3rd International Conference on New Developments in Soil Mechanics and Geotechnical Engineering,
28-30 June 2012, Near East University, Nicosia, North Cyprus

Characterization of polyurethane-stabilized ballast

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KEYWORDS**:** PRB, RFP, Ballast, Polyurethane, Track maintenance

ABSTRACT: A new but untested technology to stabilize railway substructure involves injection of polyurethane into the ballast layer. Injection of polyurethane into the ballast layer creates a composite material of ballast bound with the polyurethane, called polyurethane-stabilized ballast (PSB). In the U.S., Class 1 rail operators spend $500 Million per year for maintenance due to degradation of the ballast substructure (Chrismer and Davis 2000). Certain railway components require maintenance more frequently due to unpredicted or accelerated substructure deterioration (i.e., bolted rail joints, intersections, bridge approaches, etc.). The primary contributor to substructure deterioration is ballast fouling. As the amount of fouling increases, the deformability of the ballast layer increases, leading to higher rates of track deformation and failure. Thus, prevention or mitigation of fouling would greatly reduce costs for railway track and ballast maintenance. In this study, the criteria for polyurethane improved ballast layer effectiveness were based on: 1) extent of ballast void space filling by polyurethane within the ballast layer skeleton, 2) strength of and to what amount bonding occurred between ballast particles and polyurethane, and 3) limiting volumetric expansion of the ballast layer during injection. Parameters for use in railway substructure design were determined from tests characterizing the PSB cyclic loading response. Strategic polyurethane injection into substandard substructure is a targeting tool for enhancing strength and performance of problematic railway elements, avoid disruptive and expensive maintenance activities, and lengthen track lifecycle.

1 INTRODUCTION

Currently, no standards exist for conducting engineering tests on polyurethane-fortified materials, such as stabilized soils and aggregates. Many methods are available for mechanical analysis of polymeric cellular foams or for engineering properties of soils; however, little is understood about the permeation of expanding polymer in various soil types, under varying confining pressures, and in water-filled void-space. Concurrently, mechanical properties of geomaterials stabilized with polyurethane are not well documented. There has been use of non-expanding polyurethane in rail infrastructure. However, very few experimental and empirical methods have been developed to determine mechanical properties and lifecycle characteristics of rail substructure stabilized with polyurethane. An investigation conducted by Kennedy et al. (2009) involved cyclic loading on rail ballast stabilized with non-expanding polyurethane. The study involved testing on a full-scale track model to determine the cyclic response of the stabilized layer.

There are two targets of this research involving polyurethane application for reinforcing ballast. One is to reduce particle breakage and rearrangement; therefore, mitigating fouling generation. The other is to increase the overall strength and capacity of the track. After injection of rigid–foam polyurethane (RFP), which is a type of expanding polyurethane, *in situ* drainage capacity is eliminated. Consequently, polyurethane would need to be strategically injected to areas of ballast that experience repeated or high intensity loading. The process of strategically filling the void space would prevent infiltration of water and contaminants into the substructure, further protecting against rearrangement and settlement, and the remaining un-injected areas would still maintain drainage.

2 MATERIALS

The ballast used in this investigation was provided by the BNSF Railway Company from a quarry near Cheyenne, Wyoming. The ballast is the same granitic ballast characterized in by Ebrahimi (2011), where the particle size distribution was found using ASTM D6913 and had particle sizes ranging between 25–63 mm. Maximum dry density was achieved using the procedure developed in Ebrahimi (2011), resulting in a clean ballast void ratio (e_b)=0.62. Corresponding clean ballast dry unit weight (γ_d) and density (ρ_d) were 15.8 kN/m^3 and 1611 kg/m^3, respectively. These compaction characteristics were targeted for fabrication of each clean ballast specimen in this study.

The fouled ballast used was fabricated in the same manner as outlined in Ebrahimi (2011). Used ballast obtained from Wisconsin Southern and Railroad (WSOR) was repartitioned into a mixture with specific fouling index (FI) and moisture content (MC) as defined by Selig and Waters (1994). The fouling index consists of the addition of the percent of particles passing through a 4.75-mm (P4) sieve with the percent of particles passing a 0.0075-mm (P200) sieve. Ballast revealing an index between 20 and 39 is considered “highly” fouled. The materials used to make up the fouling mixture were reconstituted from 80% P4 and 20% P200, mixed with water to create the chosen water content, and compacted with clean ballast to make the fouled ballast continuum.

