- When ballast samples were fouled, the shear strength always decreased. Wet (35% OMC) coal dust fouling resulted in the lower ballast shear strengths than dry coal dust fouling.
- For the fully fouled case with 25% wet coal dust by weight of ballast, internal friction angle and cohesion obtained were equivalent to those properties of the wet coal dust itself. This implies that individual aggregate particles within ballast layer would then be completely separated by coal dust to most likely cause the worst track instability problems in the field.

These laboratory findings outlined in Exhibit 3 are the first detailed examination of the mechanical properties of coal dust. Accordingly, when subjected to precipitation, coal dust can hold excessive amounts of moisture to prevent free draining of the ballast, can keep ballast wet and saturated, and act as a lubricant between the ballast stones, enabling much greater movement within the ballast layer. While the fines' content (silt and clay size) of the coal dust was lower than that of most silty and clayey soils, the optimum moisture content of the coal dust found from standard Proctor compaction test was remarkably higher than that of some of the weak cohesive soils, which highlights its ability to hold much greater amounts of moisture than other weak soils. As Exhibit 3 explains in more detail, we concluded that the coal dust's high moisture holding capacity and the extremely low strength properties made coal dust the worst ballast fouling agent for its impact on track substructure and roadbed when compared to even the highly plastic type clayey soil fines.

I would also like to explain our test protocol for the research published in Exhibit 4. For this research, we conducted direct shear (shear box) laboratory tests at the University of Illinois on granite ballast samples to measure strength and deformation characteristics of both clean (new) and fouled ballast aggregates at various stages of fouling. Effects of the different fouling agents on ballast aggregate shear strength were studied when three types of fine materials, i.e., coal dust, plastic clayey soil and mineral filler, were added to clean ballast samples at various percentages by weight of ballast under both dry and wet (mostly optimum moisture content) conditions. Realistic sample preparation procedures were conducted to closely simulate field fouling scenarios. The coal dust was also used as the fouling agent and mixed with clean aggregates for achieving fouling levels of 5%, 15%, and 25% by weight of ballast under dry and wet (at 35% optimum moisture content or OMC) conditions. Test results showed that when the coal dust fouling percentage increased, the ballast shear strength steadily decreased. Wet fouling was found to exacerbate this trend. Results of ballast samples fouled with clay and mineral filler also showed decreasing trends in strength properties; however, coal dust was by far the worst fouling agent for its impact on track substructure and roadbed. Approximately 15% coal dust fouling by weight of ballast caused considerable strength reductions in the ballast. In the case of ballast fully fouled with wet coal dust at 35% optimum moisture content, the friction angles obtained were as low as the friction angle of coal dust itself.

Exposure of coal dust to moisture significantly reduces the friction component of the shear strength and can cause significant reduction in load bearing capacity. Note that even more drastic strength reductions can be realized when dry coal dust that has never been saturated or soaked in the field and therefore has a high suction potential, is subjected to inundation and 100% saturation. This was exactly the case with the 2005 derailments that occurred on the BNSF/UP Joint Line, which threatened to interrupt the supply of coal to power plants. These derailments occurred as a result of heavy precipitation after a relatively low level of precipitation for an extended period of time in the region. Both of the derailments were suspected to be attributable to coal dust fouling, where coal dust spilled over the ballasts and accumulated moisture, allegedly resulting in the loss of strength of the track. In both places where derailments happened, the ballast was heavily fouled by coal dust.

I declare under penalty of perjury that the foregoing is true and correct. Further, I certify that I am qualified and authorized to file this Verified Statement.

Executed on March 15, 2010

Erol Tutumluer

EXHIBIT 1

Erol Tutumluer, Ph.D., Professor
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Education

Ph.D., Civil Engineering, Civil Engineering, Georgia Tech, 1995
M.S., Civil Engineering, Georgia Tech, 1993
M.S., Civil Engineering, Duke University, 1991
B.S., Civil Engineering, Bogazici University, 1989

Professional Experience

8/2008-present	Professor, University of Illinois at Urbana–Champaign (UIUC)
2002-2008	Associate Professor, UIUC
8/1996-2002	Assistant Professor, UIUC
1/1996-8/1996	Post Doctoral Research Associate, UIUC

Academic Courses Taught

CEE 310 – Introduction to Transportation Engineering - undergraduate, UIUC
CEE 406 – Pavement Analysis and Design - undergraduate/graduate, UIUC
CEE 407 – Airport Facilities Design - undergraduate/graduate, UIUC
CEE 509 – Transportation Soils Engineering - graduate, UIUC
CEE 598 – Transportation Soil Stabilization - graduate, UIUC

Research Areas

Dr. Tutumluer has research interests in testing and modeling of pavement and railroad track geo-materials, use of geosynthetics in transportation facilities, characterization of aggregates using video-imaging techniques, modeling of particulate media using discrete and finite element methods, artificial intelligence in the form of neural network modeling, and mechanistic based pavement design. He has conducted several studies on anisotropy and stress dependency of aggregates affecting structural response and performance of flexible pavements with unbound aggregate layers sponsored by the Federal Aviation Administration (FAA), US Army Corps of Engineers, and the International Center for Aggregates Research (ICAR). He has also been working on size, shape, and angularity characterization of aggregates using video-imaging techniques sponsored jointly by the Federal Highway Administration (FHWA), the Illinois Department of Transportation (IDOT), and by the National Cooperative Highway Research Program (NCHRP).

Dr. Tutumluer's recent and currently ongoing research efforts include the Caterpillar, Inc. project on characterizing deformation behavior of oil sands mined in Canada, Association of American Railroads (AAR) project on discrete element modeling of railway ballast behavior, the Federal Railroad Administration (FRA) funded Ground Penetrating Radar based railroad track ballast condition assessment, Burlington Northern Santa Fe (BNSF) railroad gift grant to study characterization of fouled ballast behavior, railroad track substructure research jointly sponsored by FRA and AAR, O'Hare Modernization Program (OMP) project on subgrade support and stabilization of airport pavements, FAA project on

granular layer deformation analyses of National Airport Pavement Test Facility of full-scale test sections under trafficking, NCHRP 4-34 project on laser based aggregate characterization, Tensar International, Inc. project on modeling and design of geogrid reinforced flexible pavements, investigating effects of aggregate type and quality including recycled asphalt product (RAP) used as aggregate in pavement working platforms and base layers supported by IDOT, and nondestructive pavement evaluation using artificial intelligence in the form of modeling with neural networks and genetic algorithms supported by IDOT and NEXTRANS US DOT Region 5 University Transportation Center.

Honors and Awards

Best Paper Award, Geology and Properties of Earth Materials Section, Transportation Research Board, National Academy of Sciences, January 2009
Paul F. Kent Endowed Faculty Scholar, Civil and Environmental Engineering, UIUC, 2006
Listed in the "Incomplete List of Teachers Ranked as Excellent By Their Students," UIUC, 2003 & 2008
TRB Fred Burgraff Award for Excellence in Transportation Research, 2000
Collins Fellow, Academy of Excellence in Engineering Education, UIUC, 2000
General Electric Fellow, Academy of Excellence in Engineering Education, UIUC, 1999
General Electric Scholar, UIUC, 1997
Engineering Education Scholar, National Science Foundation, 1997

Professional Societies

Member of the American Society of Civil Engineers (ASCE)
Chair of the ASCE Geo-Institute's Pavements Committee
Affiliate of the Transportation Research Board (TRB)
Serves on TRB committees AFP70, AFP30, AFS50, AFS70(2), AFD80
Chair of TRB's AFS50(1) subcommittee on "Applications of Nontraditional Computing Tools Including Neural Nets"
Member of the American Railway Engineering and Maintenance of Way Association (AREMA)
Member of the Association of Asphalt Paving Technologists (AAPT)
Member of the American Society of Engineering Education (ASEE)
Member of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE)
- ISSMGE TC 3, Geotechnics of Pavements
- ISSMGE TC 29, Laboratory Stress Strain Strength Testing of Geomaterials

Member of the International Association for Computer Methods and Advances in Geomechanics
Voting Member of the International Society for Asphalt Pavements (ISAP)
Voting Member of the International Society for Concrete Pavements (ISCP)

Books Authored or Co-Authored, Original Editions

The Design Theory and Methodology of Asphalt Pavement Based on the Cross-Anisotropy, Co-authored by Zhenfeng Li and Erol Tutumluer, Water Publishers, China (www.waterpub.com.cn) (ISBN: 978-75084-4328-7, pages: 169, 2007)

Books Edited or Co-Edited

ASCE Geotechnical Special Publication No. 89, entitled, Recent Advances in the Characterization of Transportation Geomaterials, Proceedings Book of the Third National Conference of the Geo-Institute of ASCE, Geo-Engineering for Underground Facilities, University of Illinois at Urbana-Champaign, June 13-17, 1999. Edited by E. Tutumluer and A.T. Papagiannakis (ISBN: 0-7844-0437-2, pages: 72, 1999)

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2002. Edited by Erol Tutumluer, Yacoub M. Najjar, and Eyad Masad (ISBN: 0-7844-0709-6, pages: 241, 2004)

ASCE Geotechnical Special Publication No. 130, entitled, Advances In Pavement Engineering, Proceedings CD-ROM of the ASCE Geo-Institute Geo-Frontiers Conference, held in Austin, Texas, on January 24-26, 2005. Sponsored by the Pavements Committee, Edited by Charles W. Schwartz, Erol Tutumluer, and Laith Tashman (ISBN: 0-7844-0769-X, 2005)

ASCE Geotechnical Special Publication No. 154, entitled, Pavement Mechanics and Performance, Proceedings Book of the ASCE Geo-Institute GeoShanghai Conference, held in Shanghai, China, on June 6-8, 2006. Sponsored by the Pavements Committee and Edited by Baoshan Huang, Roger Meier, Jorge Prozzi, and Erol Tutumluer (ISBN: 0-7844-0866-1, pages: 300, 2006)

ASCE Geotechnical Special Publication No. 169, entitled, Soil and Material Inputs for Mechanistic-Empirical Pavement Design, Proceedings CD-ROM of the ASCE Geo-Institute GeoDenver Congress, New Peaks in Geotechnics, held in Denver, Colorado, on February 18-21, 2007. Sponsored by the Pavements Committee and Edited by Erol Tutumluer, Laith Tashman, and Halil Ceylan (ISBN-13 978-0-7844-0897-1, 2007)

Bearing Capacity of Roads, Railways and Airfields, Two-Volume Hardcover and CD-ROM Proceedings of the 8th International Conference on the Bearing Capacity of Roads, Railways and Airfields, Champaign, Illinois, USA, June 29–July 2, 2009; Edited by Erol Tutumluer and Imad Al-Qadi, 1600 pages (ISBN: 978-0-415-87199-0, 2009)

Journal Publications

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Anochie-Boateng, J., Tutumluer, E., and Carpenter, S.H., "Permanent Deformation Behavior of Naturally Occurring Bituminous Sands," In Transportation Research Record 2059, Journal of the Transportation Research Board, National Research Council, Washington, D.C., 2008, pp. 31-40.

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Kwon, J. and Tutumluer, E., "Geogrid Base Reinforcement with Aggregate Interlock and Modeling of the Associated Stiffness Enhancement in Mechanistic Pavement Analysis," Presented at the 88th Annual Meeting of the Transportation Research Board and Accepted for publication in an upcoming 2009 Transportation Research Record, National Research Council, Washington, D.C.

Huang, H., Shen, S., and Tutumluer, E., "Sandwich Model to Evaluate Railroad Asphalt Track-bed Performance under Moving Loads," Presented at the 88th Annual Meeting of the Transportation Research Board and Accepted for publication in an upcoming 2009 Transportation Research Record, National Research Council, Washington, D.C.

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Tutumluer, E., Seyhan, U., and Garg, N., "Characterization of Anisotropic Aggregate Behavior Under Variable Confinement Conditions," In ASCE Geotechnical Special Publication (GSP) No. 85, entitled, Application of Geotechnical Principles in Pavement Engineering, October 1998, pp. 1-12.

Seyhan, U. and Tutumluer, E., "Unbound Granular Material Characterization from Stress Path Loading Tests," In ASCE Geotechnical Special Publication (GSP) No. 89, entitled, Recent Advances in the Characterization of Transportation Geomaterials, Edited by E. Tutumluer and A.T. Papagiannakis, June 1999, pp. 49-60.

Seyhan, U. and Tutumluer, E., "Advanced Characterization of Granular Materials for Mechanistic Based Pavement Design," In Geotechnical Special Publication (GSP) No. 98, entitled, Pavement Subgrade, Unbound Materials, and Nondestructive Testing, Edited by M.S. Mamlouk, GeoDenver 2000 ASCE Geo-Institute Congress, Denver, August 3-8, 2000, pp. 51-72.

Tutumluer, E. and Seyhan U., "Characterization of Cross-Anisotropic Aggregate Base Behavior from Stress Path Tests," In ASCE Geotechnical Special Publication No. 123, entitled, Recent Advances in Materials Characterization and Modeling of Pavement Systems, Edited by E. Tutumluer, Yacoub M. Najjar, and Eyad Masad, 2004, pp. 18-34.

Ceylan, H., Tutumluer, E., and Barenberg, E.J., "Artificial Neural Networks for the Analysis of Slabs Under Simultaneous Aircraft and Temperature Loading," In ASCE Geotechnical Special Publication No. 123, entitled, Recent Advances in Materials Characterization and Modeling of Pavement Systems, Edited by E. Tutumluer, Yacoub M. Najjar, and Eyad Masad, 2004, pp. 223-238.

Pan, T. and Tutumluer, E., "Imaging Based Evaluation of Coarse Aggregate Size and Shape Properties Affecting Pavement Performance," In ASCE Geotechnical Special Publication No. 130, entitled, Advances In Pavement Engineering, Edited by Charles W. Schwartz, Erol Tutumluer, and Laith Tashman, ISBN: 0-7844-0769-X, 2005.

Kwon, J., Kim, M., and Tutumluer, E., "Interface Modeling For Mechanistic Analysis of Geogrid Reinforced Flexible Pavements," In ASCE Geotechnical Special Publication No. 130, entitled, Advances In Pavement Engineering, Edited by Charles W. Schwartz, Erol Tutumluer, and Laith Tashman, ISBN: 0-7844-0769-X, 2005.

Tutumluer, E. and Kwon, J., "Evaluation of Geosynthetics Use for Pavement Subgrade Restraint and Working Platform Construction," In ASCE Geotechnical Practice Publication No. 3, entitled, Geotechnical Applications for Transportation Infrastructure, Edited by Hani Titi, ISBN: 0-7844-0821-1, 2006, pp. 96-107.

Pan, T. and Tutumluer, E., "Evaluation of Visual Based Aggregate Shape Classifications Using the University of Illinois Aggregate Image Analyzer (UIAIA)," In ASCE Geotechnical Special Publication No. 154, entitled, Pavement Mechanics and Performance, Edited by Baoshan Huang, Roger Meier, Jorge Prozzi, and Erol Tutumluer, ISBN: 0-7844-0866-1, 2006, pp. 203-211.

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Pan, T., Tutumluer, E., and Carpenter, S.H. "Rutting Behavior of NCAT Pavement Test Track Superpave Asphalt Mixes Analyzed for Aggregate Morphology Effects," In Proceedings CD-ROM Volume 75, 81st Annual Meeting of the Association of Asphalt Paving Technologists (AAPT), Savannah, Georgia, March 27-29, 2006.

Kim, I.T. and Tutumluer, E., "Rutting Evaluation of Airport Pavement Granular Layers Considering Stress History Effects," In Airfield and Highway Pavements, Edited by I.L. Al-Qadi, Proceedings of the ASCE Transportation and Development Institute (T&DI) Airfield and Highway Pavement Specialty Conference, Atlanta, Georgia, on April 30-May 3, 2006, pp. 566-577.

Brar, H.S., Tutumluer, E., Thompson, M.R., Gosain, L., and Anderson, R., "Characterizing Subgrade Soils and Establishing Treatment Needs for a New Runway at the Chicago's O'Hare Airport," In Airfield and Highway Pavements, Edited by I.L. Al-Qadi, Proceedings of the ASCE Transportation and Development

Institute (T&DI) Airfield and Highway Pavement Specialty Conference, Atlanta, Georgia, April 30-May 3, 2006, pp. 272-283.

Al-Qadi, I.L., Tutumluer, E., and Dessouky, S., "Construction and Instrumentation of Full-Scale Geogrid-Reinforced Flexible Pavement Test Sections," In Airfield and Highway Pavements, Edited by I.L. Al-Qadi, Proceedings of the ASCE Transportation and Development Institute (T&DI) Airfield and Highway Pavement Specialty Conference, Atlanta, Georgia, April 30-May 3, 2006, pp. 131-142.

Roberts, R., Al-Qadi, I.L., Tutumluer, E., Boyle, J., and Sussmann, T., "Advances in Railroad Ballast Evaluation Using 2 GHz Horn Antennas," In Proceedings of the 11th International Conference on Ground Penetrating Radar, Columbus, Ohio, June 19-22, 2006.

Kwon, J., Tutumluer, E., Konietzky, H., and Keip, M.-A., "Investigation of Geogrid Base Reinforcement Mechanisms Considering Residual Stress and Confinement Effects," In Proceedings of the 8th International Conference on Geosynthetics, Yokohama, Japan, September 18-22, 2006.

Al-Qadi, I.L., Dessouky, S., and Tutumluer, E., "Reinforced Low-Volume Flexible Pavement Response to Accelerated Loading," In Proceedings of the 8th International Conference on Geosynthetics, Yokohama, Japan, September 18-22, 2006.

Tutumluer, E., Huang, H., Hashash, Y., and Ghaboussi, J., "Imaging Based Discrete Element Modeling of Granular Assemblies," In Proceedings of the Multiscale and Functionally Graded Materials Conference 2006 (FGM2006), Honolulu-Oahu, Hawaii, October 15-18, 2006.

