Year	Title	Author(s)
2009	Evaluation of Fatigue (Alligator) Cracking in the LTPP SPS-6 Experiment	Rahim, A. M; Fiegel, G; Ghuzlan, K.
2009	Automation of Pavement Sublayer Moisture Content Determination Using LTPP Time Domain Reflectometry Data and Micromechanics	Lee, Sang Ick; Zollinger, Dan G; Lytton, Robert Leonard; Jackson, Newton C. P.
2009	Effects of Design and Site Factors on Roughness Development in Flexible Pavements	Haider, Syed Waqar; Chatti, Karim
2009	Consideration of Climate in New AASHTO Mechanistic-Empirical Pavement Design Guide	Zapata, Claudia E.
2009	Early-Life, Long-Term, and Seasonal Variations in Skid Resistance in Flexible and Rigid Pavements	Ahammed, Mohammad Alauddin; Tighe, Susan L.
2009	Predicting Low Design Temperatures of Asphalt Pavements in Dry Freeze Regions Using Solar Radiation, Transient Heat Transfer, and Finite Element Method	Ho, Chun-Hsing; Romero, Pedro
2008	LTPP Computed Parameter: Frost Penetration	Selezneva, Olga I; Jiang, Y J; Larson, G; Puzin, Tara
2008	Simplified Model to Predict Frost Penetration for Manitoba Soils	Soliman, H; Kass, S; Fleury, N.
2008	Temperature and Precipitation Sensitivity Analysis on Pavement Performance	Smith, James Trevor; Tighe, Susan L; Andrey, Jean C; Mills, Brian
2008	LTPP Computed Parameter: Moisture Content	Zollinger, Dan G; Lee, Sang Ick; Puccinelli, Jason; Jackson, Newton C.
2008	Calibration and Validation of the Enhanced Integrated Climatic Model for Pavement Design	Zapata, Claudia E; Houston, William N.
2008	Evaluating Climate Change Impact on Low-Volume Roads in Southern Canada	Tighe, Susan L; Smith, James Trevor; Mills, Brian; Andrey, Jean C.
2008	Long Term Pavement Performance Computed Parameter: Moisture Content	Zollinger, Dan G; Lee, Sang Ick; Puccinelli, Jason; Jackson, Newton C.
2007	Development of Pavement Performance Models to Account for Frost Effects and Their Application to Mechanistic-Empirical Design	Puccinelli, Jason; Jackson, Newton C.
2007	Evaluation of Pavement Performance on DEL-23	Sargand, Shad M; Edwards, William F.
2006	Analysis of Variations of Pavement Subgrade Soil Water Content	Heydinger, Andrew G; Davies, B.O.A.
2006	Effects of Multiple Freeze Cycles and Deep Frost Penetration on Pavement Performance and Cost	Jackson, N; Puccinelli, J.

2006	Effect of Design and Site Factors on Long-Term Performance of Flexible Pavements in SPS-1 Experiment	Chatti, Karim
2006	Effects of Design and Site Factors on Roughness of Flexible Pavements in the LTPP SPS-1 Experiment	Haider, Syed Waqar; Chatti, Karim
2006	Effects of Multiple Freeze Cycles and Deep Frost Penetration on Pavement Performance and Cost	Jackson, N.; Puccinelli, J
2006	Investigations of Environmental and Traffic Impacts on "Mechanistic-Empirical Pavement Design Guide" Predictions	Zaghloul, Sameh et al
2006	Observed Effects of Subgrade Moisture on Longitudinal Profile	Stoffels, D.E; et al
2006	Resilient Modulus of Subgrade Soils A-1-b, A-3, and A-7-6 Using LTPP Data: Prediction Models with Experimental Verification	Joshi, Shaddha; Malla, Ramesh B.
2006	Seasonal Variations in the Moduli of Unbound Pavement Layers	Richter, Cheryl A.
2006	Truck/Pavement/Economic Modeling and In-Situ Field Test Data Analysis Applications - Volume 1: Influence of Drainage on Selection of Base	Sargand, Shad M; Wu, Shin; Figueroa, J. Ludwig
2006	Verification of Long-Term Pavement Performance Virtual Weather Stations: Phase I Report--Accuracy and Reliability of Virtual Weather Stations	Mohseni, Alaeddin
2005	Deterioration of Asphalt Pavement at Long-Term Pavement Performance Program Site 49-1001 in Utah	Blankenagel, Brandon J; Guthrie, W. Spencer
2005	Development of a Pavement Climate Map Based on LTPP Data	Wang, Yuhong
2005	Effect of Seasonal Moisture Variation on Subgrade Resilient Modulus	Salem, Hassan M
2005	LTPP Data Analysis: Influence of Design and Construction Features on the Response and Performance of New Flexible and Rigid Pavements	Chatti, K; Buch, N; Haider, S. W; Pulipaka, A. S; Lyles, R. W; Gilliland, D; Desaraju, P.
2005	Sensitivity Analysis of Rigid Pavement Systems Using Mechanistic- Empirical Pavement Design Guide	Guclu, Alper; Ceylan, Halil

Year	Title	Author(s)
2005	Survival Analysis of Fatigue Cracking for Flexible Pavements Based on Long-Term Pavement Performance Data	Wang, Yuhong; Mahboub, Kamyar C; Hancher, Donn E.
2004	Seasonal Monitoring Program - One Stop Shopping!	
2004	Using Long-Term Pavement Performance Data to Predict Seasonal Variation in Asphalt Concrete Modulas	Salem, H. M; Bayomy, F M; Al-Taher, M. G; Genc, I. H.
2002	Effects of Various Design Features on Rigid Airfield Pavement Design	Lee, Y-H; Yen, S-T.
2001	Evaluation of Moisture Sensitivity Properties of ADOT Mixtures on US 93. Volume I - Final Report	Sebaaly, Peter E; Eid, Zein; Epps, Jon A.
2001	LTPP Data Analysis: Factors Affecting Pavement Smoothness	Perera, R. W; Kohn, S. D.
2001	Parameter Study of Load Transfer and Curling Effects on Rigid Pavement Deflection	Lee, Y-H; Sheu, R-S.
2000	Accuracy of Weather Data in Long-Term Pavement Performance Program Database	Wu, C-L; Rada, G. R; Lopez, A; Fang, Y.
2000	Characterizing Seasonal Variations in Pavement Material Properties for Use in a Mechanistic-Empirical Design Procedure	Ovik, J. M; Birgisson, B; Newcomb, D. E.
2000	Seasonal Trends and Causes in Pavement Structural Properties	Ali, H; Selezneva, O.
2000	Temperature Predictions and Adjustment Factors for Asphalt Pavement	Lukanen, E. O; Stubstad, R; Briggs, R
2000	Variations in Backcalculated Pavement Layer Moduli in LTPP Seasonal Monitoring Sites	Briggs, R. C; Lukanen, E. O.
1999	Analysis of Time Domain Reflectometry Data from LTPP Seasonal Monitoring Program Test Sections	Jiang, Y J; Tayabji, S. D.
1999	Determination of Frost Penetration in LTPP Sections, Final Report	Ali, H. A; Tayabji, S. D.
1999	Evaluation of In-Situ Moisture Content at Long-Term Pavement Performance Seasonal Monitoring Program Sites	Jiang, Y. J; Tayabji, S. D.
1999	LTPPBind: A New Tool for Selecting Cost-Effective SUPERPAVE Asphalt Binder Performance Grades	
1998	Canadian Strategic Highway Research Program (C-SHRP) Phase III Program Proposal 1999-2004	
1998	LTPP Seasonal Asphalt Concrete (AC) Pavement Temperature Models	Mohseni, A.
1998	LTPP Data Analysis: Improved Low Pavement Temperature Prediction	

Year	Title	Author(s)
1998	Relationship between Pavement Temperature and Weather Data: Wisconsin Field Study to Verify Superpave Algorithm	Bosscher, P. J; et al
1998	Seasonal Instrumentation of SHRP Pavements - The University of Toledo	Heydinger, A. G; Randolph, B. W.
1997	Seasonal Variation in Material Properties of a Flexible Pavement	Watson, D. K; Rajapakse, R.K.N.D.
1994	Development of an Instrumentation Plan for the Ohio SPS Test Pavement (DEL-23-17.48). Final Report	Sargand, S.
1994	Influence of Stress Levels and Seasonal Variations on in Situ Pavement Layer Properties	Noureldin, A. S.
1994	Long Term Pavement Performance in Seasonal Frost Areas	Haupt, R. S. et al
1994	LTPP Seasonal Monitoring Program: Instrumentation Installation and Data Collection Guidelines	Rada, G.R. et al
1994	LTPP-SPS Automated Weather Station (AWS) Installation: Arizona DOT Open House	
1993	Development of the LTPP Climatic Database	
1993	How do Temperature and Moisture Affect Pavements? Strategic Highway Research Program Implementation	
1993	Seasonal Monitoring Program, Workshop and Instrumentation Demonstration, Delta, Colorado, June 28 through July 2, 1993	Ardani, A.

Title: Long Term Pavement Performance Computed Parameter: Moisture Content

Author(s): Zollinger, Dan G; Lee, Sang Ick; Puccinelli, Jason; Jackson, Newton C.

Date: March 2008

Publisher: Federal Highway Administration

Abstract/Synopsis:
A study was conducted to compute in situ soil parameters based on time domain reflectometry (TDR) traces obtained from Long Term Pavement Performance (LTPP) test sections instrumented for the seasonal monitoring program (SMP). Ten TDR sensors were installed in the base and subgrade layers at each of the 70 SMP test sites monitored as part of the LTPP program. A comprehensive description of a new method developed as part of the study to estimate moisture content, dry density, reflectivity, and conductivity of the soil from TDR traces is provided in the report. This new method utilizes transmission line equations and micromechanics models calibrated to site-specific conditions for each site/layer combination. Background information on existing empirical methodologies used to estimate subsurface moisture content from TDR traces is also documented. The results were compared to previous methods as well as ground truth data to evaluate the ability of the new model to predict soil parameters. The transmission line equation and micromechanics method was found to provide accurate results and was used to interpret over 270,000 TDR records stored in the LTPP database. A computer program (MicroMoist) was developed to aid in the computation of soil parameters based on TDR trace data and calibration information. Details on the program are provided along with descriptions of the tables developed to store the computed values in the LTPP Information Management System database.

Application/Use: The results of this study are applicable for use in pavement management and rehabilitation.

Contribution: Cost Savings; Improvement in Knowledge; Advancement in Technology

Present Benefit: Time Domain Reflectometry (TDR) is a nondestructive test that is beneficial for determining the in-place pavement sublayer moisture content. Improving the accuracy of this method, specifically in the interpretation of TDR data, yields better results in identifying pavement problems associated with the moisture content of the supporting layers. The effect of moisture content in the supporting soils in the pavement structure is significant on pavement performance and should be considered in rehabilitation strategies, when necessary. The LTPP database largely contributed to the findings in this project.

Future Benefit: The LTPP program and its implementation of various pavement technologies will continue to improve pavement management/rehabilitation programs. As state agencies make better use of pavement technologies, they will be able to develop and take advantage of cost-effective strategies in pavement rehabilitation programs.

Title: Development of Pavement Performance Models to Account for Frost Effects and Their Application to Mechanistic-Empirical Design

Author(s): Puccinelli, Jason; Jackson, Newton C.

Date: 2007

Publisher: Transportation Research Record: Journal of the Transportation Research Board No. 1990

Abstract/Synopsis:
Although it has long been recognized that the presence of frost is a factor in the performance of pavements, little national research has been conducted to study the long-term performance differences caused by frost exposure. To address this concern, a pooled fund study, Effect of Multiple Freeze Cycles and Deep Frost Penetration on Pavement Performance and Cost, was conducted under the direction of the FHWA Long-Term Pavement Performance data analysis program. This study not only explored the effect of frost on pavements but also differentiated between two types of frost exposure: deep frost penetration, remaining present throughout the winter months, and freeze–thaw cycling, occurring multiple times during the frost season. Performance models were developed to evaluate the independent effects of these two freezing conditions on long-term pavement performance. These models were used to make comparisons of predicted fatigue, rutting, and roughness measures in different environmental settings. Predictions revealed that significant differences existed among the various climatic scenarios. An evaluation also was conducted on the application of the models for regional calibration of the NCHRP 1-37A design procedure for locations where measured performance data are not available. An example shows that the models can be used as an effective calibration tool.

Application/Use: The results from this paper are applicable to pavement managers with pavement networks that experience frost effects.

Contribution: Improvement in Knowledge; Cost Savings; Advancement in Technology

Present Benefit: A better understanding of frost effects on pavement performance is significant for pavement managers whose pavement network is affected by frost. From this study, pavement engineers can better identify what type of frost effect is influencing their pavements and relate the frost conditions to expected pavement distress, allowing them to consider these affects in their pavement design and better predict pavement distress.

Future Benefit: The LTPP program will continue to be instrumental in the pavement industry to obtain a better understanding frost effects on pavement performance and will lead to being able to quantify these effects and account for them in new construction and rehabilitation pavement designs.

Title: Evaluation of Fatigue (Alligator) Cracking in the LTPP SPS-6 Experiment

Author(s): Rahim, A. M; Fiegel, G; Ghuzlan, K.

Date: January 2009

Publisher: International Journal of Pavement Research and Technology Vol. 2 No. 1

Abstract/Synopsis:
Evaluation of Crack, Seat, and Overlay (CS&O) pavement section performance is done in terms of fatigue cracking (also known as alligator cracks). Two categories based on weather region (namely Wet-with-Freeze (WF) and Wet-with-No-Freeze (WNF)) were used to divide data extracted from the Long Term Pavement performance (LTPP) SPS-6 experiment. Regression models were developed after these data were analyzed. California pavement section data were evaluated separately, leading to a third regression model's development. Alligator crack minimization in sections with unbound bases did not appear to be helped by thicker overlays in the WF region. In the WF region, sections with unbound bases were outperformed by sections with bound bases. In the California sections, alligator crack reduction was assisted by increasing the leveling course thickness from about 30.5 to 63.5mm. It is suggested by regression analyses that WNF region sections will outperform counterparts in California and the WF region up to an age of approximately 12 years. After 10 years of service, it is expected that the California sections will exhibit approximately 56% alligator cracks.

Application/Use: This article can be used by those responsible for pavement management and pavement design.

Contribution: Cost Savings; Lessons Learned

Present Benefit: This paper exemplifies the use of LTPP test site data and its application in evaluating current pavement designs and their performance in different climate conditions. This comparison can help pavement designers quantify performance differences of various pavement structures. With this information, more cost-effective pavement rehabilitation alternatives can be designed.

Future Benefit: The LTPP database will continue to be the go-to source for pavement related research. In fact, LTPP was relied upon heavily for the development of the M-E PDG and will continue to be the backbone of future pavement design.