The 486STAR-4 BD, referred to as rigid-foam polyurethane (RFP), is a two-component, high-density, expanding, thermoset, polyurethane-resin system. The 486STAR-4 BD was formulated by Bayer Material Science for different applications including void filling and sealing. The specific elastomer system was developed in partnership with Uretek USA Inc. Uretek USA Inc. supplied material in this study and assisted with specimen fabrication.

RFP comes in two components prior to mixing and application. As defined in a technical data sheet produced by Bayer Material Science, the liquid components are defined as “A” component and “B” component. For synthesis of thermoset polyurethane-resin foams, the two components (polyester or polyether polyol and organic polyisocyanate) are proportionately mixed, in the presence of a catalyst (Szycher 1999). The foam structure is the result of gas bubbles formed during the polyurethane polymerization process, known as *blowing*. Gas bubble formation is the result of introducing the *blowing agent* (Szycher 1999).

The cellular structure of the RFP is a closed-foam structure as defined in (Szycher 1999). For closed-cell polyurethanes, the percent of the closed cells and open cells are determined per ASTM D6226, which was used by Bayer Material Science to determine that 486STAR-4 BD typically possesses a closed cell content of 90% after polymerization. Further investigation is needed for determining the closed cell content of the RFP within the ballast pore space and overall composite material. Closed-cell content may provide understanding for overall RFP bonding properties and mechanical response.

In this study, the incorporation of RFP was observed to fill the ballast void space. After injection, the RFP would expand and flow through the ballast pore space, which resulted in expansive forces and dynamic interactions. While the RFP expands and polymerizes, RFP established bonds with materials in contact with the reacting RFP. In the case of the injected ballast samples, the bonding was significant to a level that the specimens that were fabricated from samples of ballast were self-standing and appeared very stiff. The resulting materials formed a bonded geocomposite discussed herein as polyurethane-stabilized ballast (PSB), Figure 1. The bonding with the ballast particles was a substantial and important interaction during the polyurethane foaming process. Materials such as PVC, vinyl plastic, and materials coated with oil and water-based lubricants did not bond with RFP during the polyurethane reaction. The bonding properties were unique due to the interaction of the polyurethane with the aggregates. A likely explanation for the polyurethane bonding properties with ballast may be attributed to rough surfaces of the aggregate particles and intermolecular bonds formed during the polyurethane reaction due to aggregate mineralogy.

Figure 1: A PSB specimen cut in half using a concrete masonry saw shows the complete void filling by the expanding foam (left) and a close-up photo is shown (right).

3 METHODS

Material Preparation

For preparation of each PSB specimen, the ballast was first compacted into a prefabricated mold prior to RFP injection, utilizing the compaction procedure developed in Ebrahimi (2011). For each type of mold (cylindrical molds of different sizes), a specified weight of ballast (W_b) was compacted into the initial mold volume. With the specified weight and initial volume of the compacted ballast, the void ratio and dry density were calculated using the specific gravity of ballast solids. Therefore, the void space was known for use in calculations for RFP injection quantity. Upon injection, the foaming process began and resulted in RFP filling the ballast void space; cross-section of a specimen is provided in Figure 1.

A phase diagram is shown in Figure 2 to illustrate the phase relationship of the PSB composite. The RFP injection protocol and RFP density calculations were experimentally determined during specimen fabrication. For the PSB specimens, on average, ballast particles accounted 95% of the weight and 58% of the volume. PU (airless phase of RFP) was 5% by weight and 7% by volume, RFP was 42% by volume, and Air+CO_2 made up 35% of the volume. The overall PSB density is controlled by the ballast phase density, ballast phase density is illustrated in Figure 2.

Further analysis is needed and considerations to be made for RFP reactions within specimens that possess substantial water content. Within the specimens fabricated, RFP made up 5% by weight of the PSB composite, the quantity of the RFP used in specimen fabrication is approximately the same as the typical asphalt cement (about 5% by weight) used in most Hot Mix Asphalt (HMA) mixes (NAPA 2012). Therefore, influence by weight of RFP is comparable to that of binding properties of asphalt. Finally, no premixing with aggregates is required for use of RFP, which distinguishes it from that of other aggregate stabilization materials such as cement and asphalt.