Al-Qadi, I.L., Tutumluer, E., Dessouky, S., and Kwon, J., "Mechanistic Response Measurements of Geogrid Reinforced Flexible Pavements to Vehicular Loading," In Proceedings of the Geosynthetics 2007 Conference organized by the North American Geosynthetics Society, Washington, D.C., January 16-19, 2007.

Kim, M. and Tutumluer, E., "Nonlinear Pavement Foundation Modeling for Three-dimensional Finite Element Analysis of Flexible Pavements," In Preprint CD-ROM Proceedings of the 86th Annual Meeting of the Transportation Research Board (TRB), January 21-25, 2007.

Pan, T. and Tutumluer, E., "Permanent Deformation and Strength Characteristics of Crushed Aggregates Blended with Gravel," In Preprint CD-ROM Proceedings of the 86th Annual Meeting of the Transportation Research Board (TRB), January 21-25, 2007.

Al-Qadi, I.L., Tutumluer, E., Kwon, J., and Dessouky, S., "Accelarated Full Scale Testing of Geogrid-reinforced Flexible Pavements," In Preprint CD-ROM Proceedings of the 86th Annual Meeting of the Transportation Research Board (TRB), January 21-25, 2007.

Donovan, P. and Tutumluer, E., "Analysis NAPTF Trafficking Response Data for Pavement Foundation Deformation Behavior." In Proceedings of the 2007 FAA Worldwide Technology Transfer Conference, Atlantic City, NJ, April 15-17, 2007.

Pekcan, O., Tutumluer, E., and Thompson, M.R., "Analyzing Flexible Pavements on Lime-stabilized Soils using Artificial Neural Networks," International Conference on Advanced Characterization of Pavement and Soil Engineering Materials, Athens, Greece, June 20-22, 2007.

Kim, M. and Tutumluer, E., "Investigation of Pavement Foundation Behavior using Axisymmetric and Three-dimensional Finite Element Analyses," International Conference on Advanced Characterization of Pavement and Soil Engineering Materials, Athens, Greece, June 20-22, 2007.

Huang, H., Tutumluer, E., Hashash, Y. and Ghaboussi, J., "Imaging Aided Discrete Element Modeling of Railroad Ballast," International Conference on Advanced Characterization of Pavement and Soil Engineering Materials, Athens, Greece, June 20-22, 2007.

Al-Qadi, I.L., Tutumluer, E., Dessouky, S. and Kwon, J., "Responses of Geogrid-Reinforced Flexible Pavement to Accelerated Loading," International Conference on Advanced Characterization of Pavement and Soil Engineering Materials, Athens, Greece, June 20-22, 2007.

Al-Qadi, I.L., Dessouky, S., Kwon, J., and Tutumluer, E., "Geogrid-Reinforced Low Volume Flexible Pavements: Pavement Response and Geogrid Optimal Location," In Preprint CD-ROM Proceedings of the 87th Annual Meeting of the Transportation Research Board (TRB), January 21-25, 2008.

Kwon, J., Tutumluer, E., Al-Qadi, I.L., and Dessouky, S., "Mechanistic Model Response Predictions of Geogrid Base Reinforced Flexible Pavements," In Proceedings of GeoAmericas 2008, The First Pan American Geosynthetics Conference, Cancun, Mexico, March 2-5, 2008.

Roberts, R., Al-Qadi, I.L., and Tutumluer, E., "Railroad Structure Characterization using GPR in Alaska: A Case History," In Proceedings of the 12th International Conference on Ground Penetrating Radar, Birmingham, UK, June 16-19, 2008.

Donovan, P., and Tutumluer, E., "Anti-Shakedown of Unbound Aggregate Pavement Layers Subjected to Traffic Loading with Wander," In Proceedings of the 1st International Conference on Transportation Geotechnics and the 7th Unbound Aggregates in Roads Symposium (UNBAR7), Nottingham, UK, August 25-27, 2008.

Huang, H., Tutumluer, E., Hashash, Y., and Ghaboussi, J., "Contact Stiffness Affecting Discrete Element Modeling of Unbound Aggregate Granular Assemblies," In Proceedings of the 1st International Conference on Transportation Geotechnics and the 7th Unbound Aggregates in Roads Symposium (UNBAR7), Nottingham, UK, August 25-27, 2008.

Mishra, D., Tutumluer, E., and Butt, A.A., "Types and Amounts of Fines Affecting Aggregate Behavior," In Proceedings of the 1st International Conference on Transportation Geotechnics and the 7th Unbound Aggregates in Roads Symposium (UNBAR7), Nottingham, UK, August 25-27, 2008.

Pekcan, O., Tutumluer, E., and Thompson, M.R., "Quantifying Effects of Lime Stabilized Subgrade on Conventional Flexible Pavement Responses," In Proceedings of the 1st International Conference on Transportation Geotechnics and the 7th Unbound Aggregates in Roads Symposium (UNBAR7), Nottingham, UK, August 25-27, 2008.

Kim, M., Tutumluer, E., and Mishra, D., "Flexible Pavement Response to Multiple Wheel Loading Using Nonlinear Three-dimensional Finite Element Analysis," 12th International Conference of International Association for Computer Methods and Advances in Geomechanics (IACMAG), Goa, India, October 1-6, 2008.

Pekcan, O., Tutumluer, E., and Thompson, M.R., "Artificial Neural Network Based Backcalculation of Conventional Flexible Pavements on Lime Modified Soils," 12th International Conference of International Association for Computer Methods and Advances in Geomechanics (IACMAG), Goa, India, October 1-6, 2008.

Donovan, P. and Tutumluer, E., "Effect of Aircraft Load Wander on Unbound Aggregate Pavement Layer Stiffness and Deformation Behavior," ASCE Transportation and Development Institute (T&DI) Airfield and Highway Pavement Specialty Conference, Bellevue, Washington, October 15-18, 2008.

Kim, M. and Tutumluer, E., "Implications of Complex Axle Loading and Multiple Wheel Load Interaction in Low Volume Roads," ASCE Transportation and Development Institute (T&DI) Airfield and Highway Pavement Specialty Conference, Bellevue, Washington, October 15-18, 2008.

Anochie-Boateng, J. and Tutumluer, E., "Resilient Behavior Characterization of Naturally Occurring Bituminous Sands," In Preprint CD-ROM Proceedings of the 88th Annual Meeting of the Transportation Research Board (TRB), January 11-15, 2009.

Anochie-Boateng, J. and Tutumluer, E., "Characterizing Volumetric Deformation Behavior of Naturally Occurring Bituminous Sand Materials," In Proceedings of the 7th International RILEM Symposium on Advanced Testing and Characterization of Bituminous Materials (ATCBM09), Rhodes, Greece, May 27-29, 2009.

Mishra, D., Tutumluer, E., Kern, J., and Butt, A.A., "Characterizing Aggregate Permanent Deformation Behavior based on Types and Amounts of Fines," In Proceedings of the 8th International Conference on the Bearing Capacity of Roads, Railways and Airfields, Champaign, Illinois, USA, June 29–July 2, 2009; Edited by E. Tutumluer and I.L. Al-Qadi, ISBN: 978-0-415-87199-0, 2009.

Donovan, P.R., Tutumluer, E., and Huang, H., "Use of 3-dimensional Discrete Element Model to Examine Aggregate Layer Particle Movement due to Load Wander," In Proceedings of the 8th International Conference on the Bearing Capacity of Roads, Railways and Airfields, Champaign, Illinois, USA, June 29–July 2, 2009; Edited by E. Tutumluer and I.L. Al-Qadi, ISBN: 978-0-415-87199-0, 2009.

Pekcan, O., Tutumluer, E., and Ghaboussi, J., "SOFTSYS for Backcalculation of Full-depth Asphalt Pavement Layer Moduli," In Proceedings of the 8th International Conference on the Bearing Capacity of Roads, Railways and Airfields, Champaign, Illinois, USA, June 29–July 2, 2009; Edited by E. Tutumluer and I.L. Al-Qadi, ISBN: 978-0-415-87199-0, 2009.

Anochie-Boateng, J. and Tutumluer, E., "Shear Strength Properties of Naturally Occurring Bituminous Sands," In Proceedings of the 8th International Conference on the Bearing Capacity of Roads, Railways and Airfields, Champaign, Illinois, USA, June 29–July 2, 2009; Edited by E. Tutumluer and I.L. Al-Qadi, ISBN: 978-0-415- 87199-0, 2009.

Dombrow, W., Huang, H., and Tutumluer, E., "Comparison of Coal Dust Fouled Railroad Ballast Behavior – Granite vs. Limestone," In Proceedings of the 8th International Conference on the Bearing Capacity of Roads, Railways and Airfields, Champaign, Illinois, USA, June 29–July 2, 2009; Edited by E. Tutumluer and I.L. Al- Qadi, ISBN: 978-0-415-87199-0, 2009.

Huang, H., Tutumluer, E., Hashash, Y.M.A., and Ghaboussi, J., "Discrete Element Modeling of Aggregate Behavior in Fouled Railroad Ballast," In Proceedings of the GeoHunan International Conference – Challenges and Recent Advances in Pavement Technologies and Transportation Geotechnics, Hunan, China, August 3-6, 2009.

Selected Recent Invited Lectures

"Mechanistic-Empirical Pavement Design," Workshop Lecture Jointly Presented with Dr. Dallas N. Little, Texas A&M University, at the 11th Annual Symposium of the International Center for Aggregate Research (ICAR), Austin, Texas, April 28, 2003.

"ICAR Structural Model and Mechanistic-Empirical Pavement Design," Workshop Lecture Jointly Presented with Dr. Dallas N. Little, Texas A&M University, at the 11th Annual Symposium of the International Center for Aggregate Research (ICAR), Austin, Texas, April 28, 2003.

University Invitation: "Soil Trafficability and Subgrade Stability," Invited Speaker, Department of Civil Engineering, University of Costa Rica, San Jose, Costa Rica, November 2003.

University Invitation: "Soil and Aggregate Characterization," Invited Speaker, Department of Civil Engineering, University of Costa Rica, San Jose, Costa Rica, November 2003.

University Invitation: "Mechanistic-Empirical Pavement Design," Invited Speaker, Department of Civil Engineering, University of Costa Rica, San Jose, Costa Rica, November 2003.

"Mechanistic Based Pavement Design," Invited Speaker, Seminar Lecture Jointly Presented with Dr. D.N. Little, Texas A&M University, at the 12th Annual Symposium, International Center for Aggregate Research (ICAR), Denver, Colorado, April 5, 2004.

"State-of-the-Art of Aggregate Shape Analysis Using Imaging Techniques," Invited Speaker, Seminar Lecture Jointly Presented with Dr. E. Masad, Texas A&M University, at the 12th Annual Symposium, International Center for Aggregate Research (ICAR), Denver, Colorado, April 6, 2004.

"Stress Rotations Due to Moving Wheel Loads and Their Effects on Pavement Materials Characterization," Invited Speaker, Workshop on "Pavement Engineering from a Geotechnical Perspective," 57th Canadian Geotechnical Conference GeoQuebec 2004, Quebec City, October 24, 2004.

University Invitation: "Stress Rotations Due to Moving Wheel Loads and Their Effects on Pavement Materials Characterization," Invited Speaker, Civil, Construction and Environmental Engineering Department, Iowa State University, Ames, Iowa, November 15, 2004.

University Invitation: "Imaging Based Aggregate Shape Analysis and Its Applications In Mechanics of Pavement Materials," Invited Speaker, Civil Engineering Department Seminar Series, Louisiana State University, Baton Rouge, LA, November 23, 2004.

University Invitation: "Stress Rotations Due to Moving Wheel Loads and Their Effects on Pavement Materials Characterization," Invited Speaker, Department of Civil Engineering, Bogazici University, Istanbul, Turkey, January 4 AM hours, 2005.

University Invitation: "Stress Rotations Due to Moving Wheel Loads and Their Effects on Pavement Materials Characterization," Invited Speaker, Department of Civil Engineering, Kocaeli University, Izmit, Turkey, January 4 PM hours, 2005.

"Subgrade Stability and Pavement Foundation Requirements," Invited Keynote Speaker, 15th Colombian Symposium of Pavement Engineering, Sponsored by the Pontificia Universidad Javeriana in Bogota, Melgar, Colombia, March 11, 2005.

"Imaging Based Evaluation of Course Aggregate Used in the NCAT Pavement Test Track Asphalt Mixes," Invited Speaker, 2005 Asphalt Pavements Innovations Conference, Organized by the Center for Emerging Technologies in Infrastructure at Bradley University, Peoria, April 12, 2005.

"Measurement of Particle Shape, Form, and Texture Characteristics," Invited Speaker, TRB Mid-Year Meeting on Aggregates for Highway Construction: Characterization and Performance, held during the 56th Annual Highway Geology Symposium, May 3, 2005.

"A Mechanistic Response Model for Geosynthetic Reinforced Road Pavements," Invited Speaker, 2nd Technical Textiles Conference, Sponsored by Dokuz Eylul University, Istanbul International Technical Textile and Nonwoven Fair and Exhibition - HIGHTEX, July 14, 2005.

"Building Long Lasting Pavements with Unbound Aggregate Bases," Invited Speaker, Aggregate Base Symposium, Sponsored by the Oklahoma Aggregate Association, Oklahoma City, October 4, 2005.

University Invitation: "Characterization of the Anisotropic Behavior of Unbound Aggregate Bases," Invited Speaker, Taiyuan University of Science and Technology, Taiyuan, P.R. of China, June 12, 2006.

"Geogrid Base Reinforced Asphalt Pavements: Analysis Approach and Benefits," Invited Keynote/Opening Speaker, 2nd National Geosynthetics Conference of the Turkish Chapter of International Geosynthetics Society (IGS), Bogazici University, Istánbul, Turkey, November 16, 2006.

University Invitation: "Aggregate Testing and Characterization for Transportation Facilities Design," Invited Speaker, 35th Geomechanics Colloquium, Technical University (TU) Bergakademie, Freiberg, Germany, November 17, 2006.

"Influence of Coarse Aggregate Morphology on Hot Mix Asphalt Behavior," Invited Speaker, Mini-Symposium on Pavement Modeling and Damage Mechanics held in honor Professor Samuel H. Carpenter's Accomplishments, ICAMEM Conference, Hammamet, Tunisia, December 18, 2006.

"Essentials of Mechanistic-Empirical Pavement Design and 2002 MEPDG Overview," Invited Seminar Speaker, General Directorate of Turkish Highway Agency, Ankara, Turkey, December 26, 2006.

"Geogrid Base Reinforced Asphalt Pavements: Analysis Approach, Field Validations and Benefits," Invited Speaker, Tensar Mechanistic-Empirical Pavement Design Overview, Tensar Hospitality Suite, 86th Annual Meeting of the Transportation Research Board (TRB), January 21, 2007.

"Validation of Unbound Aggregate Base Anisotropic Stiffness Characterization from Instrumented Full Scale Pavement Tests," Invited Speaker, 15th Annual Symposium, International Center for Aggregate Research (ICAR), Austin, Texas, April 10, 2007.

"Building Long Lasting Pavements with Unbound Aggregate Bases," Invited Speaker, MO/KS Aggregate Base Symposium, Sponsored by Missouri Aggregate Association and Kansas Aggregate Association, Kansas City, May 3, 2007.

University Invitation: "Geogrid Base Reinforced Asphalt Pavements: A Mechanistic-Empirical Analysis and Design Approach," Invited Speaker, Seminar Series of the Civil Engineering Department, University of Wisconsin, Madison, WI, May 21, 2007.

University Invitation: "Geogrid Base Reinforced Asphalt Pavements: A Mechanistic-Empirical Analysis and Design Approach," CCEE Distinguished Lecture, Department of Civil, Construction and Environmental Engineering (CCEE), Iowa State University, Ames, Iowa, September 28, 2007.

"Tensar Mechanistic Based Design for Geogrid Base Reinforced Flexible Pavements," Invited Keynote Speaker, 13th International Meeting on Tensar Geosynthetics, Guatemala City, Guatemala, October 15, 2007.

"Unbound Aggregate Bases," Invited Speaker, IAAP / ICAR / MLPA / NSSGA Regional Technology Transfer Seminar, Sponsored by Illinois Aggregate Association Missouri Lime Producers Association, and Illinois and Missouri Departments of Transportation, Collinsville, Illinois, October 30, 2007.

"Geosynthetics in Pavements," and "Thin Asphalt Pavements," Invited Seminar Speaker, Istanbul Asphalt Plants Industry and Trading, Inc. (ISFALT), Istanbul, Turkey, January 3 and 4, 2008.

"Overview of Current Design Techniques for Flexible Pavements with Unbound Aggregate Bases," Invited Speaker, National Aggregate Base Conference, Austin, Texas, May 14, 2008.

"State of the Art: Anisotropic Characterization of Unbound Aggregate Layers in Flexible Pavements," Invited Keynote/Opening Speaker, Symposium of Pavement Mechanics and Materials, International Conference of the ASCE Engineering Mechanics Institute (EM08), Minneapolis, Minnesota, May 18, 2008.

"Pavement Management," Invited Seminar Speaker, Istanbul Asphalt Plants Industry and Trading, Inc. (ISFALT), Istanbul, Turkey, May 29, 2008.

"Experiences with Alternative Bases," Invited Speaker, 2nd Annual National Aggregate Base Conference, National Stone, Sand and Gravel Association Annual Convention and AGG1 Forum & Expo, Orlando, Florida, March 9, 2009.

"Types and Amounts of Fines Affecting Unbound Aggregate Behavior," Invited Speaker, 17th Annual Symposium, International Center for Aggregate Research (ICAR), Austin, Texas, May 4, 2009.