Title: Automation of Pavement Sublayer Moisture Content Determination Using LTPP Time Domain Reflectometry Data and Micromechanics

Author(s): Lee, Sang Ick; Zollinger, Dan G; Lytton, Robert Leonard; Jackson, Newton C. P.

Date: 2009

Publisher: Transportation Research Board 88th Annual Meeting

Abstract/Synopsis:
Time Domain Reflectometry (TDR) is one of the reliable methods to measure in-situ moisture content of unbound base and subgrade materials. However, the waveform data obtained from TDR device does not provide in-situ moisture content directly. Rather, the data must be analyzed to determine volumetric moisture content which is final product of TDR related technology; that is, a TDR trace is analyzed to determine the value of the associated dielectric constant which is dependent upon soil surrounding the TDR probe affecting the moisture content determination. However, since existing methods to determine the dielectric constant and moisture content are immersed in systematic errors, a new approach was developed using the transmission line equation and a 3-phase micromechanics approach to improve the accuracy of the interpretation of TDR data for calculating the dielectric constant and the moisture content. Since the system identification (SID) method used to calculate parameters in the new approach is an iterative solution scheme, a computational program was required to provide a rapid, accurate, and repeatable calculation of parameters. To address this need, a program was developed to facilitate the calculation of dielectric constant, dry density, and moisture content based on the micromechanics approach. Details regarding the feature, algorithm, and result of the program are provided in this paper.

Application/Use: The development of TDR is directly applicable for forensic use in pavement management and rehabilitation.

Contribution: Improvement in Technology; Implementation/Usage

Present Benefit: Time Domain Reflectometry (TDR) is a nondestructive test that is beneficial for determining the in-place pavement sublayer moisture content. Improving the accuracy this method yields better results in identifying pavement problems associated with the moisture content of the supporting layers.

Future Benefit: The LTPP program and its implementation of various pavement technologies will continue to improve pavement management/rehabilitation programs.

Title: Effects of Design and Site Factors on Roughness Development in Flexible Pavements

Author(s): Haider, Syed Waqar; Chatti, Karim

Date: March 2009

Publisher: Journal Title Journal of Transportation Engineering Vol. 135 No. 3, American Society of Civil Engineers

Abstract/Synopsis:
This paper presents the relative influence of design and site factors on roughness development of in-service flexible pavements. The data from the specific pavement study (SPS)-1 experiment of the long-term pavement performance program were used to investigate the effects of asphalt concrete surface layer thickness, base type, base thickness, and drainage on roughness growth of flexible pavements constructed in different site conditions (subgrade type and climate). Since this is the first comprehensive study involving the SPS-1 experiment, a thorough data analysis methodology was adopted. The result of the analyses shows that among the design factors, base type was found to have the most significant effect on roughness progression. The pavement sections with asphalt-treated bases showed the best performance. Drainage and base type, when combined, also played an important role in inhibiting roughness, while base thickness has only secondary effects. In addition, climatic conditions were found to have considerable influence. Pavement sections in the wet-freeze zone exhibited a higher roughness increase. In general, pavements built on fine-grained soils have shown the worst roughness levels over time. Important interactions between design and site factors were identified; these should provide new insights in enhancing long-term flexible pavement performance.

Application/Use: Determining the most influential factors relating to pavement roughness is directly applicable to state and highway engineering professionals.

Contribution: Cost Savings; Improvement in Knowledge

Present Benefit: Pavement roughness is a significant variable in the overall performance of flexible pavements. Therefore, understanding the critical conditions and site factors affecting pavement roughness is a valuable tool for pavement designers and rehabilitation specialists that will allow them to be more effective with limited resources and achieve a higher pavement performance. The LTPP program and, specifically, the SPS-1 experiment laid the foundation for these discoveries in pavement performance.

Future Benefit: As state and highway officials increase in their understanding of the various factors affecting pavements, the end result will be more cost-effective pavement designs with better overall pavement performance. The work performed as part of the LTPP will continue to add tremendous value to the highway community.

Title: Consideration of Climate in New AASHTO Mechanistic-Empirical Pavement Design Guide

Author(s): Zapata, Claudia E.

Date: 2009

Publisher: Transportation Research Board 88th Annual Meeting

Abstract/Synopsis:
As part of the new US Mechanistic-Empirical Pavement Design Guide (MEPDG) developed under several projects sponsored by the National Cooperative Highway Research Program (NCHRP), a climatic modeling tool called the Enhanced Integrated Climatic Model (EICM) was implemented to incorporate the changes in temperature and moisture of unbound materials into the design process. The final methodology was approved by the American Association of State Highway and Transportation Officials (AASHTO) in July 2007 and soon will become the standard of practice in the U.S.A. This paper presents an overview of the EICM methodology used for the MEPDG, the models incorporated by Arizona State University to estimate input parameters, the input needed and the outputs generated by the program. A discussion on how the MEPDG makes use of the output generated by the EICM is also presented. The models presented in this paper have been calibrated using design inputs and performance data largely drawn from the national Long Term Pavement performance database and limited field testing of sections located throughout significant parts of North America. Therefore, the national calibration may not be entirely adequate for specific regions of the country or for other country; and a more local or regional calibration may be needed.

Application/Use: The results of this paper will directly affect the design standards in the pavement industry, as they have been adopted by AASHTO.

Contribution: Improvement in Knowledge; Implementation/Usage

Present Benefit: The relationship between the performance of pavements and the climates in which those pavements exist is of great benefit to pavement designers and rehabilitation specialists. As the MEPDG becomes the standard for pavement design, state agencies and pavement engineers will be able to capitalize on the benefits from this research. The LTPP database largely contributed to these discoveries and their application in pavement design.

Future Benefit: When adopted, the MEPDG will be the standard in the pavement industry and will enable state and local officials to take full advantage of the knowledge and experience gained through the LTPP program. The LTPP program has brought insight and discovery in various aspects in the pavement industry to enable designers to make more durable pavements in a more cost-effective manner.

Title: Early-Life, Long-Term, and Seasonal Variations in Skid Resistance in Flexible and Rigid Pavements

Author(s): Ahammed, Mohammad Alauddin; Tighe, Susan L.

Date: 2009

Publisher: Transportation Research Record: Journal of the Transportation Research Board No. 2094

Abstract/Synopsis:
Skidding contributes to up to 35% of wet weather accidents. Increased temperature and surface wear and polishing may affect the available friction and further increase skid-related accidents. Several studies have attempted to examine and quantify these variations mostly with inadequate or inappropriate conclusions. The surface friction of both portland cement concrete (PCC) and asphalt concrete (AC) pavements was measured monthly to determine the influencing factors and quantify the seasonal fluctuation. Skid number (SN) and pertinent data of the Long-Term Pavement Performance program were obtained for both PCC and AC pavements, incorporating all geographic and climatic regions of the United States and Canada, to determine the contributing factors and quantify the long-term and early-life variations of surface friction. Surface friction was shown to fluctuate as a result of ambient or pavement temperature fluctuation at 0.35 British pendulum number per 18°C change in temperature. The effect of prior weather was shown to be insignificant. Following construction, AC and PCC surface friction was shown to increase by 5 SN in about 18 months and 4 SN in about 2½ years. Skid resistance was shown to decrease thereafter at 0.27 SN for AC and at 0.24 SN for PCC pavements per million vehicle passes. Cumulative traffic passes, pavement age, speed, and temperature during the testing and PCC pavement surface texture types were found to be statistically significant for the prediction of long-term surface friction. AC pavement long-term surface friction was shown to be more sensitive, as compared with PCC, to predominant climatic condition.

Application/Use: This article can be used by those responsible for pavement management and pavement design.

Contribution: Improvement in Knowledge

Present Benefit: The need to maintain an adequate level of safety throughout the nation's pavement networks is a significant issue. This study showed the dominant factors affecting pavement friction, which has a direct effect on safety. The LTPP program contribution to this project was extensive by providing the skid numbers of various pavements in a variety of climatic conditions.

Future Benefit: As traffic volumes increase on the nation's pavement networks, pavement designers will need to discover the dominant factors affecting pavements, as they relate to safety issues. The LTPP database will continue to provide researchers with the information needed to pursue these issues further and discover ways to address and maintain pavements in a manner that considers the safety of those using the roads.

Title: Predicting Low Design Temperatures of Asphalt Pavements in Dry Freeze Regions Using Solar Radiation, Transient Heat Transfer, and Finite Element Method

Author(s): Ho, Chun-Hsing; Romero, Pedro

Date: 2009

Publisher: Transportation Research Board 88th Annual Meeting

Abstract/Synopsis:
This paper proposes three mathematical models using solar radiation theory, transient heat transfer theory, and finite element method to compute daily solar radiation, determine a thermal penetration depth as a boundary condition, and eventually estimate pavement temperatures. The objective of this paper is to predict low design temperatures of asphalt pavements in dry freeze regions. These step-by-step numerical analysis efforts provide pavement engineers and researchers with a perspective for prediction of low design temperatures of asphalt pavements. Daily solar radiation was calculated as input for determination of the thermal penetration depth in a semi-infinite asphalt pavement system. Using the determined thermal penetration depth as prescribed temperature in the process of finite element analysis, the pavement temperature profile including surface temperatures can be better calculated. The finite element analysis results were verified with the Strategic Highway Research Program (SHRP), Canadian SHRP (C-SHRP), Superior Performing Asphalt Pavements (SUPERPAVE) models, and validated with three sets of temperature data exported from the long term pavement performance (LTPP) program in southern Utah. Comparison results present closer agreement with three predicted models and field temperature within a reasonable accuracy.

Application/Usage: The results from this project are applicable to pavement researchers and engineers interested in predicting low design temperatures for asphalt pavements.

Contribution: Improvement in Knowledge; Advancement in Technology

Present Benefit: The ability to accurately estimate the pavement temperature is valuable for pavement engineers, especially when designing/specifying the most effective SUPERPAVE binder for a given site. The SMP experiments and climatic data from the LTPP program were utilized in this project to develop pavement temperature prediction models.

Future Benefit: As state agency pavement engineers are able to better predict pavement temperatures, they can be more strategic in selecting SUPERPAVE binders, improving their pavement design. The LTPP database will continue to be a significant tool for pavement researchers and engineers in evaluating existing prediction methods and validating new methods.

Title: LTPP Computed Parameter: Frost Penetration

Author(s): Selezneva, Olga I; Jiang, Y J; Larson, G; Puzin, Tara

Date: November 2008

Publisher: Federal Highway Administration

Abstract/Synopsis:
As the pavement design process moves toward mechanistic-empirical techniques, knowledge of seasonal changes in pavement structural characteristics becomes critical. Specifically, frost penetration information is necessary for determining the effect of freeze and thaw on pavement structural responses. This report describes a methodology for determining frost penetration in unbound pavement layers and subgrade soil using temperature, electrical resistivity, and moisture data collected for instrumented Long Term Pavement Performance (LTPP) Seasonal Monitoring Program (SMP) sites. The report also contains a summary of LTPP frost depth estimates and a detailed description of the LTPP computed parameter tables containing frost penetration information for 41 LTPP SMP sites. The frost penetration analysis methodology and the accompanying E-FROST program used in-situ soil temperature as a primary source of data to predict frost depth in unbound pavement layers. In addition to temperature data, electrical resistivity and moisture data were used as supplemental data sources for the analysis when temperatures were close to the freezing isotherm. The Enhanced Integrated Climatic Model (EICM) was used to fill intermediate gaps in the measured soil temperature data.

Application/Use: The results from this study are directly applicable to pavement engineers and pavement designers in climates that experience freeze/thaw in pavements.

Contribution: Cost Savings; Advancement in Technology

Present Benefit: SMP projects provide information related to the seasonal variations and climate conditions that pavements experience and relate those to the distress the pavement experiences. As resources are limited, it is critical that designers and rehabilitation specialists consider the effect of climate conditions on the performance of pavements. The LTPP program was pivotal in this study, enabling researchers to better understand frost penetration and its effects on pavement performance.

Future Benefit: The long term performance data collected at SMP projects will allow more effective design strategies to accommodate for climate conditions and can be used to optimize resources. Additionally, considering these factors as they relate to the MEPDG will rely on the LTPP program and, particularly, on these SMP experiments.

Title: Simplified Model to Predict Frost Penetration for Manitoba Soils

Author(s): Soliman, H; Kass, S; Fleury, N.

Date: 2008

Publisher: 2008 Annual Conference of the Transportation Association of Canada

Abstract/Synopsis:
In spring season, the top layers of pavement start to thaw while the bottom layers are still frozen. As a result, the moisture remains contained in the top layers and can not be drained. Consequently, pavement layers experience high strains therefore Spring Load Restrictions (SLR) are applied to protect pavement from early deterioration. In winter season, the winter load premium can not be allowed until frost penetration reaches a certain depth. Having a reliable model to predict the depth of frost penetration provides a time and cost effective alternative to field measurements. This paper introduces the analysis conducted to develop a simplified model to predict the frost penetration in Manitoba. The climatic and seasonal monitoring data for the Oak Lake test section, which was collected as part of the Long-Term Pavement Performance (LTPP) Program, was utilized for this purpose. The proposed frost penetration model was compared to the Northern Ontario frost penetration model and a good agreement was found between them.

Application/Use: The results of this paper are directly applicable to pavement managers in Manitoba. However, this study is also applicable to other agency pavement managers with pavement networks exposed to freeze/thaw cycles.

Contribution: Cost Savings; Improvement in Knowledge; Implementation/Usage

Present Benefit: Knowing the frost penetration is important for preventing unnecessary pavement deterioration. Therefore, the ability to use mathematical models to more accurately predict the depth of frost penetration provides a cost effective alternative to taking measurements in the field. The data collected through the LTPP program in Manitoba provided the foundation for developing this mathematical model.

Future Benefit: A significant cost savings is achievable by agencies with pavements in freeze/thaw zones as they protect their pavement network during this. LTPP is an invaluable resource for agencies looking at the effect of climate conditions and, particularly, the freeze/thaw cycle on their pavement network or other similar pavement networks. The LTPP SMP sites will continue to be of great value as various state agencies look to protect their pavement networks during the freeze/thaw season.

Title: Temperature and Precipitation Sensitivity Analysis on Pavement Performance

Author(s): Smith, James Trevor; Tighe, Susan L; Andrey, Jean C; Mills, Brian

Date: June 2008

Publisher: Fourth National Conference on Surface Transportation Weather; Seventh International Symposium on Snow Removal and Ice Control Technology Transportation Research E-Circular No. E-C126 Corp.