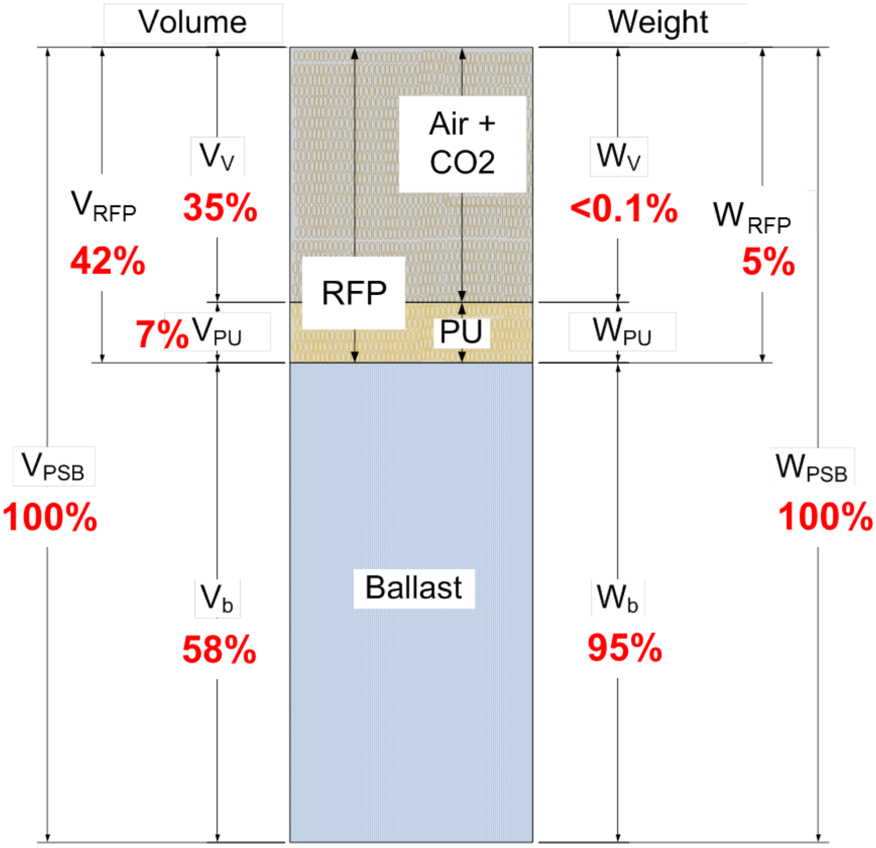

Figure 2: Phase diagram of a typical PSB specimen and average percentages for PSB compositions.

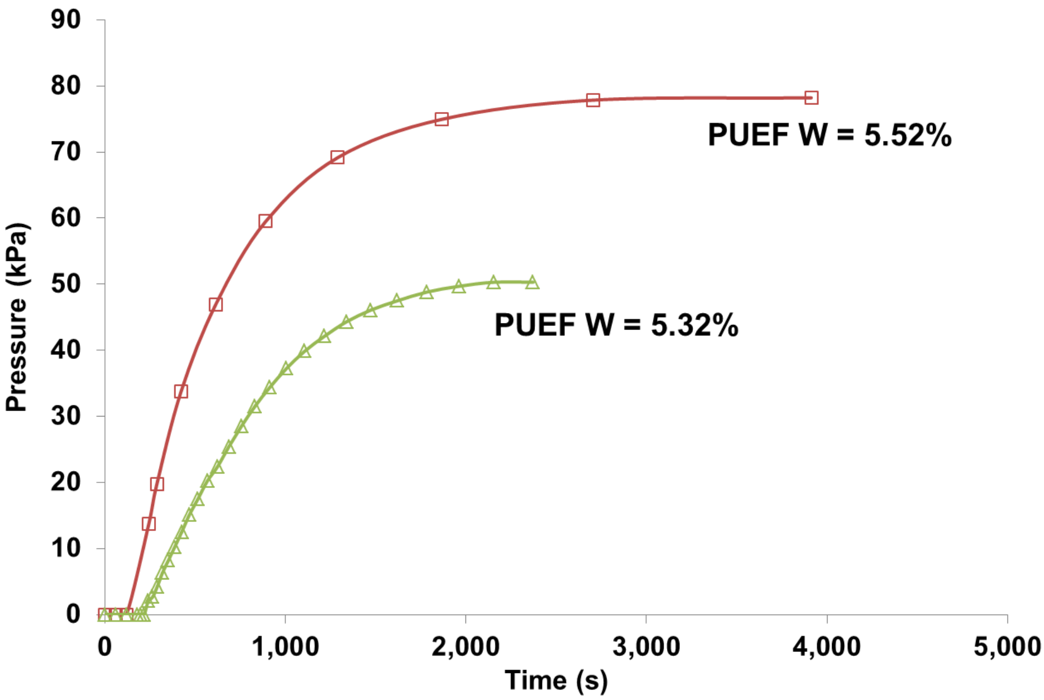

Figure 3: Vertical expansive pressure vs. time. Expansive pressure generated because of overabundance of reacting RFP within cylindrical ballast specimen.