"Recent Research into the Actual Behavior of Geogrids in Stabilization Applications" Invited Speaker, Jubilee Symposium on Polymer Geogrid Reinforcement, Institution of Civil Engineers, London, UK, September 8, 2009.

Selected Recent Reports

Thompson, M.R., Tutumluer, E., and Bejarano, M., "Granular Material and Soil Moduli," Final Report No. 1, FAA Center of Excellence for Airport Pavements, Civil Engineering, University of Illinois at Urbana-Champaign, 1997.

Tutumluer, E. and M.R. Thompson, "Anisotropic Modeling of Granular Bases," Final Report No. 2, FAA Center of Excellence for Airport Pavements, Civil Engineering, University of Illinois at Urbana-Champaign, 1998.

Tutumluer, E. and U. Seyhan, "Characterization of Unbound Aggregates Using the University of Illinois FastCell," Technical Report, Submitted to Applied Research Associates for Inclusion in the Final Report of the NCHRP Project 4-23, Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 1999.

Tutumluer, E., Rao, C., and Stefanski, J., "Video Image Analysis of Aggregates," Final Project Report, FHWA-IL-UI-278, Civil Engineering Studies UILU-ENG-2000-2015, University of Illinois Urbana-Champaign, Urbana, IL, July 2000.

Tutumluer, E., Adu-Osei, A., Little, D.N., and Lytton, R.L., "Field Validation of the Cross-Anisotropic Behavior of Unbound Aggregate Bases," Research Report 502-2, A Deliverable of the International Center for Aggregates Research (ICAR) 502 Project: Structural Characteristics of Unbound Aggregate Bases to Meet AASHTO 2002 Design Requirements, March 2001.

Seyhan, U. and E. Tutumluer, "Characterization of Anisotropic Granular Layer Behavior of Flexible Pavements," Final Report No. 18, FAA Center of Excellence for Airport Technology, Civil Engineering, University of Illinois, February 2002.

Kwon, J. and E. Tutumluer, "Geosynthetic Reinforcement of Pavement Structures," Summary Technical Report, Project IHR-R30, Submitted to the Illinois Department of Transportation, University of Illinois, Urbana, IL, August 2002.

Masad, E., Al-Rousan, T., Pascual, J., Button, J., Little, D.N., and Tutumluer, E., "Test Methods for Characterizing Aggregate Shape, Texture, and Angularity," Interim Report, Project 4-30, National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, D.C., October 2002.

Kwon, J. and E. Tutumluer, "Use of Geosynthetics In Working Platform and Pavement Construction," Final Report, Project IHR-R30, Submitted to the Illinois Department of Transportation, University of Illinois, Urbana, IL, June 2003.

Tutumluer, E., Pan, T., and Carpenter, S.H., "Investigation of Aggregate Shape Effects on Hot Mix Performance Using An Image Analysis Approach," Final Technical Report, Pooled Fund Study TPF-5(023), UILU-ENG-2005-2003, Federal Highway Administration IL Division, University of Illinois, Urbana, IL, Feb., 2005.

Masad, E., Al-Rousan, T., Button, J., Little, D.N., and Tutumluer, E., "Test Methods for Characterizing Aggregate Shape, Texture, and Angularity," Final Report, Project 4-30A, National Cooperative Highway Research Program (NCHRP), Transportation Research Board, National Research Council, Washington, D.C., May 2005.

Brar, H., Tutumluer, E., and Thompson, M.R., "Subgrade Soil Test Results for a New Runway Construction at the O'Hare International Airport," Progress Report Submitted as Technical Note No. 19, O'Hare Modernization Program, Center of Excellence for Airport Technology (CEAT), CEE Department, UIUC, Urbana, IL, July 2005.

Kim, I.T. and Tutumluer, E., "Permanent Deformation Behavior of Airport Flexible Pavement Base and Subbase Courses," FAA Center of Excellence for Airport Technology (CEAT) Report No. 28, CEE Department, UIUC, Urbana, IL, October 2005.

Brar, H., Tutumluer, E., and Thompson, M.R., "Subgrade Soil Test Results for a New Runway Construction at the O'Hare International Airport'," Progress Report, O'Hare Modernization Program, Center of Excellence for Airport Technology (CEAT), CEE Department, University of Illinois, Urbana, Illinois, March 2006.

Al-Qadi, I.L., Tutumluer, E., Dessouky, S., and Kwon, J. "Effectiveness of Geogrid-reinforcement in Flexible Pavements: A Full-Scale Testing," Construction Report, Submitted to Tensar International, Inc. UIUC, June 2007.

Al-Qadi, I.L., Tutumluer, E., Dessouky, S., and Kwon, J. "Effectiveness of Geogrid-reinforcement in Flexible Pavements: A Full-Scale Testing," Final Project Report, Submitted to Tensar International, Inc. UIUC, June 2007.

Kwon, J. and Tutumluer, E., "Development of a Mechanistic Model for Geogrid Reinforced Flexible Pavements," Project Report, Submitted to Tensar International, Inc. UIUC, June 2007.

Kwon, J. Tutumluer, E., and Pekcan, O., "Tensar Mechanistic Analysis and Design," a Software Application for Geogrid Reinforced Pavement Analysis and Design, Submitted to Tensar International, Inc. UIUC, June 2007.

Tutumluer, E., Huang, H., Hashash, Y., Ghaboussi, J., and David, D., "Image Aided Discrete Element Modeling of Aggregate Ballast Behavior," Technology Digest TD-08-012, published by Transportation Technology Center, Inc., a wholly owned subsidiary of the Association of American Railroads, March 2008.

Pekcan, O., Tutumluer, E., and Thompson, M.R., "Nondestructive Pavement Evaluation Using ILLI-PAVE Based Artificial Neural Network Models," Illinois Center for Transportation (ICT) R39-2 Project Final Report, Submitted to Illinois Department of Transportation, UIUC, July 2008.

Pekcan, O., Tutumluer, E., and Thompson, M.R., "Artificial Neural Network for Professionals (ANN-Pro) – Software and User Manual," Illinois Center for Transportation (ICT) R39-2 Project Deliverable, Submitted to Illinois Department of Transportation, UIUC, July 2008.

Pekcan, O., Tutumluer, E., and Thompson, M.R., "Soft Computing Based Pavement and Geomaterial System Identifier (SoftSYS) – Software and User Manual," Illinois Center for Transportation (ICT) R39-2 Project Deliverable, Submitted to Illinois Department of Transportation, UIUC, July 2008.

Deniz, D., Tutumluer, E., and Popovics, J., "Expansive Characteristics of Reclaimed Asphalt Pavement (RAP) Used As Base Materials," Illinois Center for Transportation (ICT) R27-27 Project Final Report, Submitted to Illinois Department of Transportation, UIUC, October 2008.

Al-Qadi, I.L., Roberts, R., Tutumluer, E., Leng, Z., and Wei, X., "New GPR Analysis Techniques for Ballast Assessment," Technology Digest, submitted to Transportation Technology Center, Inc., a wholly owned subsidiary of the Association of American Railroads, April 2009.

Editorships of Journals

Editorial Board Member, International Journal of Pavement Engineering, Taylor and Francis Group, (http://www.tandf.co.uk/journals), Co-Editors Tom Scarpas, Delft University of Technology, The Netherlands and Imad Al-Qadi, University of Illinois at Urbana-Champaign, 2004 – present.

Associate Editor, International Journal of Pavement Research and Technology, Editors-in-Chief Prof. Deng-Fong Lin, I-Shou University, Taiwan and Dr. Chung Wu, Virginia DOT, USA, Publisher: Chinese Society of Pavement Engineering, No. 300 Jhongda Rd., Jhongli City, Taoyuan County, 3200, Taiwan, R.O.C. (http://www.ijprt.org.tw), 2007 – present.

Associate Editor, Journal of Computing in Civil Engineering, Editors-in-Chief James H. Garrett, Jr., Ph.D., P.E., M.ASCE, Carnegie Mellon University and Lucio Soibelman, Ph.D., M.ASCE, Carnegie Mellon University. Publisher: ASCE, (http://pubs.asce.org/journals/computing/), 2008 – present.

Editorial Board Member, International Journal of Geomechanics, Editor-in-Chief Musharraf M. Zaman, Ph.D., University of Oklahoma, Publisher: ASCE, (http://pubs.asce.org/journals/geomechanics/), January 2009 – present.

Other Professional Service

Contributor/Co-Editor, Transportation Research Board (TRB) Circular E-C012 on "Use of Artificial Neural Networks Geomechanical and Pavement Systems," 79th Annual TRB Meeting, January 8-13, 2000 (http://www4.nationalacademies.org/trb/onlinepubs.nsf/web/circular)

Program Committee Member, 2nd International Workshop on Artificial Intelligence and Mathematical Methods in Pavement and Geomechanical Engineering Systems, University of Delaware, Newark, Delaware, August 11-12, 2000.

Planning Committee Member, ASCE Airfield Pavement Specialty Conference, Advancing Airfield Pavements, Chicago, Illinois, August 5-8, 2001.

Planning Committee Chair, "Recent Advances in Materials Characterization and Modeling of Flexible Pavements" A Symposium Sponsored by the ASCE Geo-Institute Pavements Committee at the 15th ASCE Engineering Mechanics Division Conference (EM2002) at Columbia University, New York, NY, June 2-5, 2002.

Scientific Committee Member, 6th International Conference on the Bearing Capacity of Roads, Railways and Airfields, BCRA 2002, Technical University of Lisbon, Lisbon, Portugal, 24-26 June, 2002.

Planning Committee Member, A Special Pavements Symposium at the GeoFrontiers 2005 Conference organized by the ASCE Geo-Institute, Austin, TX, January 24-26, 2005.

Scientific Committee Member, 7th International Conference on the Bearing Capacity of Roads, Railways and Airfields, BCRA 2005, Norwegian University of Science and Technology, Trondheim, Norway, June 27-29, 2005.

Planning Committee Member, Pavement Foundations Sessions at the GeoShanghai Conference organized by the ASCE Geo-Institute, Shanghai, China, June 6-8, 2006.

Technical Committee Member, ASCE Geo-Institute GeoShanghai Conference, Shanghai, China, June 6-8, 2006.

Planning Committee Chair, Pavements Track Symposium on Soil and Material Inputs for Mechanistic-Empirical Pavement Design at the GeoDenver 2007 Conference organized by the ASCE Geo-Institute, Denver, CO, February 18-21, 2007.

Scientific Committee Member, International Conference on Advanced Characterization of Pavement and Soil Engineering Materials, National Technical University of Athens (NTUA), Athens, Greece, June 20-22, 2007.

Planning Committee Chair, Pavements Track Sessions at the GeoCongress 2008 Conference organized by the ASCE Geo-Institute, New Orleans, LA, March 9-12, 2008.

Scientific Committee Member, 10th International Conference on Application of Advanced Technologies in Transportation (AATT 2008), National Technical University of Athens (NTUA), Athens, Greece, May 27-31, 2008.

Organizing Committee Member, 6th RILEM International Conference on Pavement Cracking, Chicago, Illinois, June 16-19, 2008.

International Advisory Committee Member, 1st ISSMGE International Conference on Transportation Geotechnics, University of Nottingham, United Kingdom, September 8-10, 2008.

International Advisory Committee Member, 12th International Conference of the Association for Computer Methods and Advances in Geomechanics (IACMAG), Goa, India, October 1-6, 2008.

Conference Chair, 8th International Conference on the Bearing Capacity of Roads, Railways, and Airfields (BCR^2A), University of Illinois at Urbana-Champaign, Champaign, Illinois, June 29-July 2, 2009.

International Advisory Committee Member, GeoHunan International Conference on Challenges and Recent

Advances in Pavement Technologies and Transportation Geotechnics, Hunan, China, August 3-6, 2009.

Organizing Committee Member, GeoShanghai International Conference 2010 organized by the ASCE Geo-Institute, Shanghai, China, June 3-5, 2010.

International Advisory Committee Member, GeoHunan International Conference II: Emerging Technologies for Design, Construction, Rehabilitation, and Inspections of Transportation Infrastructures, Zhangjiajie (Hunan Province), China, June 6-8, 2011.

International Advisory Committee Member, 2nd International Conference on Transportation Geotechnics, Sapporo, Hokkaido, Japan, September 10-12, 2012.

Reviewer of technical papers/books submitted for publication:

- Transportation Research Board (TRB) Research Record Series
- Geotechnical Testing Journal, ASTM
- ASTM Journal of Testing and Evaluation
- Journal of Transportation Engineering, ASCE
- Journal of Geotechnical and Geoenvironmental Engineering, ASCE
- Canadian Journal of Geotechnical Engineering

- Journal of Materials in Civil Engineering, ASCE
- Journal of Infrastructure Systems, ASCE
- Journal of Computing in Civil Engineering, ASCE
- International Journal of Geomechanics, ASCE
- Asphalt Pavement Technology, Association of Asphalt Pavement Technologists (AAPT)
- Journal of Computer-Aided Civil and Infrastructure Engineering
- International Journal of Pavement Engineering (Edited by T. Scarpas and I. Al-Qadi, Taylor & Francis Group)
- International Journal of Road Materials and Pavement Design (Edited by H.D. Benedetto, U. Isaacson, and J.B. Sousa, Hermes Science Publications)
- International Journal of Pavement Research and Technology, Editors-in-Chief Prof. Deng-Fong Lin, I-Shou University, Taiwan and Dr. Chung Wu, Virginia DOT, USA
- International Journal for Numerical and Analytical Methods in Geomechanics, (edited by Stein Sture, John Wiley and Sons)
- Prentice Hall Publishers, Upper Saddle River, New Jersey (Pavement Analysis and Design, by Yang H. Huang, 1st and 2nd Editions)

EXHIBIT 2

Erol Tutumluer's Additional Experience

My major research focus in railroad engineering has been primarily on the aspects of track substructure. My first railroad project in 2001 was jointly funded by the AAR affiliated laboratory established at UIUC and Burlington Northern Santa Fe Railroad Company. The project involved an industry survey and review of performance and remediation methods for track substructure, including ballast, subballast, and subgrade. Specifically, the industry survey provided information for AAR members on (1) general track substructure statistics, inspection, and maintenance; (2) subgrade soil problems and railroad remedial practices; and (3) ballast/subballast related problems and railroad remedial practices.

Another railroad project funded by the Federal Railroad Administration ("FRA") involved the development of ground penetrating radar ("GPR") to evaluate railway track subsurface condition and estimate track bed materials' physical properties. The objective of the project was to test previous methods of collecting GPR data. The UIUC team was responsible for evaluating the modified common midpoint GPR technique and developing ballast thickness algorithm and quantitative assessment of the ballast and sub-ballast condition, including accurate assessment of its physical state and indications of the degree of ballast fouling, which is the main indicator of ballast degradation.

I am currently working on four research projects concerning railroads: (1) Discrete Element Modeling ("DEM") of Ballast funded by the AAR-affiliated laboratory at UIUC, (2) Railroad Track Substructure Evaluation jointly funded by AAR and the FRA, (3) Investigation of Fouled Ballast Behavior funded by BNSF Railroad Company, and finally, (4) Testing of Polyurethane Elastomer Coated Railroad Ballast funded by BASF The Chemical Company. I have presented and published several papers and AAR Technology Digests related to these railroad projects, including at the American Railway Engineering and Maintenance of Way Association ("AREMA") conferences held from 2006 to 2009 and at the Transportation Research Board annual meetings since 2008.

The current AAR project focuses on the development of a combined image analysis and DEM approach for analyzing ballast aggregate behavior and improving ballast strength and stability and manufactured crosstie designs. This project also deals with the selection of proper ballast aggregate shape and angularity characteristics for mitigating track problems and failures due to ballast breakdown, powdering, and fouling; ballast deformation and degradation due to compaction and repeated loading; and ballast lateral movement and instability causing track buckle. In this project, we developed a validated image-aided DEM model to evaluate the size and shape properties of ballast aggregate to eventually engineer ballast track designs. In our ongoing efforts, we will use the developed DEM model to adequately predict field ballast deformation behavior obtained from settlement records of full-scale test sections, as well as bridge approaches and transition zones in the AAR Transportation Technology Center, Inc. ("TTCI") test track in Pueblo, Colorado.

BNSF Railway Company has funded a research project at UIUC with a focus on conducting large direct shear laboratory tests to measure strength and deformation characteristics of both clean (new) and fouled ballast aggregates at various stages of fouling with different type fine-grained materials (plastic subgrade soils, mineral filler, coal dust, etc.). This laboratory study also included studying the effects of coal dust fouling on the granite-type and limestone-type ballast aggregate behavior and evaluating reductions in strength and stability. This study resulted in important findings on the effects of coal dust and other ballast foulants.

My railroad track research program at UIUC was selected as the university research partner to collaborate with the AAR's TTCI for the "Track Substructure" cooperative research program established in 2009 and now jointly funded by the AAR and FRA. Under this multi-year track infrastructure research partnership program, the primary objectives are to determine the effects of heavy axle load traffic on track infrastructure; investigate root causes of mud holes and quantify their effects on track and track components; and finally, develop guidelines for track substructure diagnostics, remedy, design, and construction.

My other projects include stress dependency and anisotropy of aggregate behavior affecting structural response and performance of unbound aggregate layers in the transportation infrastructure sponsored by the Federal Aviation Administration ("FAA"), U.S. Army Corps of Engineers, and the International Center for Aggregates Research ("ICAR"). I have also studied the size, shape, and angularity characterization of aggregates using video-imaging and more recently Laser Detection and Ranging techniques sponsored throughout the last nine years by the Federal Highway Administration ("FHWA"), the Illinois Department of Transportation ("IDOT"), and by the National Cooperative Highway Research Program ("NCHRP"). In addition, I recently have researched establishing subgrade/subbase support, stability, and working platform requirements with virgin and recycled aggregates, including evaluating their expansive characteristics, for highway pavements, which was funded by IDOT. I have also researched airport pavements in a project funded by the O'Hare Modernization Program for Chicago's O'Hare Airport and the best value granular material for road foundation in a project funded by Minnesota Department of Transportation. In addition, I have been working on laboratory subgrade soils testing for Caterpillar, Inc., related to the mobility of some of its construction and compaction equipment on problematic soils, such as tar sands or oil sands. I am also working to model geogrid reinforced unbound aggregate roadway, railroad base, and ballast layers for a leading geosynthetic producer, Tensar International, Inc.