Abstract/Synopsis:
It is estimated that the average temperature in Canada will increase between 2°C and 5°C and precipitation will increase 0% to 10% over the next 45 years. These changes in climate will impact pavement performance and this paper attempts to predict the consequences of this performance change. Using Canadian data from the Long-Term Pavement Performance program, the "Mechanistic–Empirical Pavement Design Guide" (M-E PDG) version 1.0 is used to quantify the impact of climate change in the Canadian environment. In essence, two case studies representing Canadian conditions are presented. Specifically, how climate changes in precipitation and temperature affect the pavement performance indicators of International Roughness Index, longitudinal cracking, transverse cracking, alligator cracking, asphalt concrete deformation (rutting), and total rutting is assessed. Simulations were performed with combinations of 0%, –5%, +5%, +10% and +25% precipitation changes and 0°C, +1°C, +2°C, and +5°C temperature increases. Temperature increases have a negative impact on the pavement performance in the Canadian environment. Maintenance, reconstruction, and rehabilitation (MR&R) activities would be minimally affected with a 1°C increase in temperature. Based on the initial analysis, Canadian transportation agencies would likely not change MR&R activities until a 2°C or higher increase in temperature. The M-E PDG was not sensitive enough to distinguish between changes in precipitation or changes in transverse cracking. The CGC M2A2x and HadCM3B21 detailed climatic scenarios provide realistic prediction of the changes in pavement performance due to increases in temperature and precipitation.

Application/Use: The results from this paper are directly applicable to pavement managers in Canada, but can also be used by other agencies with an interest in the effect of temperature and precipitation on pavement performance.

Contribution: Cost Savings; Improvement in Knowledge

Present Benefit: A better understanding of the effects of temperature and precipitation conditions on overall pavement performance is significantly beneficial to pavement managers and rehabilitation specialists. With this knowledge, pavement managers can be more effective in their strategies to rehabilitate pavements in their network and re-adjust their pavement designs when climate conditions change. The LTPP database, and specifically the data collected from the LTPP sites in Canada, was pivotal in this study.

Future Benefit: As pavement design moves toward mechanistic-empirical design methods, the LTPP database will continue to be an invaluable resource for researchers and pavement engineers to show a relationship between climate conditions and their effect on pavement performance. Specifically, the seasonal monitoring program (SMP) test sections in the LTPP program will greatly contribute to furthering the general understanding of climate conditions on the behavior of pavements.

Title: LTPP Computed Parameter: Moisture Content

Author(s): Zollinger, Dan G; Lee, Sang Ick; Puccinelli, Jason; Jackson, Newton C.

Date: January 2008

Publisher: Federal Highway Administration

Abstract/Synopsis:
A study was conducted to compute in situ soil parameters based on time domain reflectometry (TDR) traces obtained from Long Term Pavement Performance (LTPP) test sections instrumented for the seasonal monitoring program (SMP). Ten TDR sensors were installed in the base and subgrade layers at each of the 70 SMP test sites monitored as part of the LTPP program. A comprehensive description of a new method developed as part of the study to estimate moisture content, dry density, reflectivity, and conductivity of the soil from TDR traces is provided in the report. This new method utilizes transmission line equations and micromechanics models calibrated to site-specific conditions for each site/layer combination. Background information on existing empirical methodologies used to estimate subsurface moisture content from TDR traces is also documented. The results were compared to previous methods as well as ground truth data to evaluate the ability of the new model to predict soil parameters. The transmission line equation and micromechanics method was found to provide accurate results and was used to interpret over 270,000 TDR records stored in the LTPP database. A computer program (MicroMoist) was developed to aid in the computation of soil parameters based on TDR trace data and calibration information. Details on the program are provided along with descriptions of the tables developed to store the computed values in the LTPP Information Management System database.

Application/Use: The results of this study are applicable for forensic use in pavement management and rehabilitation.

Contribution: Cost Savings; Improvement in Knowledge; Advancement in Technology

Present Benefit: Time Domain Reflectometry (TDR) is a nondestructive test that is beneficial for determining the in-place pavement sublayer moisture content. Improving the accuracy of this method, specifically in the interpretation of TDR data, yields better results in identifying pavement problems associated with the moisture content of the supporting layers. The effect of moisture content in the supporting soils in the pavement structure is significant on pavement performance and should be considered in rehabilitation strategies, when necessary. The LTPP database largely contributed to the findings in this project.

Future Benefit: The LTPP program and its implementation of various pavement technologies will continue to improve pavement management/rehabilitation programs. As state agencies make better use of pavement technologies, they will be able to develop and take advantage of cost-effective strategies in pavement rehabilitation programs.

Title: Calibration and Validation of the Enhanced Integrated Climatic Model for Pavement Design

Author(s): Zapata, Claudia E; Houston, William N.

Date: 2008

Publisher: Transportation Research Board

Abstract/Synopsis:
This report summarizes the results of research to evaluate, calibrate, and validate the Enhanced Integrated Climatic Model (EICM) incorporated in the original Version 0.7 (July 2004 release) of the "Mechanistic-Empirical Pavement Design Guide" (MEPDG) software with measured materials data from the Long-Term Pavement Performance Seasonal Monitoring Program (LTPP SMP) pavement sections. The report further describes subsequent changes made to the EICM to improve its prediction of moisture equilibrium for granular bases. The report will be of particular interest to pavement design engineers in state highway agencies and industry.

Application/Use: This paper can be used to evaluate the adequacy of the EICM and the impacts of environment and traffic on M-E PDG predictions.

Contribution: Improvement in Knowledge

Present Benefit: The findings from this study are beneficial to the implementation and use of the MEPDG. Additionally, an evaluation of the accuracy of the EICM will ultimately improve the pavement designs produced through the MEPDG. The LTPP database, specifically the SMP pavement sections, was critical in calibrating the EICM and validating it for use.

Future Benefit: This study will be used to understand the variability inherent in the EICM and its effect on pavement design in the MEPDG. Findings from this study may be used to modify the MEPDG. The LTPP database is an invaluable resource for pavement researchers and engineers in further understanding pavement behavior impacted by climate conditions and will continue to lead to advancements in the pavement industry.

Title: Evaluating Climate Change Impact on Low-Volume Roads in Southern Canada

Author(s): Tighe, Susan L; Smith, James Trevor; Mills, Brian; Andrey, Jean C.

Date: 2008

Publisher: Transportation Research Record: Journal of the Transportation Research Board No. 2053 Corp.

Abstract/Synopsis:
Information extracted from global climate models suggests that average temperatures and annual precipitation will increase over the next several decades, with potential implications for pavement performance and design. With Canadian data from the Long-Term Pavement Performance program, the "Mechanistic–Empirical Pavement Design Guide" was used to quantify the impacts of projected climatic changes on pavement performance of low-volume roads at six sites. A series of analyses was conducted to assess the impact of pavement structure, material characteristics, traffic loads, and changes in climate on incremental and terminal pavement deterioration and performance. Results suggest that rutting (asphalt, base, and subbase layers) and both longitudinal and alligator cracking will be exacerbated by climate change, with transverse cracking becoming less of a problem. In general, maintenance, rehabilitation, and reconstruction will be required earlier in the design life; however, the effects of climate change were found to be modest relative to effects of regional baseline climate differences and increased future traffic. For road authorities, key adaptations will relate to when and how to modify current design and maintenance practices. Pavement engineers should be encouraged to develop a protocol for considering potential climate change in the development and evaluation of future designs and maintenance programs. Incorporating other climate-related road infrastructure issues—for instance those associated with concrete pavements; surface-treated roads; and airfields, bridges, and culverts—would be beneficial. At a minimum, long time series of historic climatic and road weather observations (e.g., >30 years) should be incorporated into analyses of pavement deterioration and assignment of performance graded materials.

Application/Use: The results from this paper are directly applicable for pavement managers in Canada. However, agency pavement managers interested in the effects of climate conditions on low-traffic volume roads will also benefit from this study.

Contribution: Cost Savings; Improvement in Knowledge

Present Benefit: The relationship between pavement performance and the climate conditions that the pavement experiences is of great benefit to pavement managers, and can assist them in their maintenance, design, and rehabilitation decisions. For pavement managers, this research project is valuable in helping them plan for potential conditions in the future that will affect pavement performance. The LTPP database was a key contributor to the success of this project.

Future Benefit: The LTPP database will continue to be an invaluable resource for pavement engineers and rehabilitation specialists in further advancing the pavement industry and better understand pavement behavior. As engineers obtain a better understanding of the effects of climate conditions on pavement performance, they will be able to address pavement needs more cost-effectively. Additionally, they will also be able to better plan for pavement needs in the future and be more strategic in the allocation of limited resources to meet these needs.

Title: Evaluation of Pavement Performance on DEL-23

Author(s): Sargand, Shad M; Edwards, William F.

Date: June 2007

Publisher: Ohio Department of Transportation

Abstract/Synopsis: In 1994, the Ohio Department of Transportation (ODOT) initiated construction of an experimental pavement on US 23 north of Columbus containing 40 test sections in the Long-Term Pavement Performance (LTPP) portion of the Strategic Highway Research Program (SHRP). Dynamic instrumentation was installed in 33 sections to measure strain, deflection and pressure responses generated in the pavement structures during controlled vehicle testing and Falling Weight Deflectometer (FWD) loading. Environmental instrumentation was installed in 18 sections to continuously monitor temperature, moisture and frost depth in the pavement structures. An on-site weather station recorded climatic conditions and a weigh-in-motion (WIM) system monitored traffic loading on the test sections. This research contract represents the latest in a series of contracts initiated by ODOT to continue collecting and analyzing data from the SHRP test pavement, and to document any trends or findings of interest. Three other instrumented pavements were also monitored under this contract.

Application/Use: The results of this study are directly applicable to pavement design, traffic data collection and pavement management.

Contribution: Cost Savings; Improvement in Knowledge; Advancement in Technology.

Present Benefit: The extensive pavement monitoring and analysis conducted on the 40 test sections that comprise the Ohio Test Road provide a plethora of useful information. Evaluation results can be used to revise traffic data collection, modify pavement design procedures and alter construction specifications.

Future Benefit: Long term data collected as part of the LTPP experiment coupled with inventory data will be extremely valuable to the pavement community in the years to come, particularly in implementing the M-E PDG.

Title: Analysis of Variations of Pavement Subgrade Soil Water Content

Authors: Heydinger, Andrew G; Davies, B.O.A.

Date: April 2006

Publisher: Unsaturated Soils 2006

Conference Title: Proceedings of the Fourth International Conference on Unsaturated Soils

Abstract/Synopsis: Seasonal Monitoring Program (SMP) data available in the Long Term Pavement Performance (LTPP) database DataPave was analyzed to investigate the variations of volumetric water content. The SMP data includes volumetric water contents from time domain reflectometry (TDR) probes in pavement sections located in the United States and Canada. Water content, or the associated degree of saturation, is used to compute resilient modulus for unsaturated unbound base and subgrade soils in the Mechanistic-Empirical Pavement Design Guide (M-EPDG) that was developed for the Federal Highway Administration. The purpose of this paper is to discuss results of analysis of volumetric water content data from the most recent release of DataPave (Release 19) and the resulting variations in resilient modulus that would occur. Results from analysis of the data indicate that there are variations of volumetric water content that occur over time. For a few of the pavement sections, the variations of volumetric water content were seasonal. For most of the sections, it was not possible to determine consistent trends in the moisture variations on a temporal scale or when comparing the different climate zones, soil types (coarse or fine-grained), pavement types or depth to the water table. The volumetric water content variations typically were greater than 3 percent and less than 9 percent. These findings indicate that subgrade soils undergo varying degrees of saturation. The resilient modulus, computed using the water content variations and an empirical equation developed for the M-EPDG, can vary by as much as a factor of 2. The resilient modulus variations are generally higher in wet climates than in dry climates.

Application/Use: The results from this study are applicable to pavement design.

Contribution: Cost Savings; Improvement in Knowledge.

Present Benefit: The study provides insight on the seasonal variations in subgrade soils. This information can be used to incorporate seasonal considerations in pavement design and allow for subgrade resilient modulus values to be adjusted based on season. The findings from this study may also be useful in selecting design features that mitigate conditions of low strength subgrade.

Future Benefit: Information on seasonal variability will continue to be of interest as pavement design moves towards the M-E PDG.

Title: Effects of Multiple Freeze Cycles and Deep Frost Penetration on Pavement Performance and Cost

Authors: Jackson, Newton; Puccinelli, Jason

Date: November 2006

Publisher: Federal Highway Administration

Abstract/Synopsis: The objectives of this study are to: (1) quantify the effects of frost penetration on pavement performance in climates with deep sustained frost as compared to environments with multiple freeze-thaw cycles; (2) investigate the effect that local adaptations have on mitigating frost penetration damage; and (3) estimate the associated cost of constructing and maintaining pavements in freezing climates. The approach consisted of modeling various pavement performance measures using both climatic and nonclimatic input variables and performance data collected as part of the Long Term Pavement Performance program. Five climatic scenarios are defined in terms of climatic input variables for the models. Predicted performance measures are presented for each of the climatic scenarios and compared at a 95 percent confidence interval to determine statistically significant performance differences. Participating Pooled Fund States were queried as to standard specifications, standard designs, average life expectancies, and construction costs specific to each State Highway Agency (SHA). This data along with information acquired through literature review of SHA standard practices is summarized with consideration given to the mitigation of frost-related damage. Life cycle cost analysis for each climatic scenario using predicted performance to determine average life and average agency construction costs for standard pavement sections is also discussed and compared. The use of the performance models for local calibration as required in the National Cooperative Highway Research Program Mechanistic-Empirical design guide is explored along with the possible application of the performance models in pavement management systems.

Application/Use: This document can be used to make pavement design decisions to mitigate climatic effects. It is also useful in pavement management as the performance trends developed in the study can be used at a local level to predict service life and pavement condition.

Contribution: Cost Savings; Improvement in Knowledge.

Present Benefit: This document provides insight into the performance of pavements exposed to various climates and investigates possible mitigation techniques. The costs associated with differential performance are also discussed. The models developed were based on national data—only available for the LTPP database—and have a large inference range. The models are applicable to pavement management as well as to the implementation of the M-E PDG.

Future Benefit: The performance curves will be used in the future by agencies to supplement their pavement management data as well as to evaluate the prediction capabilities of the M-E PDG on regional basis.