Figure 4: Diagram of injection mold (left), picture of specimen fabrication molds (middle), picture of PSB cylindrical specimen (right)

Cylindrical specimen fabrication involved drilling an injection rod to the bottom of a pre-compacted ballast specimen contained within a cylindrical mold, (Figure 4). Typical RFP injections consisted of injecting a specified quantity of liquid RFP every 154-mm height (H) within the specimen. For example, a specimen with dimensions D254 mm x H508 mm would have a specified injection quantity at the base, at 154 mm from the base, at 305 mm from the base, and 457 mm from the base. Several sizes of triaxial cells were used for testing PSB deformational response, one triaxial cell is shown as Figure 5.

Triaxial Testing

Ebrahimi (2011) developed and used a triaxial cell for determining the response of clean and fouled ballast to cyclic loading. In that study, the results of cyclic triaxial testing were correlated to a full-scale model response to validate the use of triaxial testing for ballast cyclic behavior characterization. The cyclic triaxial testing procedure developed by Ebrahimi (2011) and Aursudkij (2009) was adopted in testing PSB to represent rail traffic loading on the substructure. One of the triaxial cells used in this study is illustrated in Figure 5.

Cylindrical specimens with a minimum diameter (D) of 254 mm were employed to maintain an appropriate particle diameter to specimen diameter ratio; this dimension is comparable to the one used by Anderson and Fair (2008) for triaxial testing of railway ballast. The specimens with 304-mm diameter were acceptable based on Skoglund (2002), which presented a minimum ratio (1:6) of particle-size diameter to specimen diameter. Clean ballast specimens were tested in each triaxial cell and correlated strongly with the data found in Ebrahimi (2011), separate clean ballast tests results are shown in Figure 6. Therefore, each triaxial cell was deemed appropriate for testing on the PSB cylinders.

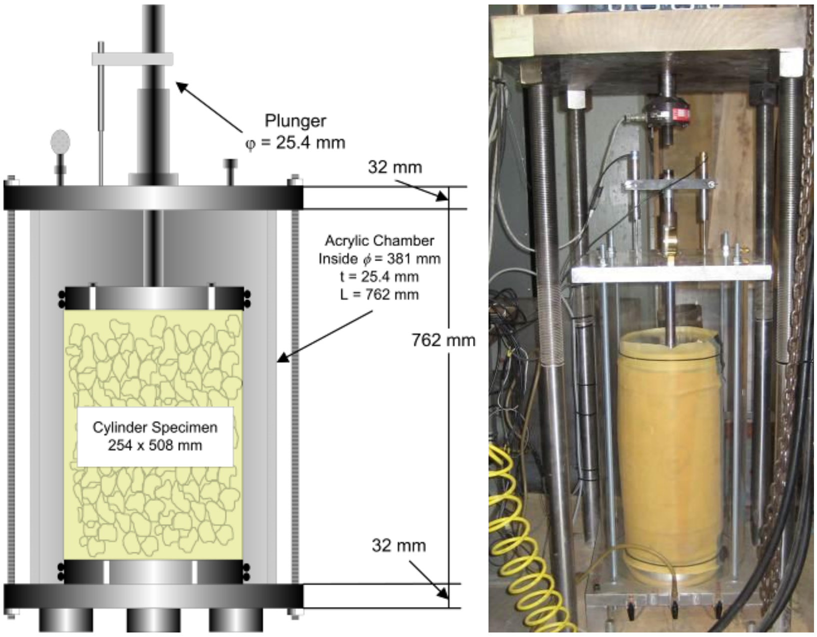

Figure 5: Triaxial chamber used for specimen with nominal dimensions 254-mm diameter x 508-mm height.