My research has resulted in high-quality peer-reviewed journal papers, an invention disclosure for U.S. patent application, a co-authored book on anisotropic behavior of aggregate materials, co-edited a two-volume hardcover Eighth International Conference Proceedings book on the Bearing Capacity of Roads, Railways and Airfields in 2009, and co-edited five ASCE Geotechnical Special Publications in relation to my involvement, including my current chair role of the ASCE Geo-Institute's Pavements Committee. To support my research programs, I have received grants from federal agencies including FRA, FHWA, FAA, U.S. Army Corps of Engineers, NCHRP and NSF; state agencies, including single grants from Illinois, Minnesota and Indiana DOTs and pool-funded research contributions from six other state DOTs; and grants from the private sector, including companies such as AAR, BNSF Railway Company, Caterpillar, Inc., BASF The Chemical Company, International Center for Aggregates Research, Chicago O'Hare Airport O'Hare Modernization Program, and Tensar International, Inc.

I have been recognized for my teaching and scholarly service. In 1997, I was named a General Electric Scholar by the UIUC College of Engineering in 1997 and also received a certificate of recognition as an Engineering Education Scholar by the National Science Foundation ("NSF"). I was named General Electric Fellow (1999) and Collins Fellow (2000) by the Academy of Excellence in Engineering Education program administered by the College of Engineering. In 2000, I was the recipient of the Transportation Research Board's Fred Burgraff award for Excellence in Transportation Research. In 2001, I was elected as a Campus Honors Program faculty member by the Chancellor of UIUC. In 2003 and 2008, my students ranked me as excellent on the list of teachers at UIUC. In January 2009, my paper entitled the "Use of

Falling Weight Deflectometer Testing to Determine Relative Damage in Asphalt Pavement Unbound Aggregate Layers" received the Best Paper Award from the Geology and Properties of Earth Materials Section of the Transportation Research Board, National Academy of Sciences.

EXHIBIT 3

Laboratory Characterization of Coal Dust Fouled Ballast Behavior

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Laboratory Characterization of Coal Dust Fouled Ballast Behavior

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ABSTRACT

Fouling refers to the condition of railroad ballast when voids in this unbound aggregate layer are filled with finer materials. As a fouling agent, coal dust coming from coal trains and accumulating in the ballast has become a major concern for railroads. This paper aims to provide a better understanding of adverse impacts of coal dust on railroad ballast drainage and load carrying functions. First, mechanical properties of coal dust were investigated at the University of Illinois through laboratory tests such as grain size distribution, Atterberg limits, specific gravity, moisture-density compaction relationships, and shear strength properties. Then, ballast aggregates were added coal dust at different percentages by weight and moisture contents to represent coal dust fouling in the field. When fouled samples were tested in large direct shear (shear box) equipment, it was found that 25% coal dust by weight of aggregates were enough to fill up all the voids in ballast corresponding to a void ratio of 43%. When the coal dust percentage in ballast samples increased, the ballast shear strength steadily decreased. In the case of ballast fully fouled with wet coal dust at 35% moisture content, the friction angles obtained from the direct shear equipment were close to the friction angle of coal dust itself. This implies that individual aggregate particles within ballast layer would be completely separated by coal dust to most likely cause the worst track instability problems in the field.

Key Words: Railroad track, ballast, fouling, coal dust, shear strength, laboratory testing

INTRODUCTION

Railroad ballast is uniformly-graded coarse aggregate placed between and immediately underneath the crossties. The purpose of ballast is to provide drainage and structural support for the heavy loading applied by trains. As ballast ages, it is progressively fouled with fine-grained materials filling the void spaces. Methods specifically used to assess track ballast condition only deal with checking visually for evidence of fouling, pumping and water accumulation (ponding) at ditches and shoulders. Additionally, ballast sampling and testing for fouling through laboratory sieve analyses generally provide some insight into the compositions of the larger aggregate particles and the amount of fines. Nonetheless, for a better evaluation of the serviceability and proper functioning of the existing ballast layer, ballast strength and deformation behavior needs to be characterized for different percentages of fine-grained materials, such as plastic soil fines, mineral filler, and more recently coal dust coming from coal trains, which can fill the voids and cause ballast fouling.

For hundreds of years, coal has been a major energy source in the United States. Indeed, there has been a historical link between the economic progress of the U.S. and the use of coal for numerous basic needs of the country, ranging from energy for domestic purposes to industrial applications and electricity generation. As the demand for coal transportation increases with the growing energy need, the coal transportation in the U.S. strongly relies on rail transport. Since rail transport, particularly a unit train, provides the most efficient means of transporting bulk commodities such as coal (Morrison, 1985), the role of rail lines in coal transport has always been predominant.

Today, Powder River Basin (PRB) coal is the largest source of incremental low-sulfur coal supplies in the U.S. (Gaalaas, 2006). From 2000 to 2005, the 5.6 percent increase in nationwide coal production chiefly stemmed from the concurrent expansion in PRB coal production, and the Burlington Northern Santa Fe/Union Pacific (BNSF/UP) joint line provided for over 60 percent of the total increase in PRB coal production (42 million tons of 69 million tons) from 2000 to 2005. However, while the National Coal Transportation Association forecast of the corresponding total coal shipments was 348 million tons, the joint line was able to achieve 325 million tons of the total forecast value because of major operating problems on the joint line (Gaalaas, 2006). In 2005, two derailments occurred in the BNSF/UP joint coal line in PRB which threatened to interrupt the supply of coal to power plants. Both of the derailments were suspected to be attributed by coal dust fouling, where coal dust spilled over the ballasts and accumulated moisture, allegedly resulting in the loss of strength of the track. In both places where derailments happened, ballast was heavily fouled by coal dust.

This paper presents findings from a comprehensive laboratory-testing program recently initiated at the University of Illinois to study effects of coal dust fouling on railroad ballast strength. Using large direct shear (shear box) tests, strength and deformation characteristics of granite type ballast material were investigated for both clean and coal dust fouled aggregates at various stages of fouling under both dry and wet conditions. The shear strength properties, i.e., cohesion intercept and friction angle, and the stress-strain response are linked to field ballast fouling levels to better assess the impact of coal dust fouling on track instability and ultimately loss of track support leading to derailments.

BALLAST FOULING

Selig and Waters (1994) proposed two indices to describe ballast fouling: (1) *fouling index* is the sum of the percent by weight of ballast sample passing the No. 4 (4.75 mm) sieve plus the percent passing the No. 200 sieve and (2) *percentage of fouling* is the ratio of the dry weight of material passing 3/8 in. (9.5 mm) sieve to the dry weight of total sample. Figure 1 shows grain size distributions obtained for both clean and fouled materials. The fouled ballast material was collected from a location of derailed (track had buckled out) section of the BNSF railroad line near milepost 43 in Utica, Nebraska in spring of 2006. As indicated, these clean and fouled samples have 1.5% and 14.0% passing the No. 200 sieve (0.075mm), respectively. Although the fines content (% passing the No. 200 sieve) of the fouled sample is not very high, the *fouling index* values computed for the clean and fouled samples were 6.9 and 45.7, respectively. In this case, a *fouling index* of 45.7 corresponds to a *percentage fouling* of nearly 38% (see Figure 1).

In a clean ballast sample, almost all aggregates are supposed to establish contact with each other at the aggregate surface to carry the load (see Figure 2a). As shown in Figure 2b, dirty or partially fouled ballast will have the voids in between contacting aggregates filled with fine particles, however, still maintaining aggregate to aggregate contact. Whereas, in a fouled ballast, due to the excessive amount of fine particles, aggregate to aggregate contacts are mostly eliminated and the aggregate particle movements are then only constrained by the fine particles filling the matrix or voids between the particles (see Figure 2c). In regards to excessive fouling conditions, for example, as in the case of 2005 PRB joint line derailments with wet coal dust completely filling all voids in ballast and pumping on the surface of railroad track, the low strength of the fouling agent will govern for carrying the wheel load. Hence, train derailments may take place due to unstable support under the crossties.

MECHANICAL PROPERTIES OF COAL DUST

Coal dust sample tested in this study was collected from the PRB Orin line milepost 62.4 and was sampled on March 10, 2007. Figures 3 and 4 depict the received coal dust sample in its loose state and close-up view, respectively. To investigate first the mechanical behavior of coal dust itself, several laboratory tests were conducted at the Advanced Transportation Research Laboratory (ATREL) of the University of Illinois at Urbana-Champaign (UIUC). The following sections briefly describe the conducted laboratory tests and present the coal dust test results.

Grain Size Analysis (ASTM C 136, ASTM C 117)

To begin with, dry and wet sieve analyses of the coal dust were performed in compliance with ASTM C 136 and ASTM C 117 test procedures. As Figure 5 indicates from the more accurate wet sieve analyses, the fines content of the coal dust sample was found to be 24%, which means 76% of the coal dust particles were primarily sand sized, coarser than 0.00295 in. (0.075 mm) or retained on No. 200 sieve. The top size (D_{max}) of the coal dust sample is 0.187 in. (4.75 mm), and the particle size corresponding to 50 percent finer by weight (D_{50}) is 0.03 in. (0.76 mm).

Atterberg Limits

The Atterberg limits tests performed indicated that the coal dust sample had a plastic limit (PL) of 50%, a considerably high liquid limit (LL) of 91% thus resulting in a plasticity index (PI) of 41%. This means, at 50% water content, the coal dust starts to exhibit plastic behavior whereas at 91% water content or higher, it behaves like a viscous liquid. Note that the LL of the coal dust is significantly higher than some known weak soils, such as Panama Organic Silt (55%), Georgia Kaolinite (48%), Venezuela Clay (40%), mica powder (75%) from Terzaghi et al. (1996).

Similarly, the PI of the coal dust also exceeds typical values for weak soils, such as Panama Organic Silt (17%), Georgia Kaolinite (16%), Venezuela Clay (25%) and mica powder (20%) (after Terzaghi et al., 1996). Therefore, the high LL and PI of the coal dust sample clearly highlighted its much higher moisture holding capability compared to many silty and clayey subgrade soils.

Specific Gravity

The specific gravity of the coal dust sample was found to be 1.28, which simply meant the density of the coal dust solids was a rather low 79.9 pcf (1.28 g/cm^3) when compared to solid densities of typical soils and aggregates. These results were in accordance with the findings of Fitch (2005), who gave a specific gravity range for coal dust from 1.3 to 1.5. On the other hand, the specific gravities of clay particles typically vary from 2.5 to 2.9 with a statistical average of 2.7 whereas the average specific gravity of sand grains is about 2.65 (Terzaghi et al., 1996). Thus, compared to most soils, the coal dust is a significantly lighter material as far as the low specific gravity of its solid constituents is considered.

Standard Proctor Compaction Test (AASHTO T99/ASTM D 698)

To establish a relationship between the water content and dry density of coal dust, standard Proctor compaction test was performed at different water contents (AASHTO T99/ASTM D698). Figure 6 shows the laboratory obtained compaction curve of the coal dust samples studied. It indicates that the optimum moisture content for the coal dust is 35%, at which the maximum dry density of 54.2 pcf (0.87 g/cm^3) is achieved with the given compactive effort.

Compared to most fine-grained soils such as clays and silts, the 35% optimum moisture content (OMC) is a very high value corresponding to a quite low maximum dry density of 54.2

pcf (0.87 g/cm^3). As far as the results of the standard Proctor compaction test are considered, the coal dust displays not only higher moisture holding capability but also significantly lower dry density compared to most fine-grained soils.

Triaxial (Unconsolidated-Undrained) Test

In this test, cylindrical coal dust specimens were sheared at their OMC (35%) and maximum dry density (54.2 pcf) determined by the previously conducted standard Proctor compaction test. A servo-pneumatic test frame was used as a UTM setup to conduct triaxial tests on small 2 in. (50.8 mm) in diameter by 4 in. (101.6 mm) high specimens. Shear strength tests were conducted under unconfined and confined conditions with the monotonic loading until failure. Figure 7 shows photos of the triaxial cell and the cylindrical coal dust specimen tested. A vertical actuator applies the axial monotonic load and the confining pressures are applied through the inside the chamber.

Since the drainage valves of the triaxial cell were closed from the beginning, the samples were not allowed to consolidate under the effect of confining pressure after they reached 100% saturation and the shearing stage was achieved under undrained conditions. Since the increase in stress was carried by the pore water (Holtz and Kovacs, 1981), the internal friction angle of the coal dust is found almost equal to zero for the undrained conditions. Figure 8 shows the Mohr circles for the unconsolidated-undrained tests and the resultant Mohr-Columb failure envelope of the coal dust. As the failure envelope levels up, it is concluded that the internal friction angle (Φ) of the coal dust is approximately 1.8 degrees, i.e., almost equal to zero, which is very typical of cohesive clayey soils tested under such undrained conditions.

Figure 9 shows applied deviator stresses graphed with vertical specimen displacements at different confining pressures. Once again, there was no effect of varying confining pressure on the shear strength of the coal dust, which was obtained as the maximum deviator stress at failure of only 3.5 psi (24.1 kPa). This is almost the same as twice the amount of cohesion intercept indicated on the y-axis in Figure 8, which is often called the unconfined compressive strength (Qu) for cohesive (Φ=0) soils.

Direct Shear Test

In this test, coal dust samples at different water contents were sheared horizontally in a 3.94 in. by 3.94 in. (100mm by 100mm) shear box under different normal loads so that the relationships between the normal stress and shear stress were established. A direct shear test equipment Humboldt ShearScan 10 direct/residual apparatus utilizing the pneumatic loading concept was used to apply the vertical load to the sample. In doing so, this self-contained model eliminates the need for loading weights used in dead weight-type systems. The ShearScan 10 is complete with a 2,000-lb. (10-kN) capacity load cell, 1-in. (25.4-mm) stroke horizontal deformation transducer, 0.4-in. (10.2-mm) vertical deformation transducer and a built-in 4-channel analog data acquisition system. Figure 10 shows a picture of the ShearScan 10 direct/residual shear test device used to shear the specimen under a series of applied normal stresses.

Table 1 summarizes the results obtained from the direct shear tests and illustrates the change in the internal friction angle of the coal dust with respect to moisture content. The internal friction angles and cohesion intercepts of the coal dust samples are tabulated with regard to the moisture contents of the test samples. Considering the significant decrease in the friction angle and as a result approximately 47% decrease in shear strength contributed by tan Φ, cohesion intercept stayed almost constant.

CLEAN AND COAL DUST FOULED BALLAST BEHAVIOR

To investigate whether the fouling condition indicated in Figure 2c takes place, i.e., fouling agent's strength dominates over the ballast layer strength properties when heavily fouled, direct shear tests were conducted at the University of Illinois on both clean and coal dust fouled ballast samples. The ballast material tested was a granite aggregate obtained from Gillette, WY and commonly used in the PRB joint line railroad track structures as the ballast layer.

Figure 11 shows the grain size distribution of the granite sample tested in compliance with ASTM C 117 test procedure. Table 2 lists the gradation sieve sizes and the percent passing each sieve properties for the clean granite aggregate. The grain size distribution conforms to the typical AREMA No. 24 ballast gradation having a maximum size (D_{max}) of 2.5 in. (63.5 mm), a minimum size (D_{min}) of 1 in. (25.4 mm), and an average particle size corresponding to 50 percent passing by weight (D_{50}) of approximately 1.77 in. (45 mm). Also listed in Table 2 are the specific gravity, unit weight and corresponding compacted air voids of the clean granite aggregates. ASTM C29 test procedure was used for finding porosity or air voids with known values of the specific gravity and volume and weight of ballast compacted.

Direct shear strength tests were performed on the reconstituted clean and coal dust fouled granite aggregate samples. Figure 12 shows the large shear box equipment used for testing at the University of Illinois. The test device is a square box with side dimensions of 12 in. (305 mm) and a specimen height of 8 in. (203 mm). It has a total 4-in. (102 mm) travel of the bottom 6-in. (152 mm) high component, which is large enough for ballast testing purposes to record peak shear stresses. The vertical (normal direction) and horizontal load cells are capable of applying and recording up to 30-kip and 20-kip load magnitudes, respectively. The device controls and the data collection are managed through an automated data acquisition system controlled by the operator through a build-in display and the test data are saved on to a personal computer.

Direct Shear Test Procedure

1. Obtain 54 lbs. (24.5 kg) of ballast aggregate
2. Compact ballast sample into lower box (14 in. x 12 in. x 6 in. or 356 mm x 305 mm x 152 mm) using two 3 in. (76 mm) lifts. Use vibratory compactor on top of a flat Plexiglas compaction platform and compact until no noticeable movement of particles is observed (see Figure 13).
3. Obtain prescribed weight of fouling material (e,g., coal dust) and water to mix with compacted ballast.
4. Spread fouling material over compacted ballast evenly in two lifts (half of material each lift). Shakedown material using vibratory compactor after each lift. If test is conducted with wet fouling material (for example, at the optimum moisture content or OMC), pour proportional amount of water over ballast after shakedown of each lift (see Figure 14). Place upper ring (3 in. or 76 mm high) on top of lower box. Align ring with sides and back edge of box (opposite of block) and fill with single lift of ballast and compact (see Figure 15).
5. Place box and ring assembly into shearing apparatus. Clamp lower box in place. Place load bearing plate on ballast and inside upper ring. Place air-bladder on bearing-plate. Close normal force load cell over air-bladder. Open air supply and set pressure using an in-line pressure regulator (see Figure 16).