Title: Effect of Design and Site Factors on Long-Term Performance of Flexible Pavements in SPS-1 Experiment

Author(s): Chatti, Karim

Date: 2006

Publisher: Transportation Research Board

Conference Title: Transportation Research Board 85th Annual Meeting

Abstract/Synopsis: Results are presented from a study to evaluate the relative influence of design and site factors on the performance of in-service flexible pavements. The data are from the SPS-1 experiment of the Long-Term Performance Pavement (LTPP) program. This experiment was designed to investigate the effects of HMA surface layer thickness, base type, base thickness, and drainage on the performance of new flexible pavements constructed in different site conditions (subgrade type and climate). Base type was found to be the most critical design factor affecting fatigue cracking, roughness (IRI), and longitudinal cracking (wheel path). The best performance was shown by pavement sections with asphalt treated bases (ATB). This effect should be interpreted in light of the fact that an ATB effectively means a thicker HMA layer. Drainage and base type, when combined, also play an important role in improving performance, especially in terms of fatigue and longitudinal cracking. Base thickness has only secondary effects on performance, mainly in the case of roughness and rutting. In addition, climatic conditions were found to have a significant effect on flexible pavement performance. Longitudinal cracking (wheel path) and transverse cracking seem to be associated with a wet-freeze environment, while longitudinal cracking (non-wheel path) seems to be dominant in a freeze climate. In general, pavements built on fine-grained soils have shown the worst performance, especially in terms of roughness. Although most of the findings from this study support the existing understanding of pavement performance, they also provide an overview of the interactions between design and site factors and new insights for achieving better long-term pavement performance.

Application/Use: This study is used by those interested in the contribution of design factors on flexible pavement performance.

Contribution: Cost Savings; Improvement in Knowledge.

Present Benefit: The present benefit for this study is an understanding in the interaction between design parameters and climate and the resultant changes in pavement performance. The LTPP database provides a means of conducting this type of study on a national scale.

Future Benefit: The findings from this study will be useful in transferring mechanistic evaluations to field performance for various design parameters.

Title: Effects of Design and Site Factors on Roughness of Flexible Pavements in the LTPP SPS-1 Experiment

Author(s): Haider, Syed Waqar; Chatti, Karim

Date: 2006

Publisher: American Society of Civil Engineers

Conference Title: Airfield and Highway Pavements. Proceedings of the 2006 Airfield and Highway Pavement Specialty Conference

Abstract/Synopsis: Although considerable mechanic-empirical research exists on the factors affecting flexible pavement roughness, it is limited in scope because of inadequate field validation and the complex interactions of structural and site factors. This paper presents the results of a study on the relative influence of design and site factors on roughness of in-service flexible pavements. The data from the SPS-1 experiment of the LTPP program were used in this study to investigate the effects of hot mix asphalt (HMA) surface layer thickness, base type, base thickness, and drainage on roughness of flexible pavements constructed in different site conditions (subgrade type and climate). Since this is the first comprehensive study of SPS-1 experimental data, a thorough methodology involving mean comparisons and multivariate ANOVA was adopted for data analyses. Among the design factors, base type was found to have the most significant effect on roughness. The best performance was shown by pavement sections with asphalt-treated bases. Drainage, when combined with base type, also plays an important role in inhibiting roughness, while base thickness has only secondary effects. In addition, climatic conditions were found to have considerable influence. Pavement sections in the wet-freeze zone exhibited levels of roughness. Also, in general, pavements built on fine grained soils have shown the worst roughness levels. While most of the findings from this study support the existing understanding of factors affecting roughness, important interactions between design and site factors were identified and provide new insights for achieving better long-term pavement performance.

Application/Use: This study is used by those interested in the contribution of design factors on flexible pavement performance.

Contribution: Cost Savings; Improvement in Knowledge.

Present Benefit: The present benefit for this study is an understanding in the interaction between design parameters and climate and the resultant changes in pavement performance. The LTPP database provides a means of conducting this type of study on a national scale.

Future Benefit: The findings from this study will be useful in comparing mechanistic evaluations to field performance for various design parameters.

Title: Effects of Multiple Freeze Cycles and Deep Frost Penetration on Pavement Performance and Cost

Authors: Jackson, N.; Puccinelli, J.

Date: November 2006

Publisher: Federal Highway Administration

Abstract/Synopsis: The objectives of this study are to: (1) quantify the effects of frost penetration on pavement performance in climates with deep sustained frost as compared to environments with multiple freeze-thaw cycles, (2) investigate the effect that local adaptations have on mitigating frost penetration damage, and (3) estimate the associated cost of constructing and maintaining pavements in freezing climates. The approach consisted of modeling various pavement performance measures using both climatic and nonclimatic input variables and performance data collected as part of the Long Term Pavement Performance program. Five climatic scenarios are defined in terms of climatic input variables for the models. Predicted performance measures are presented for each of the climatic scenarios and compared at a 95 percent confidence interval to determine statistically significant performance differences. Participating Pooled Fund States were queried as to standard specifications, standard designs, average life expectancies, and construction costs specific to each State Highway Agency (SHA). This data along with information acquired through literature review of SHA standard practices is summarized with consideration given to the mitigation of frost-related damage. Life cycle cost analysis for each climatic scenario using predicted performance to determine average life and average agency construction costs for standard pavement sections is also discussed and compared. The use of the performance models for local calibration as required in the National Cooperative Highway Research Program Mechanistic-Empirical design guide is explored along with the possible application of the performance models in pavement management systems.

Application/Use: This document can be used to make pavement design decisions to mitigate climatic effects. It is also useful in pavement management as the performance trends developed in the study can be used at a local level to predict service life and pavement condition.

Contribution: Cost Savings; Improvement in Knowledge.

Present Benefit: This document provides insight into the performance of pavements exposed to various climates and investigates possible mitigation techniques. The costs associated with differential performance are also discussed. The models developed were based on national data—only available for the LTPP database—and have a large inference range. The models are applicable to pavement management as well as to the implementation of the M-E PDG.

Future Benefit: The performance curves will be used in the future by agencies to supplement their pavement management data as well as to evaluate the prediction capabilities of the M-E PDG on regional basis.

Title: Investigations of Environmental and Traffic Impacts on "Mechanistic-Empirical Pavement Design Guide" Predictions

Author(s): Zaghloul, Sameh; Ayed, Amr; Abd El Halim, Amir; Vitillo, Nicholas P; Sauber, Robert W.

Date: 2006

Publisher: Transportation Research Board

Journal Title: Transportation Research Record: Journal of the Transportation Research Board No. 1967

Abstract/Synopsis: The "Mechanistic–Empirical Pavement Design Guide" (MEPDG) represents a major improvement on its predecessors, particularly in its comprehensive coverage of environmental impact on pavement performance. Another improvement is the approach introduced to assess and accumulate damage created by traffic. A major strength of the MEPDG is the consideration given to the interaction between environmental, material, and traffic parameters, rather than consideration of only the parameters themselves. The process through which these interactions are considered sounds very comprehensive; however, is it practical? The Enhanced Integrated Climatic Model (EICM) is a core component of the MEPDG; it controls the material properties used in the analysis to a great extent. As a result, EICM predictions have a significant impact on MEPDG-accumulated damage and therefore on predicted service life. In a previous study, an effort was made to validate EICM predictions with field-measured temperature and moisture profiles outside the MEPDG. However, this effort was not successful. Therefore, the potential impacts of the accuracy of EICM predictions on MEPDG-predicted damage and hence on expected pavement service life were investigated. Eight weather stations closest to New Jersey's Long-Term Pavement Performance Specific Pavement Study 5 site were analyzed. In addition, to address the interaction between environment and traffic in the MEPDG, analyses were run with two traffic input levels: first with Level 3 traffic data and then with Level 1 traffic data.

Application/Use: This paper can be used to evaluate the adequacy of the EICM and the impacts of environment and traffic on M-E PDG predictions.

Contribution: Improvement in Knowledge

Present Benefit: The findings from this study are beneficial to the implementation and use of the M-E PDG. Understanding sensitivity and interactions between inputs into the performance models is very useful to designers. Additionally, an evaluation of the accuracy of the EICM will ultimately improve the pavement designs produced through the M-E PDG.

Future Benefit: This study will be used to understand the variability inherent in the EICM and its effect on pavement design in the M-E PDG. Findings from this study may be used to modify the M-E PDG.

Title: Observed Effects of Subgrade Moisture on Longitudinal Profile

Author(s): Stoffels, D.E; Shelley; Lee; Woo, Seung; Bae, Abraham

Date: 2006

Publisher: Transportation Research Board

Abstract/Synopsis: This paper describes how moisture in subgrade soils is a major environmental factor considered in pavement design. The influences of subgrade moisture on roughness of longitudinal profile were investigated for 43 asphalt pavements of the Seasonal Monitoring Program (SMP) sites in the Long-Term Pavement Performance (LTPP) program. Volumetric moisture content in the subgrade was quantified as a moisture index, computing means and standard deviations for that moisture index during seasonal monitoring periods. Using the power spectral density function, roughness of a longitudinal profile was evaluated using the root mean square values in all possible ranges of wavebands. Then, the time-dependent change of the roughness values in each waveband was statistically analyzed with soil information, freezing index, and freezing cycle, focused principally on effects of moisture in subgrade. From the statistical analysis, it was concluded that moisture in the subgrade significantly affects several wavebands, including 5.0 to 31.2 m and 5.0 to 39.0 m for freezing and non-freezing sites, respectively. In non-freezing sites, as average value and variation of moisture increase, pavement surface profile deteriorates quickly. In freezing sites, it was found that moisture variation due to frost action dominantly contributes to roughness deterioration. In addition to mean moisture and moisture variation, it was found that percent passing 0.002 mm soil size and the depth to the top of subgrade are also significant factors accelerating the roughness changes in freezing and non-freezing sites, respectively.

Application/Use: The effect of moisture on pavement roughness can be used to determine if pavement drainage is a cost-effective alternative in pavement design given local conditions.

Contribution: Improvement in Knowledge

Present Benefit: The SMP portion of LTPP has provided valuable information on in situ moisture, temperature, and frost conditions of pavement sections and the variation of these conditions through the seasons. Coupling this with the measured performance data enables studies such as this to be completed.

Future Benefit: Understanding the effect of subgrade properties and in situ moisture conditions can be used in pavement design and is of particular interest in M-E based design.

Title: Resilient Modulus of Subgrade Soils A-1-b, A-3, and A-7-6 Using LTPP Data: Prediction Models with Experimental Verification

Authors: Joshi, Shaddha; Malla, Ramesh B.

Date: February 2006

Publisher: American Society of Civil Engineers

Conference Title: Proceedings of GeoCongress 2006, Geotechnical Engineering in the Information Technology Age

Abstract/Synopsis: Accurate evaluation of subgrade resilient modulus (M_R) is important for effective and economical design of flexible pavements. Resilient modulus of subgrade soil is the elastic modulus based on the recoverable strain under repeated loads and depends on several factors like soil properties, soil type, and stress states. This paper presents prediction equations to estimate M_R from a set of soil physical properties for 3 AASHTO subgrade soil types, namely A-1-b, A-3, and A-7-6. The prediction models were developed using the multiple linear regression analysis of the data extracted from Long Term Pavement Performance Information Management System (LTPP IMS) Database for 82 test specimens, approximately 1230 M_R values, from 16 states in New England and nearby regions in the U.S. and 1 province in Canada. Generalized constitutive model consisting bulk stress and octahedral shear stress was used to predict M_R of subgrade soils by developing regression equations for the k-coefficients that relate these coefficients to various soil properties, e.g. particle size, moisture contents, densities, and Atterberg limits. The R^2 values obtained for the prediction equations for k coefficients relating to the soil properties range from 0.45 to 0.79. To verify the prediction models independently, laboratory M_R tests were conducted on a few New England subgrade soils. It was observed that the predicted M_R values compared well with the laboratory measured values for A-1-b soil samples. However, because of some soil property values being outside the range used in the development of the prediction models, the comparison was poor for A-3 soil samples, and for A-7-6 soil, M_R values could not be predicted due to negative values for k_2 coefficient.

Application/Use: This study will be used by materials and pavement engineers looking for subgrade resilient modulus estimates in the New England area.

Contribution: Cost Savings, Improvement in Knowledge.

Present Benefit: Accurate estimates for subgrade resilient modulus are integral to proper pavement design. The models developed will be a useful pavement design tool, particularly in scenarios where resilient modulus data was not obtained. Information on the relationship between FWD backcalculated results and measured resilient modulus will also be useful in design.

<u>Future Benefit:</u> Future pavement designs in New England may be based on correlations derived from this study. Additional benefit will be realized in further investigations of backcalculation and FWD data.

Title: Seasonal Variations in the Moduli of Unbound Pavement Layers

Author(s): Richter, Cheryl A.

Date: 2006

Publisher: Federal Highway Administration

Abstract/Synopsis: The in situ moduli of unbound pavement materials vary on a seasonal basis as a function of temperature and moisture conditions. Knowledge of these variations is required for accurate prediction of pavement life for pavement design and other pavement management activities. The primary objective of this study is to advance the rational estimation of seasonal variations in backcalculated pavement layer moduli using data collected via the Seasonal Monitoring Program of the Long-Term Pavement Performance Program. Principal components of this endeavor included: evaluation of the moisture predictive capabilities of the Enhanced Integrated Climatic Model (EICM); development of empirical models to predict backcalculated pavement layer moduli as a function of moisture content, stress state, and other explanatory variables; and trial application of the models developed to predict backcalculated moduli for unbound pavement layers. This investigation yielded two key findings. First, it provided the impetus for developing EICM Version 2.6 by demonstrating the practical inadequacies of EICM Versions 2.0 and 2.1 when applied to the prediction of in situ moisture content, and then demonstrated that substantial improvement in the moisture predictive capability of the EICM had been achieved in Version 2.6. Second, the research identified fundamental discrepancies between layer moduli backcalculated using linear-layered elastic theory and the laboratory resilient modulus test conditions. Other important findings included (1) variation in moisture content is not always the most important factor associated with seasonal variations in pavement layer moduli, and (2) a model form that fits linear elastic backcalculated moduli reasonably well. The overall accuracy of the modulus predictions achieved in the trial application of the predictive models was not fully acceptable. Several avenues for further research to improve upon these results are identified.

Application/Use: The findings from this study were used to update the EICM, which is used directly in the M-E PDG.

Contribution: Improvement in Knowledge

Present Benefit: Improvement to the EICM provides benefit by improving the prediction capability of the M-E PDG. Additional understanding of the relationship between backcaluclated layer moduli and linear-layered elastic theory is also a direct benefit from this study.

Future Benefit: The use of the updated EICM will increase in value as the M-E PDG is implemented and used. Along those lines, understanding changes in moduli with season and the correlation between backcaclulated and laboratory values will prove to be beneficial to designers in the future.