The cyclic triaxial compression test consists of applying a constant confining pressure (σ_3) to a specimen that is contained within a membrane and sealed in a triaxial chamber. A plunger or piston that extends through a seal in the top plate of the triaxial cell applies the cyclic load. The cyclic load is applied as a haversine load pulse with peak and rest loads. The deviator stress at peak and during the rest period is given by

$$\sigma_p = \sigma_r = \frac{F_P}{A_P} \quad (1)$$

where the load from the piston (F_P) is applied through the area of the plate on top of the specimen (A_P). After each loading cycle, a non-recoverable deformation (plastic deformation, δ_P) is measured and plastic strain ε_P calculated from

$$\varepsilon_P = \frac{\delta_P}{L} \quad (2)$$

where L is the original length of the specimen. Throughout the cyclic triaxial test, plastic strain accumulates, which provides the deformational behavior of a material over the life cycle of loading. The recoverable deformation (elastic deformation, δ_E) is found by subtracting δ_P from the measured total deformation (δ_T) in each load pulse, and the elastic strain (ε_E) is calculated from

$$\varepsilon_E = \frac{\delta_E}{L} \quad (3)$$

4 RESULTS

The states of stress and cyclic loading applied in this study were determined as the representative state of stress in a track under typical railway loading in Ebrahimi (2011). The injection quantities and procedures were aimed at optimum void filling behavior that would be most similar to that in the field. For the optimum injection case, over 200,000 loading cycles the PSB specimen accumulated plastic stain 74% less than that of clean ballast and 97% less than that of fouled ballast with 15% moisture content and fouling index of 5%. The accumulation of plastic strain in a typical PSB specimens and clean ballast are shown in Figure 6.

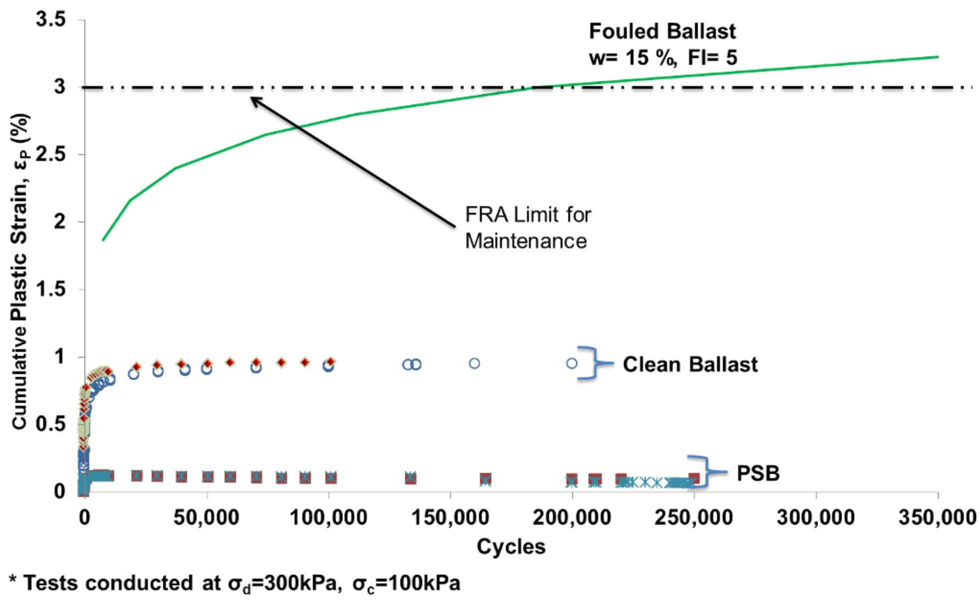

Figure 6: Cyclic triaxial compression testing on clean ballast in separate triaxial cells and on PSB specimens under a deviator stress, σ_d of 300 kPa. Fouled ballast results from Ebrahimi (2011).

Under the same loading conditions, for the clean ballast, the elastic strain decreased 26% over 200,000 cycles, whereas for the PRB specimens it decreased only 5-9%. Elastic strain results are shown in Figure 7. Resistance to change in elastic strain and resilient modulus of PSB, with respect to clean ballast, is an indicator that the material retains its elastic properties throughout many loading cycles. Alternatively, the applied state of stress may not be sufficient to cause accumulated damage to PRB during the tests conducted. Despite reduction in elastic response, which has been witnessed in many of the fabricated specimens, PSB long-term deformational performance far exceeds that of clean and ballast with any amount of fouling.