6. Adjust shear force load cell directly against the upper ring.
7. Prepare LabVIEW Data Logger software to record normal and shear force while the test is running.
8. Input shear rate of 0.48 in./min. (12.2 mm/min.) which is approximately 4% strain per minute and run test until shear force output becomes constant or 15% strain has occurred.

Direct Shear Test Results

The ballast samples were sheared horizontally in the shear box under target normal pressures of 25, 35, 45 psi (172, 241 and 310 kPa), typical ballast layer confining pressures, so that the relationships between the normal stress and shear stress could be established. The maximum shear stress at failure under each applied normal pressure was recorded from each test. This maximum shear stress typically occurred when approximately 10% shear strain was reached during testing. The shear strength $\tau_{max} = C + \sigma_n * \tan\Phi$ (where C is the cohesion intercept, σ_n is the applied normal stress, and Φ is the internal friction angle) expression was then developed for each ballast sample tested at a corresponding fouling fines content and moisture state.

Figure 17 shows the maximum shear stresses predicted under the applied normal stresses during shear box testing. As the applied normal stresses increased, the maximum shear stresses at failure or simply shear strength τ_{max} also increased primarily influenced by the ballast fouling percentage and the moisture condition of the coal dust, i.e., dry or wet at OMC = 35%. As expected, the highest shear strength values were obtained from the clean ballast at all applied normal stress levels. When ballast samples were fouled, the shear strengths typically decreased. For all the samples tested, wet coal dust fouling resulted in lower shear strengths when compared to those obtained from dry coal dust fouling. The lowest shear strength values were recorded for the fouling level of 25% by weight of ballast when wet coal dust filled all the voids at 35% moisture content.

Table 3 shows cohesion intercepts (C) and internal friction angles (from slopes of Mohr-Coulomb envelopes in Figure 17) obtained for the clean and fouled ballast samples. The highest friction angle Φ of 45.6 was achieved for the clean granite. For the case of 25% wet coal dust fouling by weight of ballast, the friction angle computed is as low as 34.5 degrees, which is very close to 33.5 degrees at OMC for the coal dust itself. Similarly, a low cohesion intercept of 5.1 psi (35 kPa) value is close to the very low unconfined compressive strength of 3.5 psi (24 kPa) for the coal dust itself. Therefore, the shearing action in the direct shear apparatus was mainly resisted by the wet coal dust governing the behavior. Again, one should note that 35% OMC condition does not represent fully saturated coal dust state. After soaking or 100% saturation, soil suction would be destroyed thus resulting in fairly lower strengths and unstable ballast conditions.

SUMMARY AND CONCLUSIONS

Mechanical properties of representative coal dust samples obtained from the Powder River Basin (PRB) joint line in Wyoming were determined through laboratory testing at the University of Illinois. From the grain size analysis of the coal dust, material finer than 0.00295 in. (0.075 mm) or No. 200 sieve size was found to be 24%. The specific gravity of the coal dust sample was 1.28. While the fines content of the coal dust was lower than that of most silty and clayey soils, the optimum moisture content (OMC) of the coal dust determined from the standard Proctor compaction test was remarkably higher than that of some of the weak cohesive soils, which highlights its ability to hold much greater amounts of moisture. Likewise, the high liquid limit, LL, and plasticity index, PI, of coal dust, i.e., 91% and 41%, respectively, also underscore its high moisture sensitivity. When subjected to precipitation, coal dust can therefore hold excessive amounts of moisture to prevent free draining of the ballast, i.e., can keep ballast wet and saturated, and act as a lubricant between the ballast stones, enabling much greater movement within the ballast layer.

As for the strength characteristics of the coal dust, the unconfined compressive strength of the coal dust tested was a remarkably low Qu = 3.5 psi (24.1 kPa) at the OMC of 35%. The results of direct shear tests indicated a large reduction in the internal friction angle of the coal dust with increasing moisture content. For instance, the internal friction angle of the coal dust was found as 33.5 degrees at 35% OMC whereas the internal friction angle corresponding to 43% moisture was only 19.2 degrees. Therefore, exposure of coal dust to moisture drastically reduces the friction component of the shear strength and can cause significant reduction in bearing capacity and load carrying ability.

Large-sized direct shear (shear box) laboratory tests were next conducted at the University of Illinois on granite ballast samples also obtained from the Powder River Basin (PRB) joint line in Wyoming to measure strength and deformation characteristics of both clean (new) and fouled ballast aggregates with coal dust at various stages of fouling. The grain size distribution of the aggregate conformed to the typical AREMA No. 24 ballast gradation with a maximum size (D_{max}) of 2.5 in. (63.5 mm) and a minimum size (D_{min}) of 1 in. The coal dust, also obtained from the PRB joint line, was used as the fouling agent and mixed with clean aggregates for achieving fouling levels of 5%, 15%, and 25% by weight of ballast under dry and wet (at 35% OMC) conditions.

From the direct shear tests, the highest shear strength values were obtained from the clean ballast at all applied normal stress levels which were representative of the stress states experienced in the ballast layer under train loading. When ballast samples were fouled, the shear strengths always decreased. Wet (35% OMC) coal dust fouling resulted in lower ballast shear strengths when compared to those obtained from dry coal dust fouling. For the case of 25% wet coal dust fouling by weight of ballast, internal friction angle and cohesion obtained were equivalent to those properties of the coal dust itself at 35% OMC. Therefore, the wet coal dust was governing the ballast behavior as the worst fouling agent for its impact on track substructure and roadbed when compared to even the highly plastic type clayey soil fines. Note that even more drastic strength reductions can be realized when dry coal dust, never been saturated or soaked in the field and therefore having a high suction potential, is subjected to inundation and 100% saturation.

ACKNOWLEDGEMENTS

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Moisture Content (%)	Internal Friction Angle, Φ (Degrees)	tan Φ	Cohesion Intercept, C (psi)
33.00	34.10	0.68	1.11
35.00	33.53	0.66	1.23
37.00	31.83	0.62	1.13
39.00	27.22	0.51	1.07
41.00	21.91	0.40	1.01
43.00	19.23	0.35	0.81

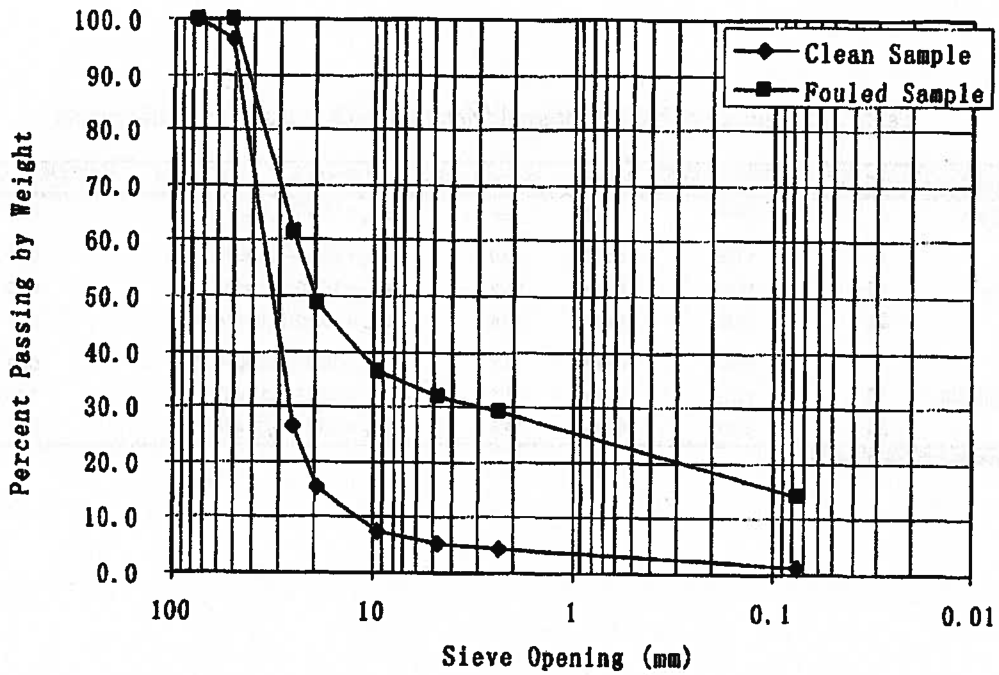
Table 2. Properties of the clean granite aggregate

Granite		
Specific gravity		2.62
Unit weight		93 pcf
Compacted Air Voids		43%
Gradation		
Sieve Size		Percent Passing
in.	mm	%
2.5	63.5	100
2	50.8	82
1.5	38.1	18
1	25.4	0
AREMA		No. 24

Table 3. Summary of ballast internal friction angles and cohesion intercepts

Condition	Fouling % *	Cohesion, c (psi)	ϕ (rad.)	ϕ (deg.)	Max Shear Stress, $\tau_{max} = c + \sigma_N \tan(\phi)$	Regression Coef, R^2
Clean	0	16.24	1.022	45.6	$\tau_{max} = 15.24+\sigma_N \tan(43.9°)$	0.99
	5	13.96	0.991	43.9	$\tau_{max} = 13.96+\sigma_N \tan(43.9°)$	0.99
Dry	15	13.46	0.773	36.2	$\tau_{max} = 13.46+\sigma_N \tan(36.2°)$	0.99
	25	10.90	0.688	36.6	$\tau_{max} = 10.90+\sigma_N \tan(36.6°)$	0.97
	5	8.89	0.963	44.7	$\tau_{max} = 8.89+\sigma_N \tan(44.7°)$	0.99
Wet (OMC)	15	11.12	0.731	37.7	$\tau_{max} = 11.12+\sigma_N \tan(37.7°)$	0.99
	25	5.10	0.744	34.6	$\tau_{max} = 5.102+\sigma_N \tan(34.5°)$	0.97

* percentage by ballast weight



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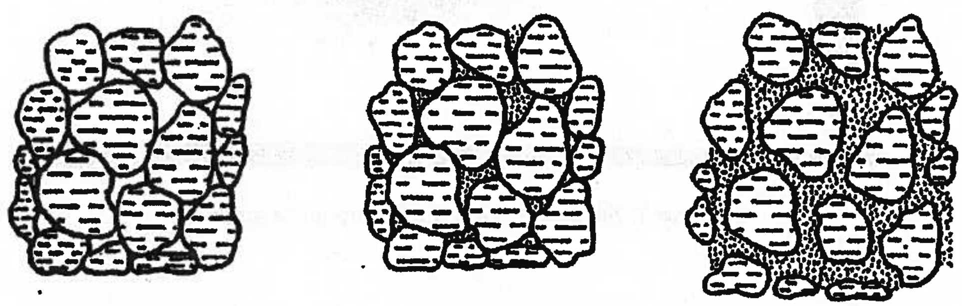
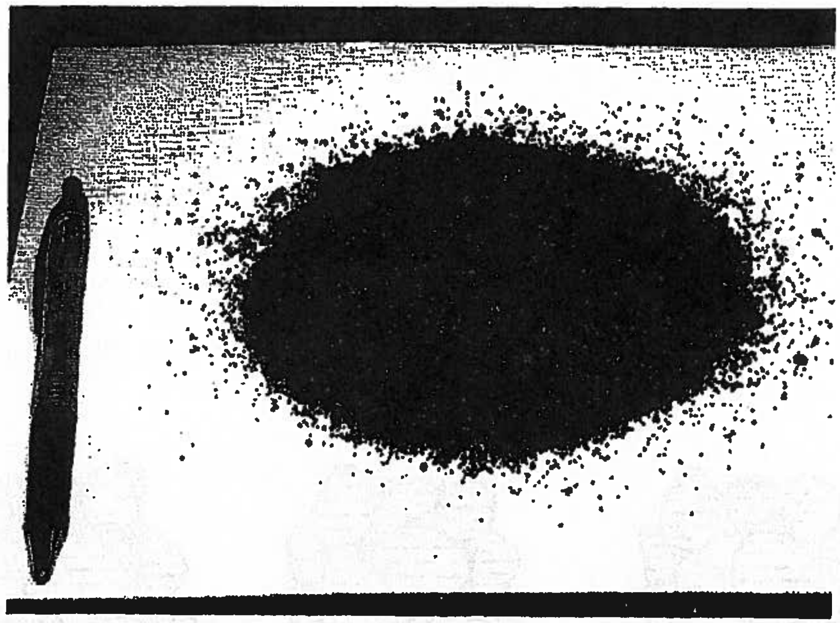


(a) clean ballast

(b) dirty ballast with fine particles filling voids

(c) fouled ballast with aggregate to aggregate contact lost

Figure 2. Critical ballast fouling stages illustrating loss of aggregate to aggregate contact



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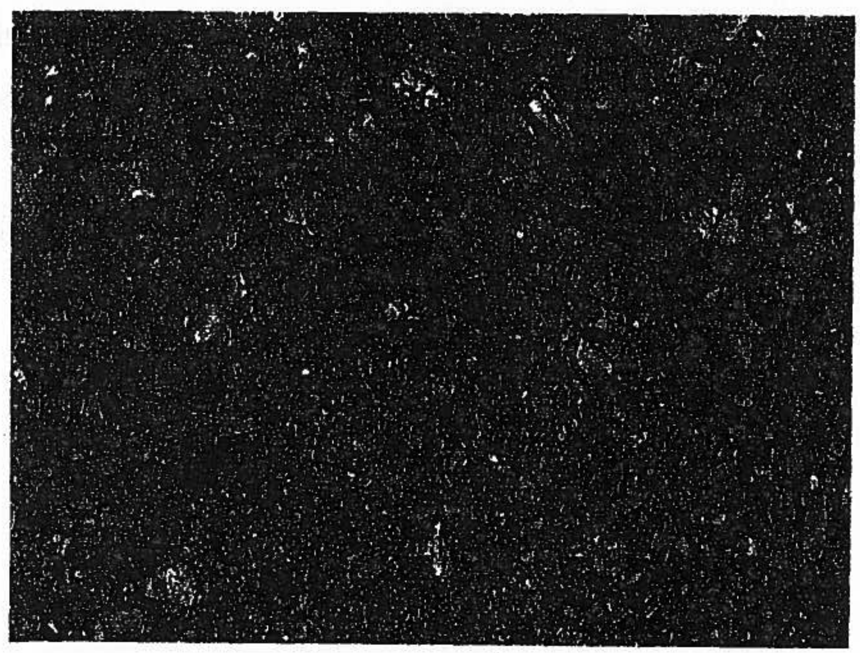

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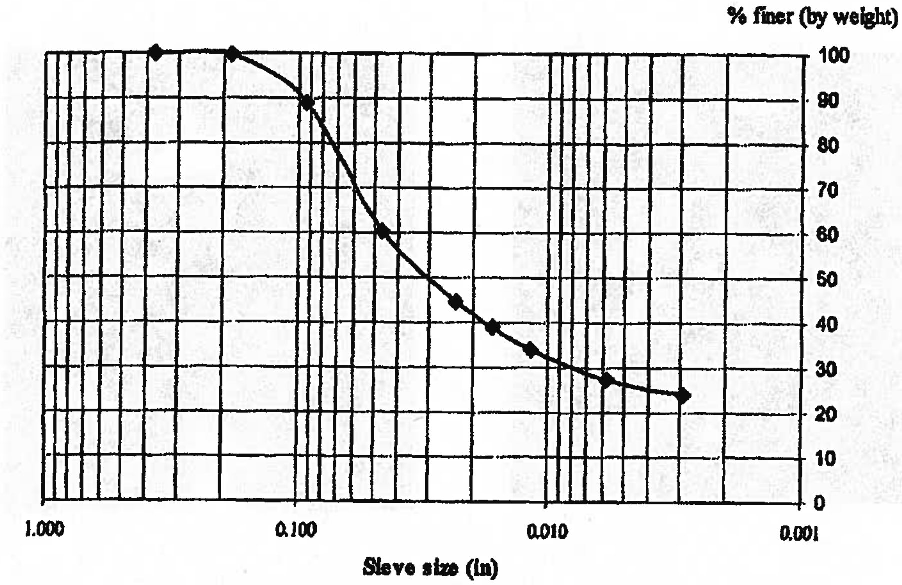

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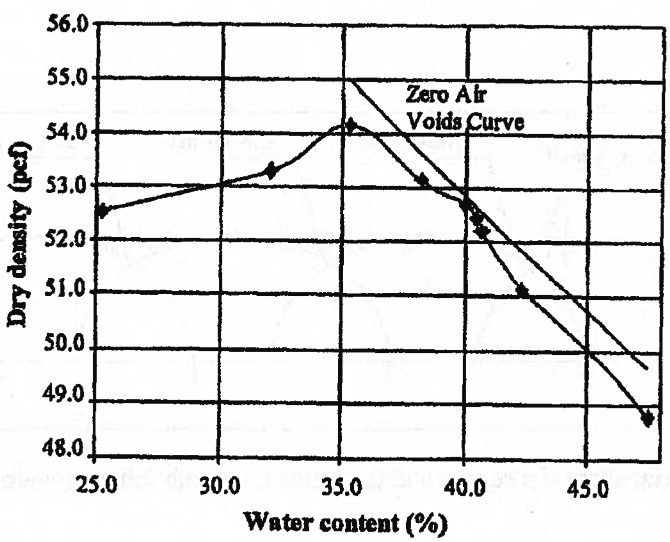

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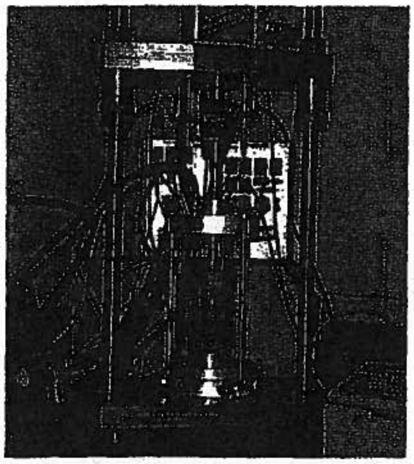