Title: Truck/Pavement/Economic Modeling and In-Situ Field Test Data Analysis Applications - Volume 1: Influence of Drainage on Selection of Base

Author(s): Sargand, Shad M; Wu, Shin; Figueroa, J. Ludwig

Date: 2006

Publisher: Ohio University, Athens; Ohio Department of Transportation; Federal Highway Administration

Abstract/Synopsis: The primary objective of this study was to investigate how base materials should be properly selected for specific types of pavement, not only considering the performance of individual layers but also how they interact in the total pavement structure. Base types considered in this study included granular (GB), lean concrete (LCB), asphalt treated (ATB), cement treated (CTB), and permeable asphalt treated (PATB) bases as constructed under both asphalt concrete (AC) and Portland cement concrete (PCC) pavements. The Long Term Pavement Performance (LTPP) Seasonal

Title: Verification of Long-Term Pavement Performance Virtual Weather Stations: Phase I Report--Accuracy and Reliability of Virtual Weather Stations

Author(s): Mohseni, Alaeddin

Date: 2006

Publisher: Federal Highway Administration

Abstract/Synopsis: Within the Long-Term Pavement Performance (LTPP) program, two sources of data are used to characterize the climatic conditions for each test section. For the majority of the test sections, data for nearby national weather stations are obtained from the National Climatic Data Center (NCDC) and are used to compute estimated data for a virtual test section located at the test section. In addition, on-site instrumentation is used to obtain site-specific climatic data for the test sections included in the Seasonal Monitoring Program and for the Specific Pavement Studies (SPS)-1, -2, and -8 project sites. This report documents a study undertaken to examine the reliability and accuracy of the LTPP climatic data. The study confirmed that accurate daily, monthly, and yearly estimates of climatic data for a project location can be derived by using the NCDC weather data for several nearby weather stations. The variation in the climatic data was also characterized.

Application/Use: This report can be used to understand the nature and variability of climatic data reported in the LTPP database

Contribution: Cost Savings, Improvement in Knowledge.

Present Benefit: The climatic database provides estimates of environmental conditions at every LTPP test section, and can be used to select proper PG binder or crack sealant materials. The database can also be used to evaluate the contribution of climatic effects on pavement performance.

Future Benefit: The LTPP climatic database will continue to be used in pavement research as well as M-E PDG calibration/validation. LTPP offers performance data on a national matrix of test sections. Including climatic information is essential to properly account for pavement performance variations.

Title: Deterioration of Asphalt Pavement at Long-Term Pavement Performance Program Site 49-1001 in Utah

Author(s): Blankenagel, Brandon J; Guthrie, W. Spencer

Date: 2005

Publisher: Transportation Research Board

Journal Title: Transportation Research Record: Journal of the Transportation Research Board No. 1933

Abstract/Synopsis: Highway 191 near Bluff, Utah, features a well-monitored section of the Tong-Term Pavement Performance (LTPP) Program. Constructed in 1980, this section of flexible pavement performed well for nearly 13 years. Through this time, cracking of the asphalt layer was minimal. In the fourteenth year, however, the extent of longitudinal cracking in the wheel path increased and necessitated placement of a chip seal on the pavement surface. The purpose of this research was to determine the cause of pavement deterioration using LTPP data. Deflection basins obtained from falling-weight deflectometer testing were analyzed to investigate the extent to which structural degradation influenced deterioration of the pavement. Pavement layer modulus values were plotted against time and clearly show that weakening of the pavement base layer immediately preceded the occurrence of cracking. The geography of the site, as documented in photographs, supports the conclusion that inadequate water drainage at the site permitted saturation of the aggregate base layer during a period of midsummer flooding. This finding emphasizes the importance of specifying non-moisture-susceptible base materials and providing necessary drainage works in pavement design.

Application/Use: This paper is directly applicable to pavement design in Utah; however, the results can be applied to other agencies as well.

Contribution: Cost Savings; Improvement in Knowledge

Present Benefit: Pavement failure investigations are extremely valuable because they provide information into the failure mechanisms. The lessons learned from these types of studies can be used to mitigate failures through design and materials selection.

Future Benefit: The future benefit will be in the form of better performing and more efficient pavements that have been designed to mitigate potential failure sources.

Title: Development of a Pavement Climate Map Based on LTPP Data

Author(s): Wang, Yuhong

Date: 2005

Publisher: Federal Highway Administration; American Society of Civil Engineers

Abstract/Synopsis: It has long been recognized that climate factors have important influences on pavement performance. To help investigate this influence, the Strategic Highway Research Program (SHRP) Long-Term Pavement Performance (LTPP) research has been using onsite or virtual weather stations to record climate information on test sections. The data will facilitate the study of the quantitative relationship between climate and pavement performance. This paper discusses how to develop a climate map using cluster analysis on performance-related climate data from the LTPP database, which contains nearly 1,000 virtual weather stations recorded for more than 17 years. The aim of developing this map is to help researchers, who are performing data analysis on the LTPP database, to incorporate or separate climate factors in their models. Another potential use of this map is to help highway practitioners get climate pattern information for their geographical areas so that they can apply the same design criteria, construction requirements, and maintenance strategies to those regions with similar climate patterns.

Application/Use: The climatic map developed under this project465 p depai40 in pavement design.

Contribution: Improvement in Knowledge

Present Benefit: LTPP has developed 5 pextensive climatic database. It 65 p depaid by designers to estimate precipitation, temperatures, frost penetration, and other climatic factors important to pavement performance. The climatic database is also pai40 to research as climatic factors 65 p deaccounted for in prediction models and analyses.

Future Benefit: The availability of comprehensive climatic data will continue to be beneficial as additional research is conducted on pavement performance and the contribution of environment on performance.

Title: Effect of Seasonal Moisture Variation on Subgrade Resilient Modulus

Author(s): Salem, Hassan M.

Date: 2005

Publisher: Federal Highway Administration; American Society of Civil Engineers

Abstract/Synopsis: It is well known that environmental changes have severe effects on pavement performance. While an asphalt layer may be more sensitive to temperature, a soil or untreated pavement layer might be more affected by the change in moisture. This research aims at quantifying the effect of subgrade moisture variation, caused by environmental changes, on a subgrade's resilient modulus and including its effects in the design process for new and rehabilitated pavements. To achieve this objective, data representing different soil types in non-freeze zones at various Long-Term Pavement Performance Seasonal Monitoring Program (LTPP-SMP) sites were downloaded from the DataPave 3.0 software. The downloaded data were analyzed to establish the effect of subgrade moisture variation on a subgrade's resilient strength represented by the backcalculated elastic modulus. The analysis indicated that moisture in the subgrade layer is related to the precipitation intensity. The study also revealed that a Seasonal Adjustment Factor (SAF) could be used to shift the subgrade modulus from a normal season to another. The SAF is considered a key input in the mechanistic-based pavement design system. It allows the inclusion of the seasonal effects on the layer moduli for different seasons. In this paper, a method is presented for calculating the SAF for the subgrade soils. Using the collected data, regression analysis was performed and correlation equations were developed. These equations relate the backcalculated subgrade modulus to the subgrade moisture content and to other soil properties. The SAF relates the change in the moisture content to the change in the modulus value.

Application/Use: The findings from this study are directly applicable to M-E pavement design.

Contribution: Improvement in Knowledge

Present Benefit: Understanding changes in subgrade modulus as a function of changes in moisture content is beneficial in pavement design. It allows designers to select pavement sections that efficiently account for these seasonal variations.

Future Benefit: As pavement design moves towards M-E PDG practices, understanding modulus changes will be an essential part of the process. The results from this study will be useful in estimating subgrade modulus values in different seasons.

Title: LTPP Data Analysis: Influence of Design and Construction Features on the Response and Performance of New Flexible and Rigid Pavements

Author(s): Chatti, K; Buch, N; Haider, S. W; Pulipaka, A. S; Lyles, R. W; Gilliland, D; Desaraju, P.

Date: 2005

Publisher: National Cooperative Highway Research Program

Journal Title NCHRP Web Document No. 74

Abstract/Synopsis: This report documents and presents the results of a study on the relative influence of design and construction features on the response and performance of new flexible and rigid pavements, included in SPS-1 and SPS-2 experiments. The SPS-1 experiment is designed to investigate the effects of hot mix asphalt (HMA) layer thickness, base type, base thickness, and drainage on flexible pavement performance, while the SPS-2 experiment is aimed at studying the effect of portland cement concrete (PCC) slab thickness, base type, PCC flexural strength, drainage, and lane width on rigid pavement performance. The effects of environmental factors, in absence of heavy traffic, were also studied based on data from the SPS-8 experiment. Various statistical methods were employed for analyses of the LTPP NIMS data (Release 17 of DataPave) for the experiments. In summary, base type seems to be the most critical design factor in achieving various levels of pavement performance for both flexible and rigid pavements, especially when provided with in-pavement drainage. The other design factors are also important, though not at the same level as base type. Subgrade soil type and climate also have considerable effects on the influence of the design factors. Although most of the findings from this study support the existing understanding of pavement performance, the methodology in this study provides a systematic outline of the interactions between design and site factors as well as new insights on various design options.

Application/Use: This study can be used by those interested in the contribution of design factors on flexible and rigid pavement performance.

Contribution: Cost Savings; Improvement in Knowledge.

Present Benefit: The present benefit for this study is an understanding in the interaction between design parameters and climate and the resultant changes in pavement performance. The LTPP database provides a means of conducting this type of study on a national scale. Findings can be used to optimize cost-effective design alternatives.

Future Benefit: The findings from this study will be useful in transferring mechanistic evaluations to field performance for various design parameters.

Title: Sensitivity Analysis of Rigid Pavement Systems Using Mechanistic- Empirical Pavement Design Guide

Author(s): Guclu, Alper; Ceylan, Halil

Date: 2005

Publisher: Iowa State University, Ames

Conference Title: Proceedings of the 2005 Mid-Continent Transportation Research Symposium

Abstract/Synopsis: Pavement design procedures available in the literature do not fully take advantage of mechanistic design concepts, and as a result, heavily rely on empirical approaches. Because of their heavy dependence on empirical procedures, the existing rigid pavement design methodologies do not capture the actual behavior of Portland Cement Concrete (PCC) pavements. However, reliance on empirical solutions can be reduced by introducing mechanistic-empirical methods, now adopted in the newly released Mechanistic-Empirical Pavement Design Guide (MEPDG). This new design procedure incorporates a wide range of input parameters associated with the mechanics of rigid pavements. A study was undertaken to compare the sensitivity of these various input parameters on the performance of concrete pavements. Two Jointed Plain Concrete Pavement (JPCP) sites were selected in Iowa. These two sections are also part of the Long Term Pavement Performance (LTPP) program, where a long history of pavement performance data exists. Data obtained from the Iowa Department of Transportation (Iowa DOT) Pavement Management Information System (PMIS) and LTPP database were used to form two standard pavement sections for the comprehensive sensitivity analyses. The sensitivity analyses were conducted using the MEPDG software to study the effects of design input parameters on pavement performance, specifically faulting, transverse cracking, and smoothness. Based on the sensitivity results, the rigid pavement input parameters were ranked and categorized from most sensitive to insensitive to help pavement design engineers to identify the level of importance for each input parameter. The curl/warp effective temperature difference (built-in curling and warping of the slabs) and PCC thermal properties are found to be the most sensitive input parameters. Based on the comprehensive sensitivity analyses, the idea of developing an expert system is introduced to help the designer identify the input parameters that can be modified to satisfy the predetermined pavement performance criteria.

Application/Use: This paper is useful in implementing the M-E PDG for PCC pavements and of particular interest for pavement designers in Iowa.

Contribution: Improvement in Knowledge

Present Benefit: The M-E PDG implementation process consists of evaluating the sensitivity of the predictions. This paper provides insight into sensitivity for PCC pavements and will aide in establishing the level of effort necessary to quantify material properties used in the M-E PDG.

<u>Future Benefit:</u> As additional agencies begin implementing the M-E PDG, findings from this study will continue to be used as a reference. The LTPP database will also be utilized by many agencies in the implementation process.

Title: Survival Analysis of Fatigue Cracking for Flexible Pavements Based on Long-Term Pavement Performance Data

Author(s): Wang, Yuhong; Mahboub, Kamyar C; Hancher, Donn E.

Date: 2005

Publisher: American Society of Civil Engineers

Journal Title: Journal of Transportation Engineering Vol. 131 No. 8

Abstract/Synopsis: The study presented in this paper analyzed the development patterns of fatigue cracking shown in flexible pavement test sections of the Long-Term Pavement Performance (LTPP) Program. A large number of LTPP test sections exhibited a sudden burst of fatigue cracking after a few years of service. In order to characterize this type of LTPP cracking data, a survival analysis was conducted to investigate the relationship between fatigue failure time and various influencing factors. After dropping insignificant influencing factors, accelerated failure time models were developed to show the quantitative relationship between fatigue failure time and asphalt concrete layer thickness, Portland cement concrete base layer thickness, average traffic level, intensity of precipitation, and freeze-thaw cycles. The error distribution of the accelerated failure time model was found to be best represented by the generalized gamma distribution. The model can also be used to predict the average behavior of fatigue failures of flexible pavements.

Application/Use: The evaluation of fatigue cracking can be used to predict average fatigue performance, which is applicable in pavement management.

Contribution: Improvement in Knowledge

Present Benefit: This analysis investigates the contribution of key factors on fatigue accumulation and provides a pavement performance prediction tool. This is beneficial to those interested in predicting average fatigue performance for a given set of conditions.

Future Benefit: LTPP will continue to benefit the pavement community by providing quality data for research.

Title: Seasonal Monitoring Program - One Stop Shopping!

Date: 2004

Publisher: Transportation Research Board

Journal Title: Product Brief

Abstract/Synopsis: The Strategic Highway Research Program (SHRP) established a seasonal monitoring program (SMP) within its Long-Term Pavement Performance (LTPP) program. The objective of this SMP was to "provide data needed to attain a fundamental understanding of the magnitude and impact of temporal variations in pavement response and material properties due to the separate and combined effects of temperature, moisture and frost/thaw variations." This Product Brief briefly describes the SMP CD-ROMs, which were built to provide all the information about the program. The CD-ROMs include the following topics: Introduction to the SMP, Data Tutorial, SMP Videos, SMP Installation Guide, Data User's Guide, Table Navigator, and Document Navigator.

Application/Use: The SMP CD-ROMs provide users with the tools and data necessary to evaluate a wide range of seasonal impacts on pavement performance.

Contribution: Improvement in Knowledge; Implementation/Usage; Advancing Technology.

Present Benefit: The Seasonal Monitoring Program provided substantial advancement in technology and knowledge. Significant effort was expended by the LTPP team in developing a system to measure moisture content within the pavement structure using time domain refelectometry. The same holds true for the use of electrical resistivity in monitoring frost penetration.

The collection of temperature, moisture, and frost data has been instrumental in developing relationships between pavement response and in situ conditions. Pavement temperature prediction models have been developed based on the data. This has resulted more accurate FWD adjustments to account for temperature. Correlations between pavement response and seasonal conditions have been useful in determining the proper time to apply load restrictions.

Future Benefit: The data collected as part of SMP will assist in understanding mechanistic properties of pavement structures and how those properties change through the seasons. The instrumentation applied to pavement monitoring will also be useful in evaluating new materials and pavement structures as they are developed. A thorough understanding of seasonal properties is fundamental in mechanistic-empirical design.

Title: Using Long-Term Pavement Performance Data to Predict Seasonal Variation in Asphalt Concrete Modulas

Author(s): Salem, H. M; Bayomy, F M; Al-Taher, M. G; Genc, I. H.

