elongated particles had the most particle breakage and degradation, which contributed to the highest field settlements. The ballast DEM model currently does not consider particle breakage. This is a future research area to enhance and fully develop the UIUC ballast DEM model as a performance prediction tool.

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