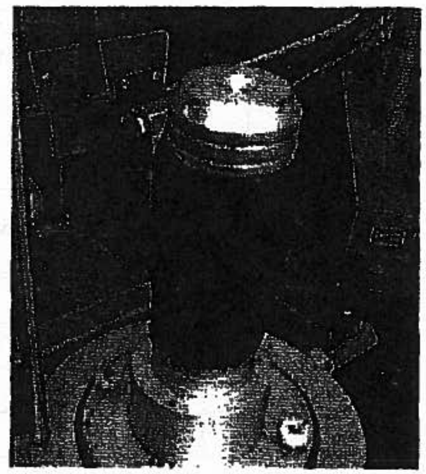

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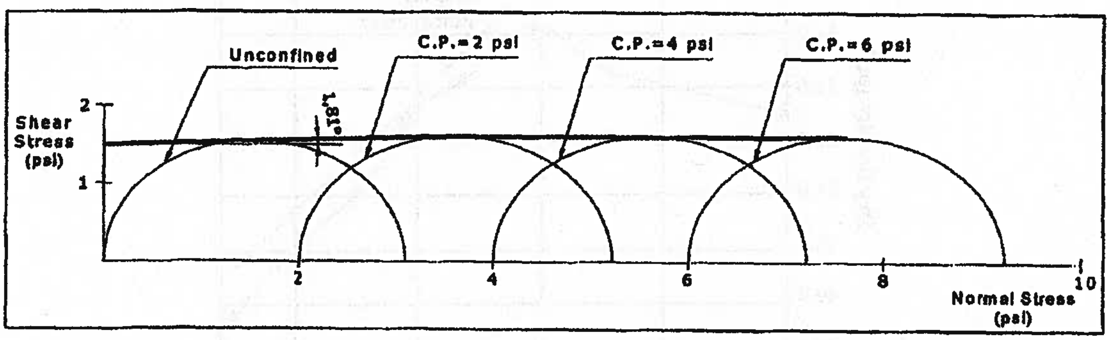

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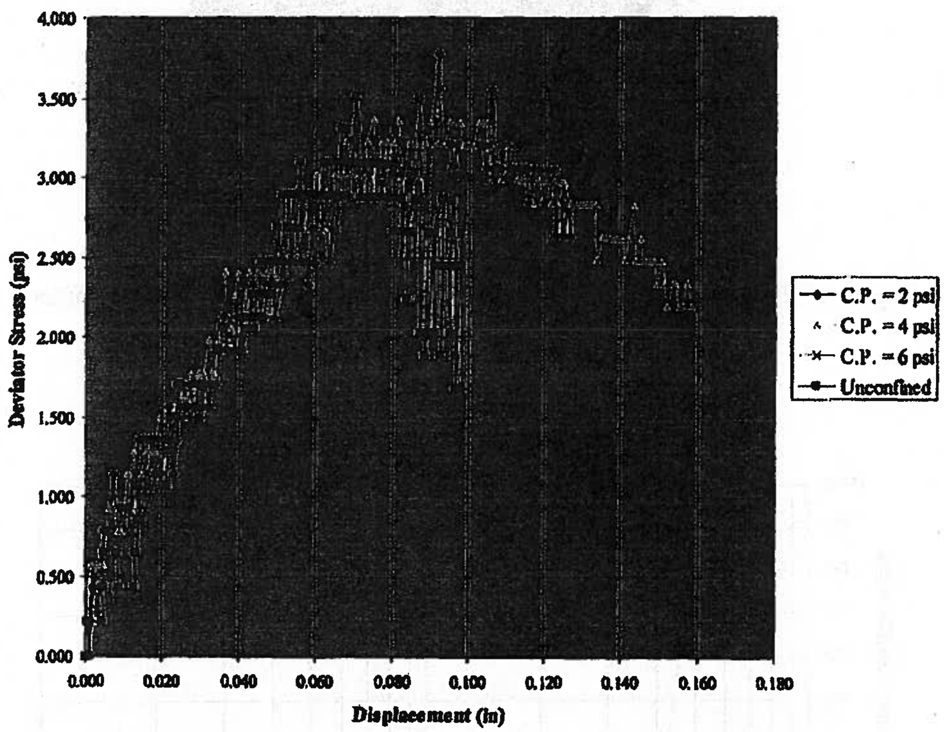

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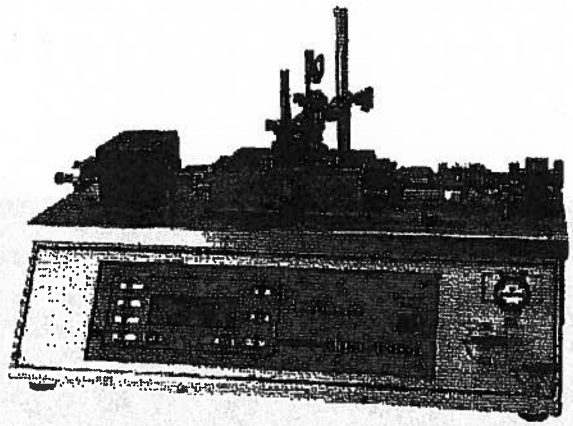

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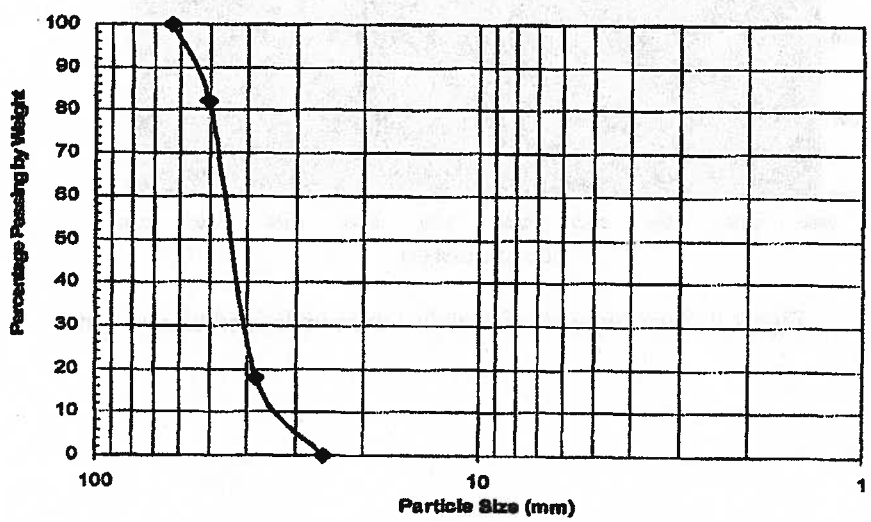

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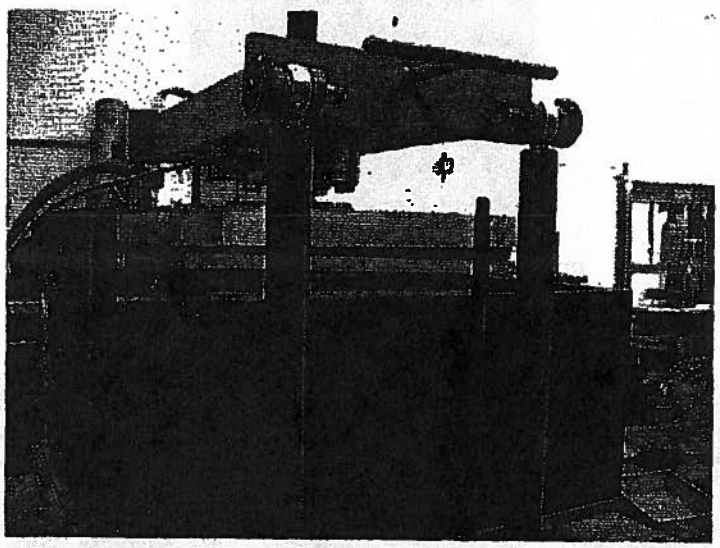

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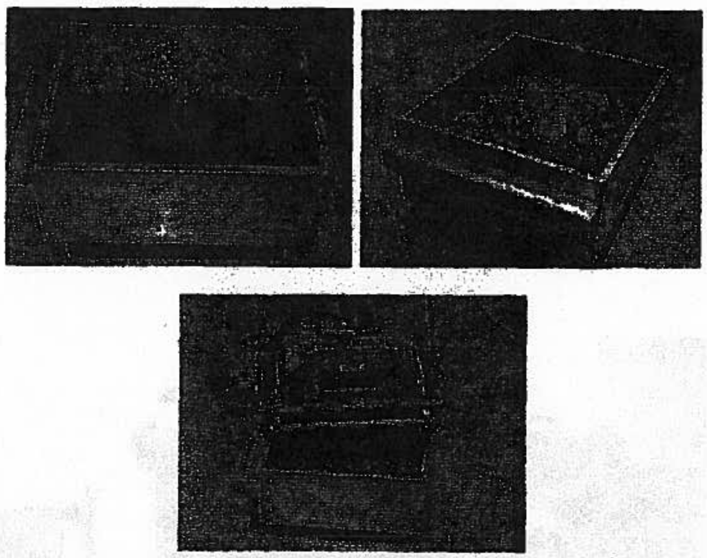

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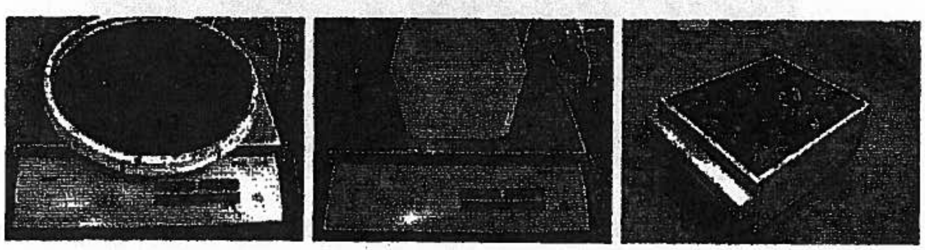

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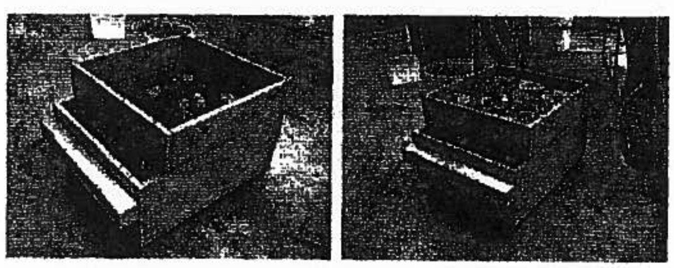

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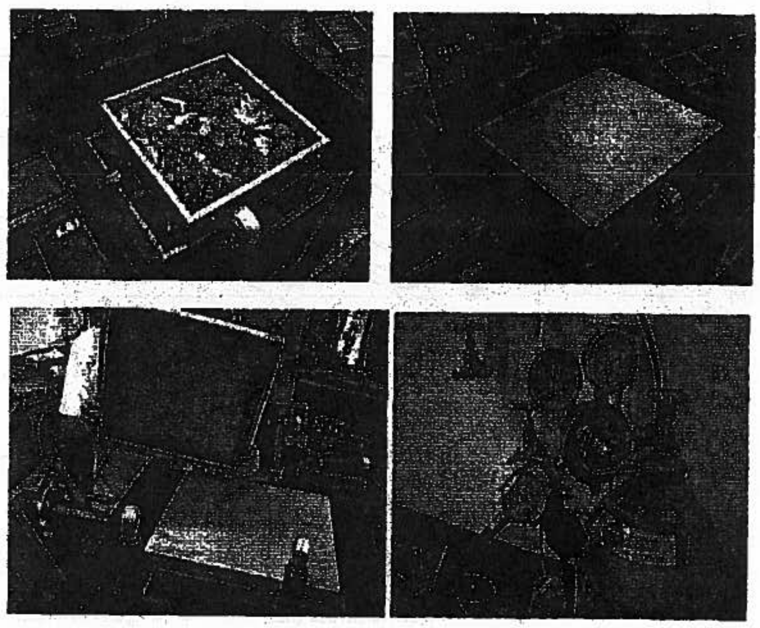

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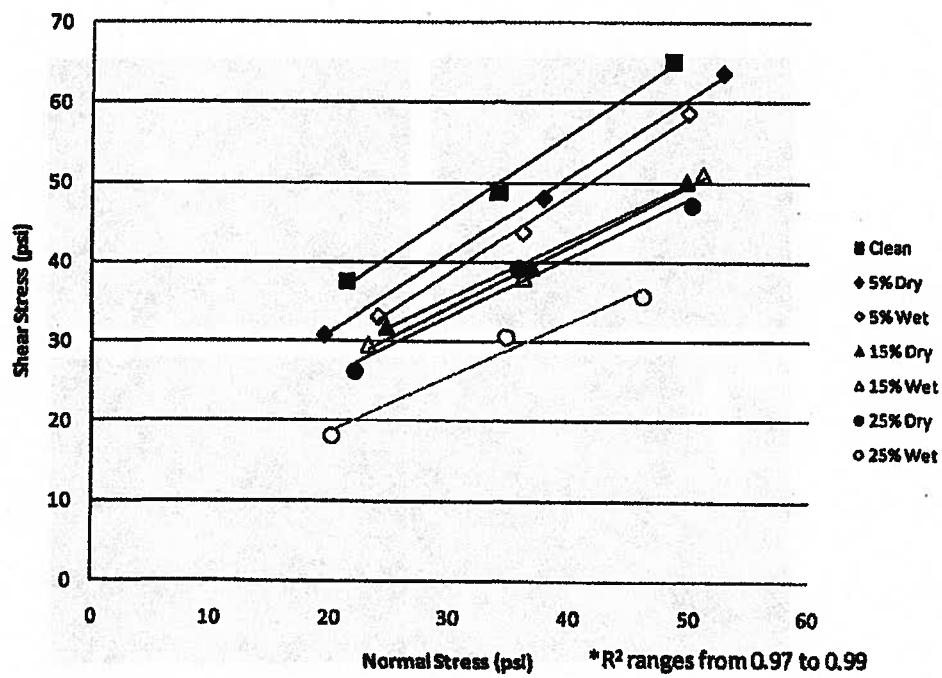

Figure 17. Direct shear box ballast strength test results

EXHIBIT 4

Laboratory Characterization of Fouled Railroad Ballast Behavior

Hai Huang, Erol Tutumluer, and William Dombrow

Fouling refers to the condition of railroad ballast when voids in this unbound aggregate layer are filled with relatively finer materials or fouling agents, which commonly come from breakdown of the ballast aggregate, outside contamination such as coal dust from coal trains, or subgrade soil intrusion. Effects of different fouling agents on ballast aggregate shear strength were studied at the University of Illinois. Through the use of a large direct shear (shear box) device, the strength properties of both clean and fouled ballast samples were determined when three types of fine materials—coal dust, plastic clayey soil, and mineral filler—were added to clean ballast samples at various percentages by weight of ballast under both dry and wet [mostly optimum moisture content (OMC)] conditions. Realistic sample preparation procedures were conducted to closely simulate field-fouling scenarios. Test results showed that when the coal dust fouling percentage increased, the ballast shear strength steadily decreased. Wet fouling was found to exacerbate this trend. Results of ballast samples fouled with clay and mineral filler also showed decreasing trends in strength properties; however, coal dust was by far the worst fouling agent for its impact on track substructure and roadbed. Approximately 15% coal dust fouling by weight of ballast was statistically significant to cause considerable strength reductions. In the case of ballast fully fouled with wet coal dust at 35% OMC, the friction angles obtained were as low as the friction angle of coal dust itself.

Railroad ballast is uniformly graded coarse aggregate placed between and immediately underneath the crossties. The purpose of ballast is to provide drainage and structural support for the loading applied by trains. As ballast ages, it is progressively fouled with materials finer than aggregate particles, filling the void spaces. Methods specifically used to assess track ballast condition deal only with checking visually for evidence of fouling, pumping, and water accumulation (ponding) at ditches and shoulders. Additionally, ballast sampling and testing for fouling through laboratory sieve analyses generally provide some insight into the compositions of the larger aggregate particles and the amount of fines. Nonetheless, for a better evaluation of the serviceability and proper functioning of the existing ballast layer, ballast strength needs to be characterized for different percentages of fine materials, such as plastic soil fines, mineral filler, and more recently coal dust coming from coal trains, which can fill the voids and cause ballast fouling.

Since rail transport, particularly a unit train, provides the most efficient means of transporting bulk commodities such as coal, the role of rail lines in coal transport has always been predominant. In 2005, two derailments occurred in the joint coal line of Burlington Northern Santa Fe (BNSF) and Union Pacific in Powder River Basin (PRB) in Wyoming, the largest source of incremental low-sulfur coal supplies in the United States. The derailments threatened to interrupt the supply of coal to power plants. Both derailments were suspected to be attributed to coal dust fouling, in which coal dust spilled over the ballasts and accumulated moisture, resulting in the loss of strength of the track. The ballast was heavily fouled by coal dust where both of the derailments occurred.

This paper presents findings from a comprehensive laboratory testing program initiated at the University of Illinois to study the effects of different fouling agents—coal dust, plastic clayey soil, and mineral filler—on railroad ballast strength. Using large direct shear (shear box) tests, strength and deformation characteristics of granite type ballast material were investigated for clean ballast and ballast fouled by different agents at various stages under both dry and wet conditions. The shear strength properties, such as cohesion intercept and friction angle, are linked to field ballast fouling levels to better assess the impact of fouling on track instability and ultimately loss of track support, leading to derailments.