Date: 2004

Publisher: Transportation Research Board

Journal Title: Transportation Research Record No. 1896

Abstract/Synopsis: The seasonal variation of the asphalt concrete (AC) modulus with changes in pavement temperature is discussed. The main goal of the research was to develop (a) regression models that enable design engineers to assess seasonal changes in AC modulus and (b) an algorithm for calculating a seasonal adjustment factor (SAF) that allows estimating AC modulus in any season from a known reference value. The study is based on analyzing data collected at Long-Term Pavement Performance (LTPP) program sites in both freezing and nonfreezing zones. The data were obtained from the LTPP database in the DataPave 3.0 software. The approach adopted in this study was to select LTPP-seasonal monitoring program sites that represent various climatic regions and use the backcalculated modulus and pavement temperature data to develop regression models for the modulus-temperature relationships for various sites in both freezing and nonfreezing zones. Two regression models were developed to relate the variation in modulus with the variation in pavement temperatures in various seasons for both freezing and nonfreezing zones. These models incorporate AC layer properties such as thickness, bulk specific gravity, air voids, and asphalt binder grade. A model for determining the SAF was also developed.

Application/Use: The findings from this study are directly applicable to pavement design.

Contribution: Improvement in Knowledge

Present Benefit: Understanding changes in AC modulus as a function of changes in temperature is beneficial in pavement design. It allows designers to select pavement sections and materials that efficiently account for these seasonal variations.

Future Benefit: As pavement design moves towards M-E PDG practices, understanding modulus changes will be an essential part of the process. The results from this study will be useful in estimating AC modulus values in different seasons.

Title: Effects of Various Design Features on Rigid Airfield Pavement Design

Author(s): Lee, Y-H; Yen, S-T.

Date: 2002

Publisher: American Society of Civil Engineers

Conference Title: Designing, Constructing, Maintaining, and Financing Today's Airport Projects. Proceedings of the Twenty-Seventh International Air Transport Conference

Abstract/Synopsis: Regardless of a shorter or longer joint spacing, a better or worse load transfer mechanism, and environmental effects, the required minimum slab thickness will be the same using the current airfield pavement design procedure. Thus, the primary objective of this paper is to investigate the effects of many design features including finite slab sizes, thermal curling, moisture warping, and the presence of a second subbase layer on rigid airfield pavements in attempts to expand the applicability of the proposed thickness design procedure. The Corps of Engineers full-scale test pavement data were reanalyzed and several prediction models were utilized to estimate the critical edge stress for design. Stress adjustment factors for finite slab width and length were determined and found to be negligible for the test data. Since the concept of transformed section was frequently utilized and sometimes misused in the literature to account for the stress reduction due to a bonded or unbonded second layer, a more complete treatment of this concept was presented. Subsequently, the stress adjustment factor was estimated assuming all subbase layers were unbonded. Climatic data close to the test track locations were obtained from the Long-Term Pavement Performance (LTPP) database and the stress adjustment factor due to effective temperature differentials was estimated. As a result, an alternative structural deterioration model was proposed for future trial analysis and design. The primary benefit of this study and recommendations for future implementation and investigations are discussed.

Application/Use: This is directly applicable to airport pavement design.

Contribution: Improvement in Knowledge

Present Benefit: This paper is an example of how climatic data collected at an LTPP test section can be applied to other nearby areas and projects. The LTPP climatic database is fairly large and may be used along with the virtual weather station procedures to approximate weather conditions in areas relatively close to operating LTPP weather stations.

Future Benefit: The LTPP climatic database will continue to add benefit as researchers and designers utilize the years of data collected. This data, coupled with the virtual weather station calculation procedures, can be used to estimate climatic conditions for project locations of interest.

Title: Evaluation of Moisture Sensitivity Properties of ADOT Mixtures on US 93. Volume I - Final Report

Author(s): Sebaaly, Peter E; Eid, Zein; Epps, Jon A.

Date: 2001

Publisher: University of Nevada, Reno; Arizona Department of Transportation; Federal Highway Administration

Abstract/Synopsis: In 1993, the Arizona Department of Transportation (ADOT) constructed pavement test sections as part of the Long Term Pavement Performance (LTPP) Specific Pavement Studies (SPS). The test sections are located on US 93 north of Kingman, Arizona, and consist of both SPS-1 and SPS-9 experiments constructed at the same location. As early as 1996 it was reported that fatigue cracking was occurring in the SPS-9 SUPERPAVE sections. A field visit in 1998 by personnel from ADOT, LTPP and the FHWA revealed that the SPS-9 SUPERPAVE test sections were experiencing premature fatigue cracking while the SPS-1 test sections which used Marshall Mix designs had not experienced any distress. The survey team concluded that moisture sensitivity may be the primary cause of the premature fatigue of the SUPERPAVE designed HMA mixtures. An investigation into this premature failure was subsequently initiated. This report describes the performance of the SPS-9 sections and documents the laboratory evaluation of mixtures and cores from the three sections in an effort to assess the appropriateness of the SUPERPAVE moisture damage requirements. The three evaluated sections included: a SUPERPAVE designed section with 1" nominal maximum size, a SUPERPAVE designed section with 3/4'" nominal maximum size, and an ADOT Marshall designed section with ¾" nominal maximum size.

Application/Use: This study is useful to Arizona for adopting SUPERPAVE mix design procedures.

Contribution: Improvement in Knowledge; Advancement in Technology; Lessons Learned

Present Benefit: The LTPP SPS-9 experiment offers side-by-side comparisons of SUPERPAVE mixtures and agency standard mixtures. Because all other factors are constant, the study provided an excellent means of comparing mixture performance. This study has provided Arizona DOT with information on the difference between the mix design procedures. The findings may be used to adjust mix design specifications to meet the needs in Arizona.

Future Benefit: Performance data collected at SPS-9 experiments will be useful in evaluating long term performance of SUPERPAVE mixture relative to agency standard mixtures. This information will be useful in refining mix design procedures to optimize performance in a given region.

Title: LTPP Data Analysis: Factors Affecting Pavement Smoothness

Author(s): Perera, R. W; Kohn, S. D.

Date: 2001

Publisher: National Cooperative Highway Research Program; Soil and Materials Engineers, Incorporated

Journal Title: NCHRP Web Document 40

Abstract/Synopsis: In this research project, data available in the Long Term Pavement Performance (LTPP) Information Management System (IMS) were used to determine the effect of factors such as design and rehabilitation parameters, climatic conditions, traffic levels, material properties, and extent and severity of distress that cause changes in pavement smoothness. For the purposes of this research, the International Roughness Index (IRI) was used as the measure of pavement smoothness. The LTPP program consists of two complementary programs, the General Pavement Studies (GPS) and Specific Pavement Studies (SPS). Chapter 1 of this project report provides an introduction. Chapter 2 presents the review of literature related to factors affecting pavement smoothness and roughness development in pavements. Chapter 3 presents the data elements that were selected for analysis and data synthesis methods that were used with the data obtained from the IMS. Chapter 4 presents the data analysis methods that were utilized during the study. Chapter 5 describes roughness characteristics of new pavements, and describes the results obtained from the SPS-1 and SPS-2 experiments. Chapter 6 describes roughness characteristics of rehabilitated pavements, and describes results obtained from SPS-5 and SPS-6 experiments. Chapter 7 presents the results obtained for GPS experiments in the first design phase, which are GPS experiments 1 through 5. Chapter 8 presents the results obtained for GPS experiments 6 and 7, which are overlaid pavements. Chapter 9 presents the conclusions and recommendations for future research.

Application/Use: This study is valuable to those involved in selecting and designing pavements, including rehabilitation alternatives.

Contribution: Cost Savings; Improvement in Knowledge.

Present Benefit: The findings from this report are beneficial because they quantify the contribution of various design parameters as well as rehabilitation techniques to roughness accumulation. This is important to designers attempting to select the most appropriate alternative with consideration given to end user cost and perception.

Future Benefit: The evaluation conducted as part of this project will continue to be useful. Currently, rehabilitation is the most common type of major asphalt concrete pavement improvement. Quantifying the relationship between strategy and roughness accumulation will prove to be beneficial in the years to come. This information can be used to select treatment options that will provide pavements that remain smoother for longer periods of time.

Title: Parameter Study of Load Transfer and Curling Effects on Rigid Pavement Deflections

Author(s): Lee, Y-H; Sheu, R-S.

Date: 2001

Publisher: National Center for Asphalt Technology

Conference Title: Second International Symposium on Maintenance and Rehabilitation of Pavements and Technological Control. Segundo Simposio Sobre Manutencao e Rehabilitacao de Pavimentos e Controle Technologico

Abstract/Synopsis: Extensive re-backcalculation analysis of test sections of the Long Term Pavement Performance (LTPP) general pavement studies indicated that extreme difficulties in interpreting in situ deflection measurements of rigid pavements have been encountered, probably due to the effects of temperature curling, moisture warping, and loss of subgrade support. Thus, effects of adjacent slabs and temperature curling on rigid pavement deflections were examined in this work. The ILLISLAB finite element program was used for the analysis. Both dense liquid and elastic solid foundation options were analyzed. To allow the analysis of a curled slab resting on an elastic solid foundation, some proper corrections were made and verified. Two additional dimensionless variables were identified for the curling effects on elastic solid foundation. Both doweled and undoweled joints were treated as having shear load transfer only. Many factorial finite element runs were carefully selected and conducted to obtain generalized deflection databases. Prediction models for deflection adjustment factors were developed using local regression techniques. Ongoing research is underway to develop an integrated backcalculation program to facilitate analysis of more practical rigid pavement backcalculation problems.

Application/Use: This study is applicable to those interested in evaluating FWD data on concrete pavements.

Contribution: Improvement in Knowledge; Advancement in Technology.

Present Benefit: This study offers backcalculation results for rigid test sections in the LTPP database, which can be used by others interested in material layer properties. Adjustments made for slab curl may be useful to individuals analyzing FWD data. Also, the prediction models and deflection adjustment factors may also be incorporated into other pavement evaluations.

Future Benefit: This study will provide benefit to those using FWD data to conduct pavement evaluations. The LTPP database is beneficial in this regard as it allows various backcalculation procedures to be evaluated and refined, which can then be applied to other projects.

Title: Accuracy of Weather Data in Long-Term Pavement Performance Program Database

Author(s): Wu, C-L; Rada, G. R; Lopez, A; Fang, Y.

Date: 2000

Publisher: Transportation Research Board

Journal Title: Transportation Research Record No. 1699

Abstract/Synopsis: To provide accurate climatic data for pavements under the Long-Term Pavement Performance (LTPP) Program, a climatic database was developed in 1992 and subsequently revised and expanded in 1998. In the development of this database, up to five nearby weather stations were selected for each test site. Pertinent weather data for the selected weather stations were obtained from the U.S. National Climatic Data Center and the Canadian Climatic Center. With a 1/R-squared weighting scheme, site-specific climatic data were derived from the nearby weather station data. The derived data were referred to as "virtual" weather data. To evaluate the effect of environmental factors on pavement performance and design, automated weather stations (AWS) were installed at LTPP Specific Pavement Study Projects 1, 2, and 8 to collect on-site weather data. Since the virtual weather data were developed for all LTPP test sites and will be used for future pavement performance studies, it is essential that the derived virtual data be accurate and representative of the actual on-site climatic conditions. The availability of the AWS weather data has provided an opportunity to evaluate whether virtual weather data can be used to represent on-site weather conditions. Daily temperature data and monthly temperature and precipitation data were used in this experiment. On the basis of the comparisons made between the virtual and on-site measured (AWS) data, it appears that climatic data derived from nearby weather stations using the 1/R-squared weighting scheme estimate the actual weather data reasonably well and thus can be used to represent on-site weather conditions in pavement research and design.

Application/Use: This report can be used to understand the nature and variability of climatic data reported in the LTPP database.

Contribution: Cost Savings, Improvement in Knowledge.

Present Benefit: The climatic database provides estimates of environmental conditions at every LTPP test section. The database can also be used to select appropriate PG binders or crack sealants. The database can also be used to evaluate the contribution of climatic effects on pavement performance.

Future Benefit: The LTPP climatic database will continue to be used in pavement research as well as for M-E PDG calibration/validation. LTPP offers performance data on a national matrix of test sections. Including climatic information is essential to properly account for variations in pavement performance.

Title: Characterizing Seasonal Variations in Pavement Material Properties for Use in a Mechanistic-Empirical Design Procedure

Authors: Ovik, J. M; Birgisson, B; Newcomb, D. E.

Date: 2000

Publisher: University of Minnesota, Minneapolis; Minnesota Department of Transportation

Abstract/Synopsis: Recent advances in flexible pavement design have prompted agencies to move toward the development and use of mechanistic-empirical (M-E) design procedures. This report analyzed seasonal trends in flexible pavement layer moduli to calibrate an M-E design procedure specific to Minnesota. Seasonal trends in pavement layer moduli were quantified using data from the Minnesota Road Research Project (Mn/ROAD) and Long Term Pavement Performance Seasonal Monitoring Program (LTPP SMP) sites located in Minnesota. The relationships investigated were between climate factors, subsurface environmental conditions, and pavement material mechanical properties. The results show that pavement layer stiffness is highly responsive to changes in the average daily temperature and available moisture. Five seasons were used to characterize the seasonal variations in pavement layer moduli for design purposes. Seasonal factors were used to quantify the cyclic variations in the pavement layer stiffness for a typical year. The maximum stiffness of the pavement layers is reached when temperatures are cooler. The hot mix asphalt layer moduli are at a minimum in the summer when temperatures are high. The granular base layer moduli are at a minimum during the early spring-thaw period when excess moisture is unable to drain. Finally, the fine-grained subgrade layer moduli are at a minimum in late spring and summer due to the low permeability and slow recovery of the material. The Integrated Climate Model (ICM) was used in this study to compare predicted data to actual data from Mn/ROAD. It was found that the ICM data compared favorably, however, the ICM was not able to predict the spring-thaw period.

Application/Use: This report is directly applicable to pavement design in the Minnesota region.

Contribution: Cost Savings; Improvement in Knowledge.

Present Benefit: Findings from this study provide useful information on the mechanistic property changes in pavement materials. This can be used to make cost-effective design decisions on effective subgrade resilient modulus values.

Future Benefit: The study will provide future benefit in calibrating and implementing the M-E PDG in the Minnesota area.

Title: Seasonal Trends and Causes in Pavement Structural Properties

Author(s): Ali, H; Selezneva, O.