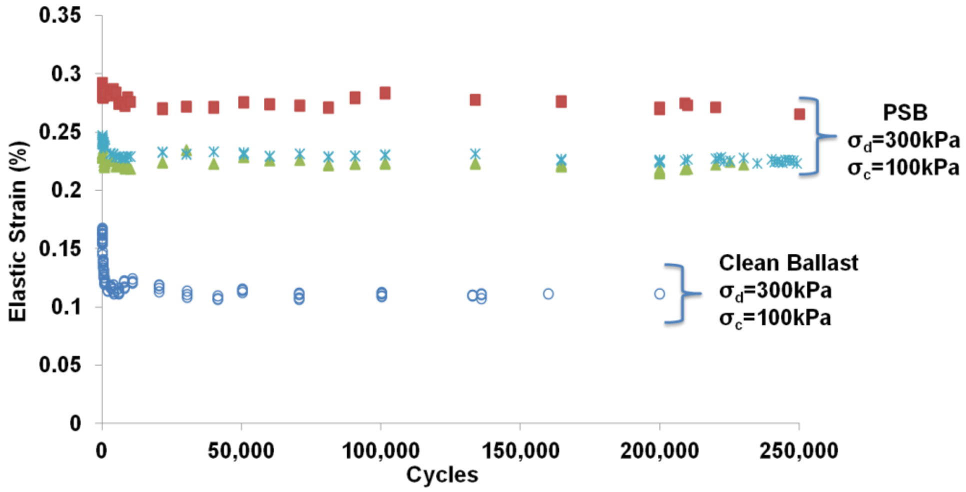

Figure 7: Comparison of elastic strain measured throughout cyclic triaxial test between typical clean ballast and PSB specimens. Tests were conducted at the same deviator and confining stresses.

Since PSB has maintains elastic response while resisting accumulation of plastic strain, the material would be beneficial for use in areas of the track where preservation of track geometry is crucial. Several railway elements would benefit from stabilization where maintenance access is difficult and where construction methods are disruptive to railway traffic (e.g., bridge approaches, crossings, and turnouts). The polyurethane stabilization method presented in this study provides a maintenance approach for enhancing railway capacity and reducing maintenance intervals for problematic railway elements where conventional methods can be costly, cause railway traffic interruption, or require track reconstruction.

5 SUMMARY AND CONCLUSION

Injection of expanding foam into aggregates and soils may generate a more isotropic material since more uniform void space filling is observed and bonds are established with aggregate more homogeneously due to the expansion and flow process through the pore space. Large differences in mechanical behavior of clean ballast before and after polyurethane stabilization indicate that the introduction of RFP to ballast creates a geocomposite with different and generally superior mechanical properties than clean ballast. The materials tested and described in this report were injected in a way that enabled ease of the injection procedure, laboratory testing, and specimen transportation. Further investigation is required to minimize injection quantity while maintaining optimal performance.

ACKNOWLEDGEMENTS

These finding were made possible by the collaboration and contribution of the National Center for Freight & Infrastructure Research & Education (CFIRE); Randy Brown and Steve Read with Uretek USA; Henry Lees with BNSF Railway Company; Ali Ebrahimi with Geosyntec; and Ben Warren.

REFERENCES

Anderson,W.F. and Fair,P., (2008), Behavior of railroad ballast under monotonic and cyclic loading, Journal of Geotechnical and Geoenvironmental Engineering ASCE, 134(3): 316-328.

ASTM D6226, (2010), Standard test methods for open cell content of rigid cellular plastics, Annual Book of ASTM Standards, ASTM International, West Conshohocken, Pennsylvania.

ASTM D6913, (2009), Standard test methods for particle-size distribution (gradation) of soils using sieve analysis, Annual Book of ASTM Standards, ASTM International, West Conshohocken, Pennsylvania.

Aursudkij, A., McDowell, G.R., and Collop, A.C., (2009), Cyclic loading of railway ballast under triaxial conditions and in a railway test facility, Granular Matter,11: 391–401.

Chrismer, S., and Davis, D., (2000), Cost comparisons of remedial methods to correct track substructure instability, Transportation Research Record, 1713, Paper #00-019: 10-15.

Ebrahimi, A. (2011) Deformational behavior of fouled railway ballast, PhD Thesis, Department of Civil and Environmental Engineering University of Wisconsin-Madison.

Kennedy, J.H., Woodward, P.K., Medero, G., and McKinney, J. (2009), Full-scale cyclic geopavement & railway accelerated fatigue testing, Presented at the International Conference on Railway Engineering, London, 2009.

National Asphalt Paving Association (2012).

Selig, E.T. and Waters, J.M., (1994), Track Geotechnology and Substructure Management, Thomas Telford, New York.

Skoglund, K.A., (2002), A study of some factors in mechanistic railway track design, Ph.D. dissertation, Norwegian University of Science and Technology.

Szycher, M. (1999), Szycher's Handbook of Polyurethanes, Boca Raton, Florida.