BALLAST FOULING AND ITS MECHANISM

Fouling materials in ballast have been traditionally considered not favorable for railroad ballast performance. Early research studies reported that around 70% of the fouling materials were from ballast breakdown (*1–3*). Railroad company internal studies also noted that almost all fouling fines in the railroad track were commonly from aggregate breakdown (*4*). According to Selig and Waters (*5*), ballast breakdown on average accounts for up to 76% of the ballast fouling, followed by 13% infiltration from subballast, 7% infiltration from ballast surface, 3% subgrade intrusion, and 1% due to tie wear.

Selig and Waters (*5*) proposed two indices to describe ballast fouling: (*a*) fouling index is the sum of the percent by weight of ballast sample passing the 4.75 mm (No. 4) sieve plus the percent passing the 0.075 mm (No. 200 sieve) and (*b*) percentage of fouling is the ratio of the dry weight of material passing the 9.5 mm (⅜ in.) sieve to the dry weight of total sample. They also proposed that the particles retained on the 0.075 mm (No. 200 sieve) are treated as "coarse fouling materials" and particles passing the 0.075 mm (No. 200 sieve) are "fine fouling materials" (*5*).

Raymond (*6*) suggested that if fouled ballast had to be used, the liquid limit (LL) of the fines should be less than 25 to maintain the function of drainage. Raymond (*7*) also found that the aggregate breakdown was significantly influenced by the type and especially hardness of the mineral aggregate. Harder aggregates had fewer breakdowns than softer aggregates did. Later, Raymond (*8*) noted

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that the wear of tie was more significant at the worst fouled track locations, possibly due to the abrasive effects of the slurry formed by fouling fines and water.

Chiang (*9*) conducted a series of ballast box repeated loading tests on fouled ballast. Test results indicated that ballast settlement typically increased as the amount of fouling material in ballast increased. Similarly, Han and Selig (*10*) conducted ballast box tests to evaluate the impact of fouling on ballast settlement. They concluded that the degree of ballast fouling indeed had a major impact on the ballast settlement. With an increase in the percentage fouling, both the initial and final ballast settlements increased significantly. Investigations on the strength of fouled ballast and studies on the fouling mechanism, however, have been somewhat limited.

In terms of the stability and load carrying ability of the fouled ballast layer, three volumetric phases can be identified for the different conditions of fine materials filling the void space (Figure 1). Phase I shows a clean or very slightly fouled ballast sample with almost all aggregates establishing contact with each other at the aggregate surface to sufficiently carry the load (Figure 1*a*). As shown in Figure 1*b*, Phase II will have the voids in between aggregates filled with enough fine particles to significantly reduce the strength; however, aggregate-to-aggregate contact is maintained. In a Phase III fouled ballast condition, because of the excessive amount of fine particles, aggregate-to-aggregate contacts are mostly eliminated, and the aggregate particle movements are then constrained only by the fine particles filling the matrix or voids between the particles (Figure 1*c*).

Because ballast in Phase III is no doubt unacceptable and needs immediate remedial action, ballast in Phases I and II is particularly worth studying from the aspect of how different fouling agents at different phases would affect ballast strength and therefore track stability. It is also of great importance to know the dividing line between Phase I and II because it is also the suggested starting point of maintenance activities, such as ballast cleaning. Hypothetically, if ballast aggregate particles are assumed to be spheres, it is possible to define the maximum size of the fouling materials through three-dimensional packing order computations for large and small spheres. Accordingly, Equation 1 defines the radius r of a single fouling particle approximated as a sphere to fit in between three large contacting spherical particles, each having a radius R, without separating them.

$$r=\left(\sqrt{\frac{32}{27}}-1\right)R \qquad (1)$$

Considering that the maximum size of ballast aggregates is often limited to $2R = 76$ mm (3 in.), the largest diameter of a single fouling particle can then be 6.7 mm (0.26 in.), which is smaller than the 9.5 mm (⅜ in.) suggested by Selig and Waters (*5*).

CLEAN AND FOULED BALLAST STRENGTH BEHAVIOR

Materials Tested

The ballast material tested was a granite aggregate obtained from Gillette, Wyoming, and commonly used in the PRB joint line railroad track structures as the ballast layer. Figure 2 shows the grain size distribution of the granite sample with a specific gravity of 2.62 tested in compliance with ASTM C117 test procedure. The granite aggregate size distribution conforms to the typical American Railway Engineering and Maintenance-of-Way Association (AREMA) No. 24 ballast gradation having a maximum size (D_{max}) of 63.5 mm (2.5 in.), a minimum size (D_{min}) of 25.4 mm (1 in.), and an average particle size corresponding to 50% passing by weight (D_{50}) of approximately 45 mm (1.77 in.).

From the average size of the clean ballast (45 mm), an average particle fouling size of 4 mm was chosen in this study based on Equation 1. Accordingly, the three types of fouling materials studied with this granite type ballast aggregate were coal dust, refractory clay representing a cohesive fine-grained subgrade soil, and mineral filler obtained from the crushing operations of the same granite aggregate. Figure 2 shows the typical gradations and Table 1 lists the engineering properties of these fouling materials with the moisture density information obtained from the standard Proctor ASTM D 698 test procedure. The coal dust sample tested in this study was also collected from the PRB Orin Line, Milepost 62.4, and was sampled March 10, 2007.

Testing Apparatus

Direct shear strength tests were performed on the reconstituted clean and fouled granite aggregate samples. Figure 3 shows the large shear box equipment used for testing at the University of Illinois. The test device is a square box with side dimensions of 305 mm (12 in.) and a specimen height of 203 mm (8 in.). It has a total 102-mm (4-in.) travel of the bottom 152-mm (6-in.) high component, which is large enough for ballast testing purposes to record peak shear stresses. The vertical (normal direction) and horizontal load cells are capable of

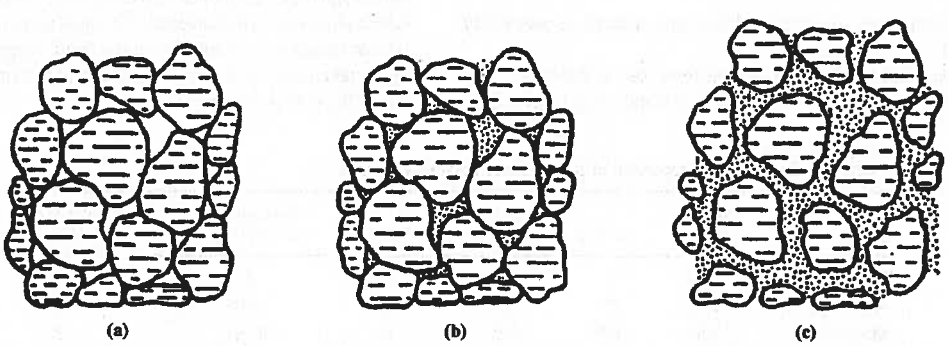

FIGURE 1 Critical ballast fouling phases: (*a*) clean ballast (Phase I), (*b*) partially fouled ballast (Phase II), and (*c*) heavily fouled ballast (Phase III).

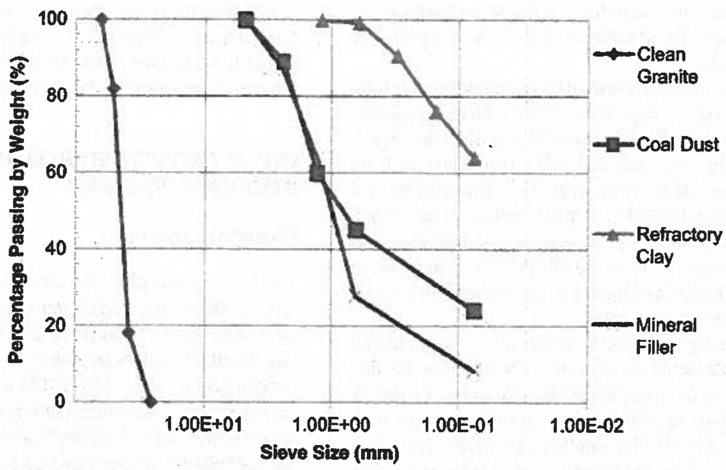

FIGURE 2 Grain size distributions of the clean ballast and fouling materials.

applying and recording up to 50-kN load magnitudes. The device controls and the data collection are managed through an automated data acquisition system controlled by the operator through a built-in display, and the test data are saved on a personal computer.

Sample Preparation

Clean ballast samples were prepared in the lower shear box to the condition similar to the field according to the following steps:

1. Place aggregates in the lower box by lifts (usually two 76-mm lifts).
2. For each lift, use vibratory compactor on top of a flat Plexiglas compaction platform and compact until no noticeable movement of particles is observed (Figure 4).
3. Record the weight of aggregate used.
4. Place upper ring (76 mm high) on top of lower box. Align ring with sides and back edge of box (opposite of block); fill with single lift of ballast and compact (Figure 4).

Granite ballast samples fouled by coal dust were prepared in a manner similar to the clean sample procedure by spreading coal dust on the ballast surface and spraying water, if needed. The individual steps are as follows:

1. Obtain clean aggregates of the same weight as previously recorded.
2. Compact ballast sample into the lower box in two lifts.
3. Obtain prescribed weight of coal dust and water (Figure 5).
4. Spread coal dust over compacted ballast evenly in two lifts (half of material each lift). Shake down material using vibratory compactor after each lift. If test is conducted with wet fouling material [for example, at the optimum moisture content (OMC)], pour proportional amount of water over ballast after shakedown of each lift (Figure 5). Note that this preparation procedure realistically simulated the actual coal dust accumulation in the ballast layer as a result of vibration caused by train loading.
5. Follow Step 4 from the clean sample preparation procedure.

Granite samples fouled with clay were prepared following a different procedure to simulate subgrade intrusion. The individual steps are as follows:

1. Obtain clean aggregates of the same weight as previously recorded.
2. Obtain described weight of clay and water.
3. Place the clay in the bottom of the lower box. If test is conducted with wet clay, thoroughly mix clay with water before placing in the lower box.
4. Place aggregates over the clay and compact in two lifts.
5. Follow Step 4 from the clean sample preparation procedure.

For preparing granite samples fouled with mineral filler, the clean ballast and the mineral filler with designated weights were premixed before placement in the lower box. The goal was to simulate the actual ballast breakdown conditions in the field. Aggregate breakdown could take place with chipped pieces and mineral filler uniformly filling the voids in the ballast layer.

TABLE 1 Engineering Properties of the Selected Fouling Materials

	Specific Gravity	LL (%)	Plastic Limit (%)	OMC[a,b] (%)	Maximum Dry Density[b] (kg/m³)	Passing 0.075-mm or No. 200 Sieve (%)
Coal dust	1.28	91	50	35	874	24
Refractory clay	2.60	37	19	16	1,806	64
Mineral filler	2.62	NP[c]	NP[c]	11	2,193	8

[a]OMC = optimum moisture content.
[b]Obtained from standard Proctor ASTM D698 test procedure.
[c]NP = nonplastic.

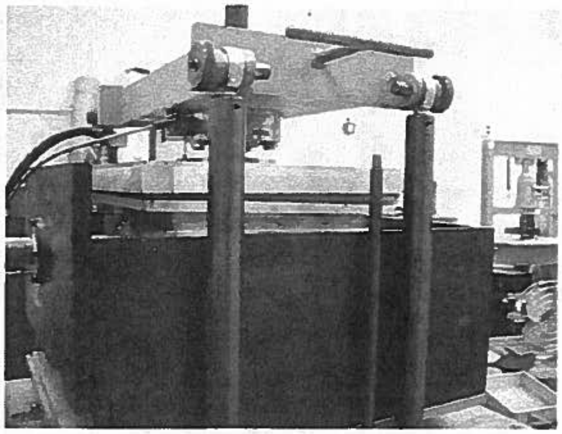

FIGURE 3 Direct shear strength test equipment at the University of Illinois.

Before testing, the box and ring assembly were placed in the shearing apparatus. The lower box was clamped in place, and the load-bearing plate was placed on the ballast but inside the upper ring. The air bladder was placed on the load-bearing plate, the air supply was opened, and normal pressure was set using an in-line pressure regulator (Figure 6). The load cell recording the applied shear force was adjusted directly against the upper ring. The Labview data logger software was initiated to record normal and shear forces during testing. The loading speed was set to an input shear rate of 12.2 mm/min (0.48 in./min), which is approximately 4% strain per minute, and the tests were run until the shear force output peaked or 15% strain occurred.

Sample Volumetrics

After the sample preparation, volumetric properties of the shear box sample were calculated on the basis of the granite aggregate properties. It is worth noting that, for all tests, the same amount of

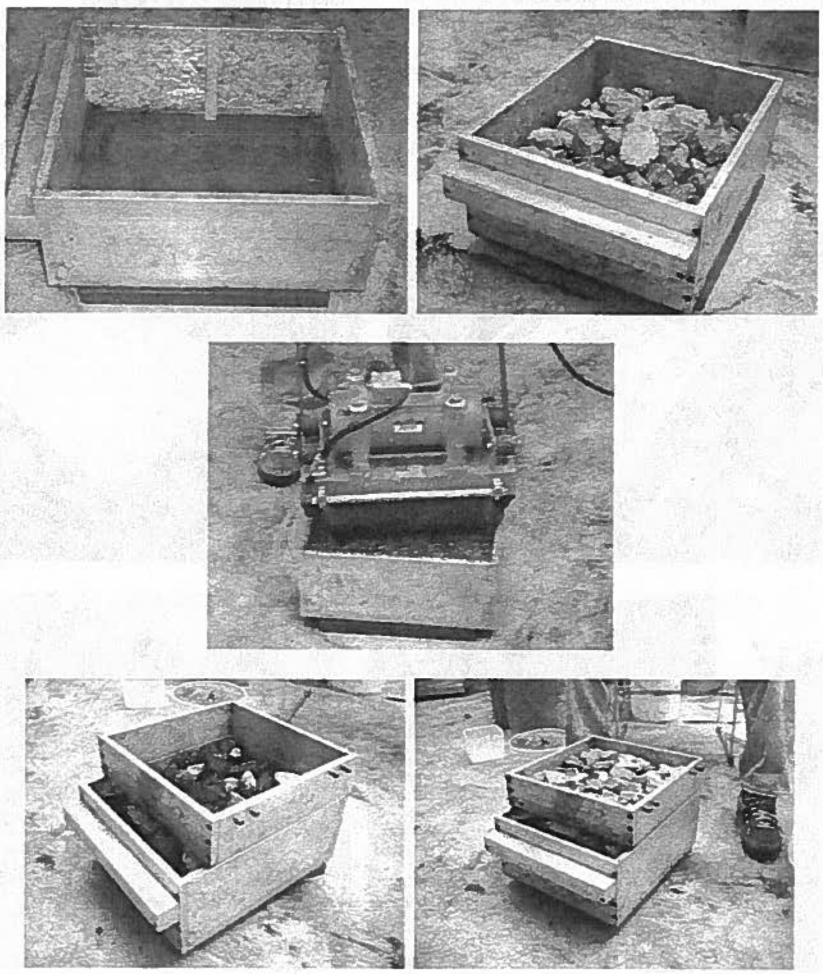

FIGURE 4 Stages of ballast compaction and upper ring loading.

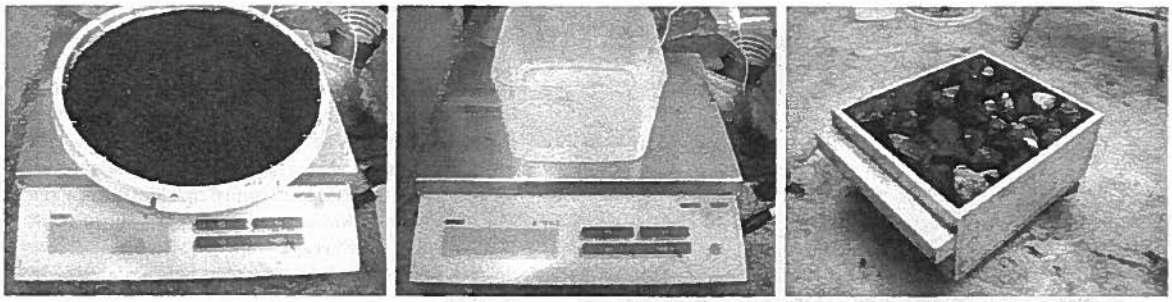

FIGURE 5 Coal dust being mixed as the fouling material.

material was used to prepare approximately the same number of aggregate contacts and a similar aggregate skeleton. That is, the voids available for fouling material to fill in were kept the same in all cases. This void space was found for the clean granite sample to be 43% of the total volume, which corresponds to a void ratio of 0.75 or 75% of the aggregate volume. ASTM C29 test procedure was used for finding porosity or air voids with the known values of the specific gravity and box volume and the weight of ballast compacted.

For the aggregate fouled with coal dust, 25% coal dust by weight of aggregate was found to completely fill in the voids of the clean granite, thus referred to here as "fully coal dust fouled" condition after sample preparation. Similarly, 32% clay by weight of aggregate and 40% mineral filler by weight of aggregate were observed to completely fill in the same void space of the clean granite for the fully fouled conditions for clay and mineral filler, respectively.