Date: 2000

Publisher: American Society for Testing and Materials

Conference Title: Symposium on Nondestructive Testing of Pavements and Backcalculation of Moduli: Third Volume

Abstract/Synopsis: The seasonal monitoring program (SMP) of the long term pavement performance (LTPP) program provides an excellent opportunity to study the seasonal trends in pavement response. In 64 pavement sections in the United States and Canada, falling weight deflectometer (FWD) testing is performed monthly every other year, subsurface temperature is measured hourly, subsurface moisture and freezing conditions are measured monthly, and climate factors such as ambient air temperature, solar radiation, wind speed, and precipitation are collected continuously. In this study, a number of SMP sections were used to establish some general and statistically significant trends. The relationship between the elastic modulus of the AC layer and the temperature gradient within the layer was investigated. The relationship between the frost penetration in unbound layers and their backcalculated modulus was studied. Modeling such variability using linear and nonlinear formulations was attempted, and the practical implications of such effects on the data collection practice are discussed.

Application/Use: This study is directly applicable to pavement structural and materials design.

Contribution: Improvement in Knowledge

Present Benefit: Understanding changes in material properties due to seasonal variation in temperature, precipitation, and frost condition is beneficial to pavement designers and materials engineers. This allows pavement rehabilitation or reconstruction alternatives to properly account strength changes throughout the year, ultimately leading to more cost-effective designs.

Future Benefit: The ability to estimate in situ material properties in the various seasons will be necessary for designing pavements in accordance with the M-E PDG.

Title: Temperature Predictions and Adjustment Factors for Asphalt Pavement

Author(s): Lukanen, E. O; Stubstad, R; Briggs, R.

Date: 2000

Publisher: Braun Intertec Corporation; Federal Highway Administration

Abstract/Synopsis: This report presents the results of an analysis of the response that deflections and backcalculated asphalt moduli have to the pavement temperature. The study used deflection and temperature data from 40 sites monitored in the Seasonal Monitoring Program of the Long Term Pavement Performance (LTPP) program. The report presents improved methods of estimating the temperature within an asphalt pavement based on the measurement procedures used for the LTPP program. The data necessary to estimate the temperature within the asphalt included the surface temperature, time of day, depth below the surface, and the average air temperature from the previous day. Backcalculation of the asphalt modulus from the deflection data of the 40 sites was related to pavement temperature, and a method of estimating what the modulus of the asphalt would be at different temperatures is presented. Deflection and deflection basin shape factor response to temperature was also evaluated, resulting in relationships for each of the items evaluated with pavement temperature. Items evaluated include the deflection under the load plate (center sensor), center sensor minus offset sensors, center sensor divided by offset sensors, AREA factor, and the F-1 factor. The relationships were then used to develop procedures for adjusting for the effects of temperature.

Application/Use: The findings and relationships developed in this study are directly applicable to FWD data collection and analysis.

Contribution: Cost Savings; Improvement in Knowledge.

Present Benefit: Knowing the relationship between FWD backcalulation and pavement temperature is essential in using FWD data for design and evaluation purposes. Results obtained from FWD data are dependent on the temperature during data collection. This study identifies adjustments to be made to standard temperatures for use in design and evaluation processes. Accurate temperature-response relationships result in improved designs.

Future Benefit: The SMP experiment conducted as part of LTPP will continue to benefit the pavement community. SMP data includes in situ material properties, climatic, and response data. This information can be used to study the effect of season and temperature on pavement response.

Title: Variations in Backcalculated Pavement Layer Moduli in LTPP Seasonal Monitoring Sites

Author(s): Briggs, R. C; Lukanen, E. O.

Date: 2000

Publisher: American Society for Testing and Materials

Conference Title: Symposium on Nondestructive Testing of Pavements and Backcalculation of Moduli: Third Volume

Abstract/Synopsis: Seasonal variations in structural parameters were calculated from falling weight deflectometer data on 25 long term pavement performance (LTPP) flexible seasonal monitoring sections. In all, 23,976 deflection basins were analyzed. The deflection basins were collected monthly between the fall of 1993 and the spring of 1995. The test locations were distributed around North America from Saskatchewan to South Texas and from Idaho to Maine. The sections all consisted of asphalt surfacing and granular bases over subgrades. Asphalt thicknesses ranged from 46 to 277 mm. Seasonal variations observed on selected sections in this database and documented in this paper include variations in asphalt materials with temperature, variations in moduli of the unbound materials with precipitation, and variations in moduli of unbound materials due to freeze/thaw.

Application/Use: This paper is applicable to the evaluation of FWD data as well as seasonal variation.

Contribution: Improvement in Knowledge

Present Benefit: Understanding changes in material properties due to seasonal variation in temperature, precipitation, and frost condition is beneficial to pavement designers and materials engineers. This allows pavement rehabilitation or reconstruction alternatives to properly account strength changes throughout the year, ultimately leading to more cost-effective designs.

Future Benefit: The ability to estimate in situ material properties in the various seasons will be necessary for designing pavements in accordance with the M-E PDG.

Title: Analysis of Time Domain Reflectometry Data from LTPP Seasonal Monitoring Program Test Sections

Authors: Jiang, Y J; Tayabji, S. D.

Date: 1999

Publisher: ERES Consultants, Incorporated; Federal Highway Administration

Abstract/Synopsis: Time domain reflectometry (TDR) has become one of the most reliable methods for measuring in-situ soil moisture content. TDR sensors developed by the Federal Highway Administration (FHWA) are being used in the Long-Term Pavement Performance (LTPP) Seasonal Monitoring Program (SMP) to monitor the in-situ moisture content at selected LTPP sites. The main goal of the study reported here was to develop procedures to produce good estimates of in-situ gravimetric moisture content. All the TDR traces in the LTPP database were processed using the approach described in this report. To estimate the in-situ gravimetric moisture content, methods were selected to interpret TDR traces. An algorithm and a computer program, Moister, were developed to implement these TDR interpretative methods. After that, the apparent length of the TDR trace and the dielectric constant of the unbound material were computed. Models were developed to relate dielectric constant with in-situ volumetric moisture content. Finally, gravimetric moisture content was computed using the volumetric moisture content value and dry density of the soil. A diagnostic study of the computed gravimetric moisture content was also conducted to evaluate the reasonableness of the computed moisture contents. As part of the overall LTPP data analysis effort, it is expected that the information on the seasonal variation in the moisture content of the unbound base, subbase, and subgrade layers will be used to develop improved understanding of the seasonal variation in the load-carrying capacity of pavements and the subsequent effect on pavement performance.

Application/Use: This report is useful to pavement designers, materials engineers, and researchers.

Contribution: Improvement in Knowledge; Advancement in Technology; Implementation/Usage.

Present Benefit: This study is beneficial in documenting procedures that can be used to estimate moisture content from TDR traces. This approach could be used by others to collecting in situ moisture condition data to estimate seasonal variability in subgrade resilient modulus for design purposes.

The end result of this project was the addition of valuable moisture data in the LTPP database. This information coupled with performance monitoring and response data will be extremely useful to researchers.

Future Benefit: The TDR equipment specification, installation protocols, and data will continue to add value. Trace data is available for the development of new interpretation techniques and moisture content estimates. Additionally, the equipment and installation practices can be applied to other applications.

Title: Determination of Frost Penetration in LTPP Sections, Final Report

Authors: Ali, H. A; Tayabji, S. D.

Date: 1999

Publisher: ERES Consultants, Incorporated; Federal Highway Administration

Abstract/Synopsis: To better understand the environm

Title: Evaluation of In-Situ Moisture Content at Long-Term Pavement Performance Seasonal Monitoring Program Sites

Authors: Jiang, Y. J; Tayabji, S. D.

Date: 1999

Publisher: Transportation Research Board

Journal Title: Transportation Research Record No. 1655

Abstract/Synopsis: Time domain reflectometry (TDR) has become one of the most reliable nondestructive methods for measuring in situ soil moisture content. TDR sensors developed by the Federal Highway Administration are being used in the Long-Term Pavement Performance (LTPP) Seasonal Monitoring Program (SMP) to monitor the in situ moisture content at 64 LTPP sites. The main goal of this study is to develop procedures to produce good estimates of in situ gravimetric moisture content. All the TDR traces in the LTPP information management system database that were recorded at LTPP SMP test sections were processed using the approach described in this paper. To estimate the in situ gravimetric moisture content, methods were selected to interpret TDR traces. An algorithm and a computer program, Moister, were developed to implement these TDR interpretation methods. Then the apparent length of the TDR trace and the dielectric constant of the unbound material were computed. Models were developed to relate dielectric constant with in situ volumetric moisture content. Finally, gravimetric moisture content was computed using the volumetric moisture content value and dry density of the soil. A diagnostic study of the computed gravimetric moisture content was also conducted to evaluate the reasonableness of the computed moisture content.

Application/Use: This report is useful to pavement designers, materials engineers, and researchers.

Contribution: Improvement in Knowledge; Advancement in Technology.

Present Benefit: This study is beneficial in documenting procedures that can be used to estimate moisture content from TDR traces. This approach could be used by others collecting in situ moisture condition data to estimate seasonal variability in subgrade resilient modulus for design purposes.

The end result of this project was the addition of valuable moisture data in the LTPP database. This information coupled with performance monitoring and response data will be extremely useful to researchers.

Future Benefit: The TDR equipment specification, installation protocols, and data will continue to add value. Trace data is available for the development of new interpretation techniques and moisture content estimates.

Title: LTPPBind: A New Tool for Selecting Cost-Effective SUPERPAVE Asphalt Binder Performance Grades

Date: 1999

Publisher: Federal Highway Administration

Journal Title: Product Brief

Abstract/Synopsis: A limited amount of pavement temperature data was available when the Strategic Highway Research Program (SHRP) developed its SUPERPAVE system. As such, specifications for SHRP's SUPERPAVE Performance Grade (PG) asphalt binders were based on the lowest and highest temperatures expected at a site. Recently, the Long Term Pavement Performance (LTPP) program used data from its Seasonal Monitoring Program to quantify the relationship between air and pavement temperatures. This evaluation resulted in the development of improved low and high pavement temperature models for selecting SUPERPAVE PG asphalt binders. Now these improved models are available in a new software program called LTPPBind. This Product Brief explains what LTPPBind is, who can benefit from it, its various tools and features, and the LTPPBind system requirements.

Application/Use: LTPPBind software can be used to select the appropriate PG binder grading for a given climate and design reliability. It is also useful in selecting crack sealant with material properties that match climatic demands of the project.

Contribution: Cost Savings; Implementation/Usage.

Present Benefit: Improper binder selection in pavement design can lead to premature pavement failures and costly repairs. LTPPBind provides the means to select PG binder grading that matches the climatic demands and reliability of the project. This improves pavement performance and reduces the probability of premature failure. Similarly, LTPPBind can be beneficial in selecting appropriate crack sealant. Crack sealant with the appropriate material properties will not fail prematurely. This improves pavement performance and slows future deterioration. An estimated $50 million/year has been saved as a result of designers utilizing the LTPPBind software.

Future Benefit: Proper selection of binder and crack sealant will lead to an overall improvement in pavement performance. As agencies implement pavement management programs with optimal maintenance timing, it is critical to select crack sealants that will perform well for many years.

Title: Canadian Strategic Highway Research Program (C-SHRP) Phase III Program Proposal 1999-2004

Date: 1998

Publisher: Transportation Association of Canada

Abstract/Synopsis: The Canadian Strategic Highway Research Program (C-SHRP) was launched in 1987 to systematically extract the benefits from research undertaken by the Strategic Highway Research Program (SHRP) in the United States. This program was initiated in response to the continuing deterioration of highway infrastructure, with the intention of making significant advances in traditional highway engineering and technology through the concentration of research funds on four key technical areas. C-SHRP aims to solve high priority highway problems in Canada that are related to SHRP topics. The goal of both SHRP and C-SHRP is to improve the performance and durability of highways and to make them safer for motorists and highway workers. The initial SHRP and C-SHRP research contributed 138 products to improve highway systems and initiated the 20-year Long-Term Pavement Performance (LTPP) studies. Since 1994, activities have concentrated on technology transfer to put the research findings into practice and on continuation of the LTPP studies. Fifty-three of the research products have been put into practice by at least one agency in Canada. An additional 14 are partially implemented. The third term proposed for C-SHRP (1999-2004) will spread the use of these products to other sponsoring agencies to improve the performance, durability and economy of the nation's highway system.

Application/Use: The C-SHRP program will be useful for pavement engineers in Canada.

Contribution: Cost Savings; Improvement in Knowledge; Advancement in Technology.

Present Benefit: The C-SHRP program has provided additional data that supplements the LTPP program. In particular, the program has allowed test sections in extreme northern climates to be monitored. This provides additional research data and improves the experimental design.

Future Benefit: Canadian provinces and northern-tiered states will benefit from the C-SHRP program by having a data source that can be used to better understand pavement performance in cold climates. Additionally, these agencies will use the data to calibrate and validate the M-E PDG.

Title: LTPP Seasonal Asphalt Concrete (AC) Pavement Temperature Models

Authors: Mohseni, A.

Date: 1998

Publisher: Pavement Systems (PavSys); Federal Highway Administration

Abstract/Synopsis: SUPERPAVE binders are selected based on the lowest and highest pavement temperatures expected at a job. The original SUPERPAVE specifications were developed with limited data for validating the low-temperature algorithm for pavement temperatures. The lowest air temperature was assumed for the lowest pavement temperature. In areas with extremely low temperatures, this conservative approach has led to the selection of more restrictive binder grades than may be necessary. These binder grades usually require that modifiers be added to the asphalt, which increases the cost of the project. The initial round (Loop-1) of the Long Term Pavement Performance study's Seasonal Monitoring Program (LTPP-SMP) - the collection of pavement and air temperatures at 30 test sites throughout North America - was completed in 1995. The availability of these data makes it possible to evaluate and refine existing pavement temperature algorithms. Two new temperature data bases that combine the SMP data with weather station data from the original SUPERPAVE binder specifications were developed under this study. These data bases are used as tools throughout the study to further refine the existing low- and high-temperature models. This report proposes revisions to the Strategic Highway Research Program (SHRP) Performance Grading System for asphalt binder selection. Revised models for determining the low- and high-temperature component of SUPERPAVE performance-based binders are presented and compared with existing models and resulting performance grades.

Application/Use: This study is directly applicable to binder selection in AC pavements.

Contribution: Cost Savings; Improvement in Knowledge; Advancement in Technology.

Present Benefit: The pavement and air temperature data collected at LTPP-SMP sites provided an excellent source to make refinements in prediction algorithms. Improved models result in more accurate estimates of actual pavement temperatures. With this information, materials engineers can select the appropriate binder without excessive conservatism, thereby reducing costs without sacrificing performance.

Future Benefit: The LTPP-SMP data will continue to benefit the pavement community. The data can be used to models temperature and moisture changes in pavements and correlate these variations to pavement response. The information will be extremely valuable in moving towards an M-E pavement design approach.