Direct Shear Test Results

The ballast samples were sheared horizontally in the shear box under target normal pressures of 172, 241, and 310 kPa (25, 35, and 45 psi), typical ballast layer confining pressures, so that the relationships between normal stress and shear stress could be established. The maximum shear stress at failure under each applied normal pressure

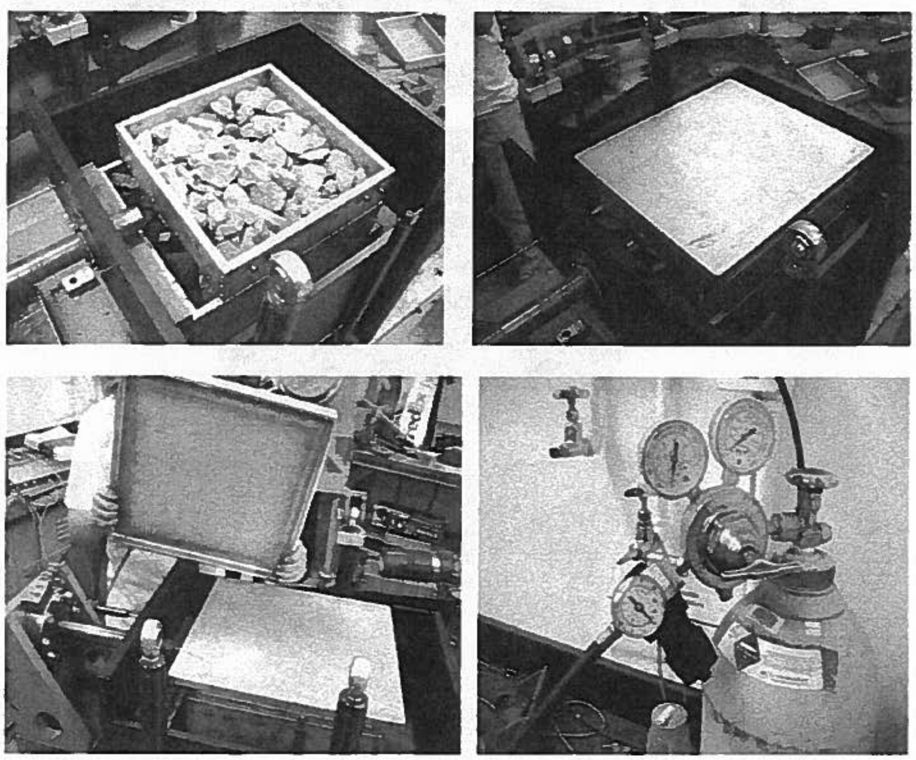

FIGURE 6 Setup of the direct shear box apparatus.

was recorded from each test. This maximum shear stress typically occurred when approximately 10% shear strain was reached during testing. The shear strength expression $\tau_{max} = C + \sigma_n * \tan\Phi$ (where C is the cohesion intercept, σ_n is the applied normal stress, and Φ is the internal friction angle) was then developed for each ballast sample tested at a corresponding fouling fines content and moisture state.

Figure 7 shows the maximum shear stresses predicted under the applied normal stresses during shear box testing for coal dust fouling in comparison with the clean granite test results. As the applied normal stresses increased, the maximum shear stresses at failure or simply shear strength τ_{max} also increased, primarily influenced by the ballast fouling percentage and the moisture condition of the coal dust (i.e., dry or wet at OMC = 35%). As expected, the highest shear strength values were obtained from the clean ballast at all applied normal stress levels. When ballast samples were fouled, the shear strengths typically decreased. For all the samples tested, fouling with wet coal dust resulted in lower shear strengths when compared with those obtained from fouling with dry coal dust. The lowest shear strength values were recorded for the fouling level of 25% by weight (fully fouled) of ballast when wet coal dust was at 35% moisture content.

Figure 8 shows the maximum shear stresses predicted under the applied normal stresses during shear box testing for clay fouling in comparison with the clean granite test results. Limited data were obtained because of the difficulties encountered during sample preparation, especially for wet clay fouling. According to the test results, the clean ballast sample still gave the highest strength. With clay being the fouling agent, the trend of decreasing strength with increasing fouling percentage could not be observed as clearly as in the case of coal dust fouling. In the clay fouling cases, the cohesion intercept (C) in the strength equation increased and the friction angle (Φ) typically decreased with the increasing fouling percentage, which made shear strength of samples less sensitive to varying normal stresses and confining pressures, as expected. This effect was even more significant in the cases fouled with wet clay, because wet clay served as a lubricant, with much lower friction angles (Φ) overall compared with the clean granite sample. It still makes sense, however, since the cohesion increased because the clay paste in the voids supplied some bonding strength, whereas the friction angle decreased because of the lubricating effect of clay paste within the aggregate-to-aggregate contact.

Figure 9 shows the maximum shear stresses predicted under the applied normal stresses during shear box testing for mineral filler fouling in comparison with the clean granite test results. In the dry case, results were similar to results from clay fouling. Once again, the clean ballast sample gave the highest shear strength. In the dry fouling cases, the cohesion intercept (C) in the strength equation increased and the friction angle (Φ) typically decreased with the increasing fouling percentage, similar to the general trend observed for samples fouled with clay. However, for the wet mineral filler tests at only 11% OMC, samples at all fouling levels behaved very closely to dry conditions, with the data points almost falling in the same line, thus indicating that mineral filler as a fouling agent is not as sensitive to moisture as the cohesive clay.

Figure 10 compares, under wet conditions, the maximum shear stresses obtained from the clean granite with those of the coal dust, clay, and mineral filler fouled samples at 5%, 15%, and 25% by weight of ballast. Note that for the 25% clay fouled samples, clay moisture content was at the LL of 37% instead of OMC, which is very close to 35% OMC of the samples fouled by coal dust. Yet, the wet coal dust sample fouled at 25% gave the worst-case scenario with the lowest shear stress values among all the samples tested. Then came the wet mineral filler fouled at 25% by weight of ballast and the wet clay fouled at 15% by weight of ballast, as indicated with the dashed lines in Figure 10. This implies that railroad ballast layers fouled with coal dust are at much higher risk of causing track instability and failures, especially after heavy precipitation, when compared with ballasts fouled because of mineral filler accumulation from aggregate breakdown or even cohesive subgrade soil intrusion.

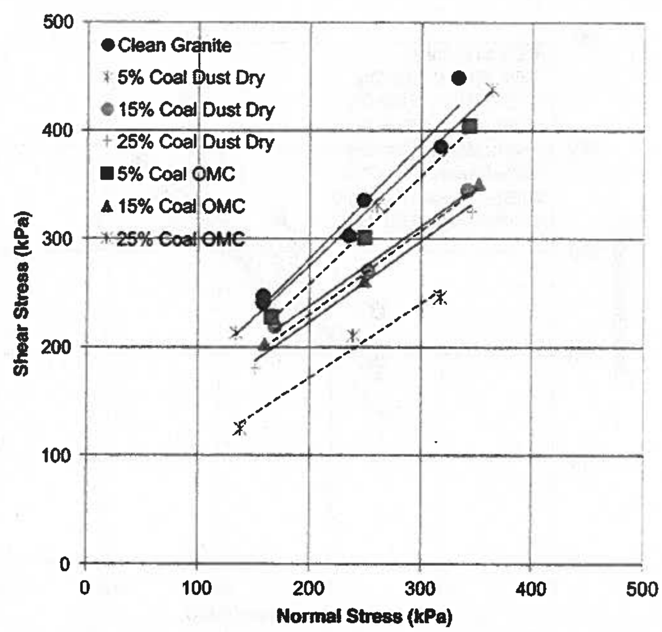

FIGURE 7 Direct shear box test results of ballast samples fouled with coal dust.

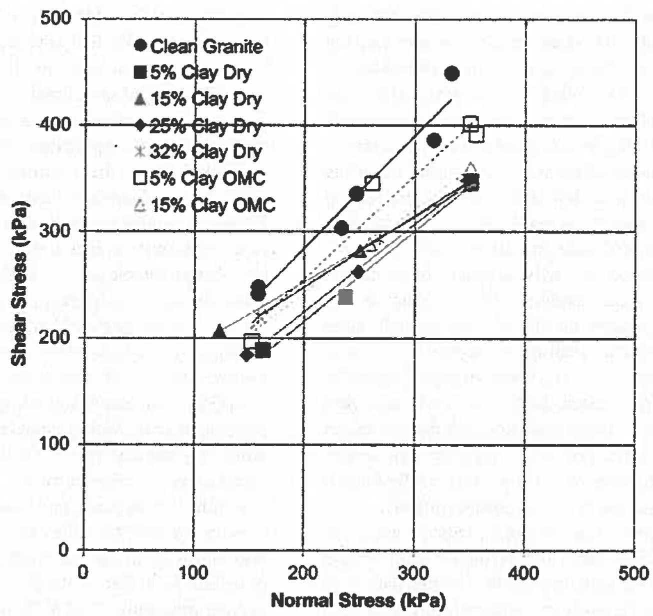

FIGURE 8 Direct shear box test results of ballast samples fouled with clay.

Because the coal dust fouling was found to be the most detrimental case, a statistical analysis was performed for the significance of the different coal dust levels affecting the critical stages of ballast fouling. As described early in this paper, it is important to determine at what fouling level a significant drop in strength would be realized. That is, there is a need to determine the reasonable dividing line between Phase I and II. For this purpose, an F-test statistical approach was used to evaluate the differences between the strength lines graphed in Figure 7. With a value of significance (p-value) of 0.0014 (much less than 0.05), 15% coal dust fouling was found to significantly decrease the strength of ballast. Because all other strength lines in Figure 7 are below the 15% dry coal dust fouling line, 15% coal dust by weight is considered to be the critical stage of coal dust fouling in terms of ballast shear strength.

Table 2 lists cohesion intercepts (C) and friction angles (Φ) obtained from the ballast testing program. High correlation coefficients, R^2

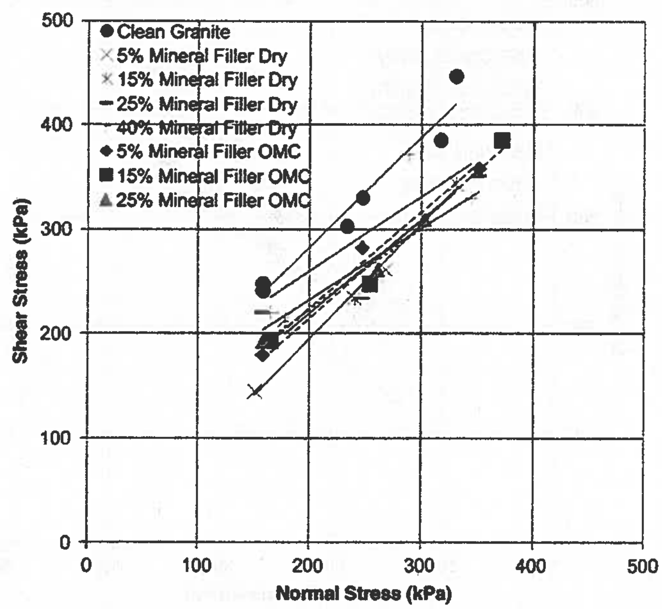

FIGURE 9 Direct shear box test results of ballast samples fouled with mineral filler.

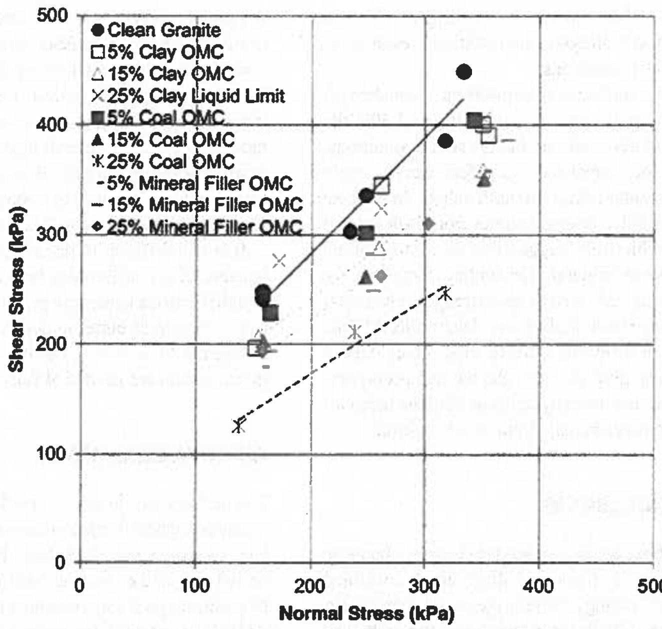

FIGURE 10 Comparisons of three fouling scenarios under wet conditions.

values, were typically obtained for the established shear strength equations except for two mineral filler samples. The clean granite typically had the highest friction angle (Φ) of 46.6°, except for the friction angle of 47.7° obtained for the low 5% dry mineral filler sample. For the case of 25% wet coal dust fouling, the friction angle computed is as low as 34.5°. This value is very close to the friction angle of 33.5°, obtained from a parallel research study (*11*), for the pure coal dust direct shear samples tested at OMC. Similarly, a low cohesion intercept of 35 kPa (5.1 psi) is close to the very low unconfined compressive strength of 24 kPa (3.5 psi) also obtained for the coal dust shear strength properties (*11*). This implies that the shearing action for the 25% coal dust fouled sample was mainly resisted in the direct shear apparatus by the wet coal dust governing the behavior. Again, one should note that 35% OMC condition does not

TABLE 2 Shear Box Direct Shear Strength Test Results

			$\tau_{max} = C + \sigma_n * \tan \Phi$			Shear Strength τ_{max} (kPa)	
Fouling Agent	Percentage by Weight of Clean Ballast	Moisture Condition (see Table 1)	Cohesion C (kPa)	Friction Angle (Φ)	Correlation Coefficient, R^2	200-kPa Normal Stress	300-kPa Normal Stress
Clean	0	Dry	72	46.6	.96	283	389
Coal dust	5	Dry	80	44.4	.99	276	374
	15	Dry	93	36.2	.99	239	312
	25	Dry	75	36.6	.98	224	298
	5	OMC	61	44.7	.99	259	359
	15	OMC	77	37.7	.99	231	309
	25	OMC	35	34.5	.97	173	242
Clay	5	Dry	44	40.5	.99	215	300
	15	Dry	131	31.2	.99	252	313
	25	Dry	59	39.5	.99	224	307
	32	Dry	114	33.7	.97	247	314
	5	OMC	61	44.1	.95	255	352
	15	OMC	85	38.0	.99	241	319
	25	LL	144	36.1	.98	290	363
Mineral filler	5	Dry	0	47.7	.99	195	305
	15	Dry	41	41.6	.93	219	308
	25	Dry	94	34.6	.85	232	301
	40	Dry	116	35.7	.71	260	332
	5	OMC	40	42.6	.98	224	316
	15	OMC	26	43.4	.97	215	309
	25	OMC	66	38.0	.98	222	300

represent a fully saturated coal dust state. After soaking or 100% saturation, soil suction would be destroyed, thus resulting in even lower strengths and unstable ballast conditions.

Table 2 also lists for direct comparison purposes the shear strength values computed under normal stress levels of 200 and 300 kPa (29.0 and 43.5 psi), typical field railroad ballast stress conditions. Most of the trends already mentioned and their effects can be clearly seen by comparing the computed shear strength values. In the case of ballast fouled by mineral filler, strength values from both dry and wet tests were very close, which may suggest that the 11% optimum moisture had a minor effect on mineral filler fouling. However, the clay fouled ballast samples at OMC give higher strength values than the dry clay fouled samples, which implies that clayey soils at OMC have higher shear strength properties. Since most geomaterials compacted at OMC usually give the best mechanical properties, future research will need to also investigate fouled ballast behavior when moisture content increases beyond optimum conditions.

SUMMARY AND CONCLUSIONS

A large direct shear (shear box) device was used to conduct laboratory tests at the University of Illinois on granite ballast samples obtained from the PRB joint line in Wyoming. The tests measured strength and deformation characteristics of both clean (new) and fouled ballast aggregates with three different fouling agents—coal dust also obtained from the PRB joint line, plastic clay, and nonplastic mineral filler obtained by crushing the same granite aggregate—at various stages of fouling. The grain size distribution of the aggregate conformed to the typical AREMA No. 24 ballast gradation with a maximum size (D_{max}) of 63.5 mm (2.5 in.) and a minimum size (D_{min}) of 25.4 mm (1 in.). Each fouling material was mixed with clean aggregates for achieving fouling levels of 5%, 15%, 25%, and sometimes up to 40% by weight of ballast under dry and wet, mostly OMC, conditions. The coal dust material was spread on the clean aggregate specimen and vibrated on top to achieve its percolation into the voids in an effort to realistically simulate coal dust falling off trains into the ballast layer in the field. The plastic refractory clay and the mineral filler were mixed with granite aggregates by means of different sample preparation techniques, again to simulate realistic field-fouling scenarios of subgrade intrusion and aggregate breakdown, respectively.

From the direct shear tests, the highest shear strength values were obtained from the clean ballast samples at all applied normal stress levels, which were representative of typical stress states experienced in the ballast layer under train loading. When ballast samples were fouled, the shear strengths always decreased. This result was mostly apparent with lower friction angles and cohesion intercepts. Wet fouling generally resulted in lower ballast shear strengths when compared with those obtained from fouling with dry coal dust. Primarily because of increasing cohesive nature (i.e., cohesion intercepts) with increasing fouling percentages, plastic refractory clay fouled samples exhibited slight increases in shear strength under both dry and wet conditions. However, samples fouled with mineral filler at 5%, 15%, and 25% were somewhat insensitive to the low 11% moisture content increase from the dry condition and resulted in similar shear strength values.

Coal dust was by far the worst fouling agent for its impact on track substructure and roadbed, and it caused the most drastic decreases in shear strength, especially at high fouling levels. Through statistical evaluation, 15% dry coal dust fouling by weight of ballast was shown to be sufficiently significant to cause critical fouling and decrease considerably the ballast strength. For the case of 25% wet coal dust fouling by weight of ballast, the lowest shear strength properties, internal friction angle and cohesion, obtained were equivalent to those properties of the coal dust itself at 35% OMC. Note that even more drastic strength reductions can occur when dry coal dust, which has never been saturated or soaked in the field and therefore has a high suction potential, is subjected to inundation and 100% saturation.

It is still difficult to make unique conclusions on ballast fouling because of the differences between laboratory and field conditions and difficulties in sample preparation process. This study is a first step of trying to better understand fouling and its effect on ballast strength and stability. Further studies and different methods of investigation are needed to fully understand ballast fouling.

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