Title: LTPP Data Analysis: Improved Low Pavement Temperature Prediction

Date: 1998

Publisher: Federal Highway Administration

Journal Title: TechBrief

Abstract/Synopsis: The Seasonal Monitoring Program (SMP), an element of the Long-Term Pavement Performance (LTPP) study, was initiated in 1991. One of the key objectives of SMP is to provide field data to validate models for relating environmental conditions and in situ properties of pavement materials. The initial phase (Loop-1) of the program -- collecting pavement and air temperatures at 30 test sites throughout North America -- was completed in 1995. The availability of these data made it possible to evaluate and refine existing low pavement temperature models for asphalt binder selection. This LTPP data analysis was conducted to verify the existing Strategic Highway Research Program's (SHRP) low pavement temperature models and develop an LTPP model for SUPERPAVE binder selection.

Application/Use: The findings from this study are applicable to the selection of binder grade in pavements.

Contribution: Cost Savings; Improvement in Knowledge.

Present Benefit: The LTPP database was used to develop temperature prediction models for use in PG binder grade selection. This has been beneficial in improving materials selection and pavement performance.

Future Benefit: The temperature prediction models will continue to be useful. Proper binder selection leads to more cost-effective and better-performing pavements.

<u>Title:</u> Relationship between Pavement Temperature and Weather Data: Wisconsin Field Study to Verify Superpave Algorithm

<u>Authors</u>: Bosscher, P. J; Bahia, H. U; Thomas, S; Russell, J. S.

<u>Date:</u> 1998

<u>Publisher:</u> Transportation Research Board

<u>Journal Title:</u> Transportation Research Record No. 1609

<u>Abstract/Synopsis:</u> Six test sections were constructed on US-53 in Trempealeau County by using different performance-graded asphalt binders to validate the SUPERPAVE pavement temperature algorithm and the binder specification limits. Field instrumentation was installed in two of the test sections to monitor the thermal behavior of the pavement as affected by weather. The instrumentation was used specifically to monitor the temperature of the test sections as a function of time and depth from the pavement surface. A meteorological station was assembled at the test site to monitor weather conditions, including air temperature. Details of the instrumentation systems used and analysis of the data collected during the first 22 months of the project are presented. The analysis was focused on development of a statistical model for estimation of low and high pavement temperatures from meteorological data. The model was compared to the SUPERPAVE recommended model and to the more recent model recommended by the Long-Term Pavement Performance (LTPP) program. The temperature data analysis indicates a strong agreement between the new model and the LTPP model for the estimation of low pavement design temperature. However, the analysis indicates that the LTPP and SUPERPAVE models underestimate the high pavement design temperature at air temperatures higher than 30 degree C. The temperature data analyses also indicate that there are significant differences between the standard deviation of air temperatures and the standard deviation of the pavement temperatures. These differences raise some questions about the accuracy of the reliability estimates used in the current SUPERPAVE recommendations.

<u>Application/Use:</u> This study is directly applicable to binder selection in AC pavements in Wisconsin.

<u>Contribution:</u> Cost Savings; Improvement in Knowledge; Advancement in Technology.

<u>Present Benefit:</u> The pavement and air temperature data collected at LTPP-SMP sites provided an excellent source to make refinements to the prediction algorithms. Improved models result in more accurate estimates of actual pavement temperatures. With this information, materials engineers can select the appropriate binder without excessive conservatism thereby reducing costs without sacrificing performance.

<u>Future Benefit:</u> The LTPP-SMP data will continue to benefit the pavement community. The data can be used to model temperature and moisture changes in pavements and to correlate these variations to pavement response. This information will be extremely valuable in moving towards an M-E pavement design approach.

Title: Seasonal Instrumentation of SHRP Pavements - The University of Toledo

Authors: Heydinger, A. G; Randolph, B. W.

Date: 1998

Publisher: Toledo University; Ohio Department of Transportation; Federal Highway Administration

Abstract/Synopsis: Seasonal Monitoring Program (SMP) instrumentation was installed in five sections at the Ohio Test Pavement in Delaware County, Ohio using Strategic Highway Research Program (SHRP) protocols developed for the Long-Term Pavement Performance (LTPP) group of the Federal Highway Administration (FHWA). The SMP instrumentation monitors pavements for temperature and pavement bases and subgrade soils for variations of moisture, temperature and frost penetration. Time Domain Reflectometry (TDR) instrumentation was installed onsite in two sections for monitoring the moisture. Thermal conductivity sensors (TCS) were installed in four sections to measure soil moisture suction. Laboratory soil-water characteristic tests were conducted on remolded subgrade soil. The TDR volumetric moisture contents typically varied by 10 percent to 15 percent from the driest to the wettest periods, but sometimes the variations were larger. The lower water contents occurred during the late winter/early spring months and the higher contents occurred during the late summer early fall months. This reflects the climatic conditions that occurred. Some of the TDR moisture contents exceeded 40%, which is greater than the soil porosity and therefore not possible. An equation for TDR volumetric water content developed for the FHWA yields lower water contents. Most of the TCS are no longer within calibration. Data from sensors in calibration indicate very low matric suctions, which is consistent with high water contents. Soil-water characteristic relationships were obtained for the subgrade soil using triaxial and pressure plate apparatus. The relationships from the two tests are comparable. The soil exhibits some hysteresis when comparing drying and wetting curves.

Application/Use: The findings from this study can be used to understand the instrumentation and data collected at the Ohio Test Pavement.

Contribution: Cost Savings; Improvement in Knowledge; Lessons Learned.

Present Benefit: This study provides information on the in situ seasonal changes of pavement structures. With this information, designers can properly account for changes in subgrade strength throughout the year to determine cost-effective pavement structural designs. The study also provided information on the equipment used to collect in situ data. Valuable insights into the capabilities of this equipment can be gleaned from this report.

Future Benefit: Equipment evaluation information provided here can be used by those interested in monitoring in situ conditions at other locations. Additionally, the information can be used to interpret the data collected at the site. The data will be beneficial in calibrating and validation the M-E PDG as well as using the M-E PDG for pavement design purposes.

Title: Seasonal Variation in Material Properties of a Flexible Pavement

Authors: Watson, D. K; Rajapakse, R.K.N.D.

Date: 1997

Publisher: International Road Federation

Conference Title: XIIIth World Meeting of the International Road Federation

Abstract/Synopsis: Seasonal variations in temperature and moisture cause considerable changes in the load carrying capacity of pavements in geographical areas subject to extreme freeze thaw conditions. Pavement engineers in these areas must be able to quantify the variation in the load carrying capacity of a pavement in order to design it adequately. The seasonal monitoring program (SMP) of the U.S. long term pavement permanence performance (LTPP) study of FHWA is monitoring seasonal variations in falling weight deflectometer (FWD) deflections, air temperature, rainfall, soil temperature, moisture content, and soil electrical resistance at numerous sites across North America. The present study relates changes in pavement load carrying capacity represented by the pavement layer resilient moduli to selected environmental factors on the SMP site near Oak Lake, Manitoba.

Application/Use: The findings from this study are directly applicable to flexible pavement design.

Contribution: Improvement in Knowledge

Present Benefit: Understanding changes in subgrade modulus as a function of changes in moisture content is important in pavement design. It allows designers to select pavement sections that efficiently account for these seasonal variations.

Future Benefit: As pavement design moves towards M-E PDG practices, understanding modulus changes will be an essential part of the process. The results from this study will be useful in estimating subgrade modulus values in different seasons.

Title: Development of an Instrumentation Plan for the Ohio SPS Test Pavement (DEL-23-17.48). Final Report

Authors: Sargand, S.

Date: 1994

Publisher: Ohio University, Athens; Ohio Department of Transportation; Federal Highway Administration

Abstract/Synopsis: A Specific Pavement Studies (SPS) program, formulated under the Strategic Highway Research Program (SHRP), consists of nine experiments, four of which will be included in this DEL-23 project. Since the basic instrumentation plan proposed by SHRP was limited, Ohio Department of Transportation opted to develop a more comprehensive plan for DEL-23. The Ohio Test Road consists of SPS-1, SPS-2, SPS-8, and SPS-9 experiments, all constructed for this project where the climate, soil, and topography are uniform throughout. In this comprehensive instrumentation plan, thirty-three sections are to be instrumented. LTPP guidelines require four instrumented sections in each of the SPS-1 and SPS-2 experiments for the study of seasonal factors and dynamic response. DEL-23 includes an additional nine instrumented sections for the SPS-1 experiment, twelve sections for the SPS-2 experiment, and two sections each in the SPS-8 and SPS-9 experiments to study structural response parameters. A total of eighteen sections will be instrumented for the study of seasonal factors, ten more sections than required by SHRP. This report provides a detailed description of types of sensors, installation methodology, calibration procedures and wiring schematics for instrumentation of pavements for the Ohio SHRP SPS Test Road to measure environmental factors and structural response. Environmental or climatic parameters include temperature, base and subbase moisture, and frost depth. Structural response parameters entail strain, deflection, pressure, and joint opening.

Application/Use: This report can be used by those studying data collected at the Ohio Test Road or those interested in installing similar equipment.

Contribution: Improvement in Knowledge; Advancement in Technology; Implementation/Usage.

Present Benefit: The data collected at the Ohio Road Test and stored in the LTPP database is very valuable information for mechanistic pavement evaluation. This report provides insight into the equipment installed at the site. Data collected with this instrumentation—coupled with the performance monitoring conducted on the test sections—will provide valuable insight into transfer functions for M-E analysis.

Future Benefit: The LTPP pavement sections at the Ohio Test Road will continue to provide valuable information, particularly in calibrating and validating the M-E PDG.

Title: Influence of Stress Levels and Seasonal Variations on in Situ Pavement Layer Properties

Authors: Noureldin, A. S.

Date: 1994

Publisher: Transportation Research Board

Journal Title: Transportation Research Record No. 1448

Abstract/Synopsis: Presented is a small-scale investigation of how stress levels and seasonal variations affect pavement layer characteristics. Monitoring such effects is basic to the effort conducted under the Strategic Highway Research Program (SHRP) Long-Term Pavement Performance (LTPP) studies currently under the FHWA jurisdiction. Illustrated are the influences of stress levels, seasonal temperature variations, seasonal moisture variations, and accumulated equivalent single axle loads (ESALs) on (a) center deflection (D sub o) measured by the falling-weight deflectometer; (b) in situ asphalt concrete modulus (E sub AC); (c) in situ granular layer modulus (E sub g); (d) in situ subgrade resilient modulus (MR); (e) in situ AASHTO effective structural number (SN sub eff); and (f) variability within a section for each of the structural factors above. Analysis of results suggests that MR is the parameter most affected by a change in stress level, followed by E sub g, E sub AC, and SN sub eff. On the other hand, E sub AC is the parameter most affected by the change in temperature, followed by D sub o, SN sub eff, E sub g and MR. Variations in MR and E sub g with temperature are believed to be associated indirectly with variations in E sub AC and temperature. Changes in E sub AC and temperature result in changes in stress levels imposed on the underlying pavement layers that cause variations in MR and E sub g. Accumulation of ESALs under dry conditions affect E sub AC, followed by D sub o, E sub g, SN sub eff, and MR, in order of diminishing effect. In addition, seasonal moisture variations affect D sub o and MR, followed by E sub g, E sub AC and SN sub eff. And variability within a section for each of the structural factors increases with an increase in temperature, moisture level, or accumulated ESALs. Among the structural factors, SN sub eff has the lowest within-section variability, whereas E sub g has the greater within-section variability.

Application/Use: This paper can be used by those interested in the seasonal variation of pavement responses.

Contribution: Improvement in Knowledge; Advancement in Technology.

Present Benefit: The LTPP program has devoted significant resources in establishing a data collection mechanism for subsurface moisture content, subsurface temperature, and frost penetration. The technology utilized by the LTPP program can also benefit in other applications. Additionally, the data collected at these sites provides valuable information on the daily and seasonal variation of in situ conditions, which is useful in pavement design.

Future Benefit: Understanding the changes in material properties through the seasons will be useful in refining design procedures to properly account for these variations. The SMP sites provide a link between in situ conditions and pavement response, which is a critical component to mechanistic-empirical analysis.

Title: Long Term Pavement Performance in Seasonal Frost Areas

Authors: Haupt, R. S; Janoo, V; Coenye, S; Simonsen, E.

Date: 1994

Publisher: Swedish Road and Transport Research Institute

Conference Title: Strategic Highway Research Program (SHRP) and Traffic Safety on Two Continents, Proceedings of the Conference

Abstract/Synopsis: One of the primary goals of the Strategic Highway Research Program (SHRP) is to collect and evaluate data that will influence revisions to current design guides. To help achieve this goal, a twenty-year Long Term Pavement Performance (LTPP) program was established. Six LTPP sites have been identified in the State of Vermont. In addition, the Vermont Agency of Transportation (VAOT) has selected two other sites for its study. The test locations all differ in traffic loading, pavement structure, and subgrade conditions. Three of the LTPP sites and both of the VAOT sites have been instrumented with moisture and temperature sensors. Groundwater wells, weigh-in-motion (WIM), and weather monitoring stations were also installed at these sites. This paper presents the type of instrumentation used and some of the data currently available from these test sites.

Application/Use: This paper can be used by those interested in the instrumentation installed at LTPP SMP test sites for pavement analysis and design purposes.

Contribution: Improvement in Knowledge; Advancement in Technology; Implementation/Usage.

Present Benefit: The LTPP program has devoted significant resources in establishing a data collection mechanism for subsurface moisture content, subsurface temperature, and frost penetration. The technology utilized by the LTPP program can benefit other applications. Additionally, the data collected at these sites provides valuable information on the daily and seasonal variation of in situ conditions, which is useful in pavement design.

Future Benefit: Understanding the changes in material properties through the seasons will be useful in refining design procedures to properly account for these variations. The SMP sites provide a link between in situ conditions and pavement response, which is a critical component to mechanistic-empirical analysis.

Title: LTPP Seasonal Monitoring Program: Instrumentation Installation and Data Collection Guidelines

Author(s): Rada, G.R; Elkins, G.E., Henderson, B., Van Sambeek, R.J., Lopez, Jr., A.

Date: 1994

Publisher: FHWA, Office of Engineering and Highway operations R&D, McLean, VA

Abstract/Synopsis: This report describes the operation theory, installation procedures and operation guidelines for instrumentation selected to monitor changes in internal pavement moisture and thermal regimes, frost/thaw conditions, and external climate at test sections in the long-term pavement performance seasonal monitoring study. The instrumentation includes time domain reflectometry to measure moisture content of unbound materials, thermistor sensors to measure pavement temperature gradients and air temperature, electrical resistivity probes to measure frost locations, a piezometer to measure the depth of ground water table and tipping-bucket rain gauge to measure precipitation. These measurements of the external climate and the resulting changes in the pavement material will be coupled with monthly or more frequent deflection measurements, seasonal roughness measurements, elevation profile and distress surveys to study the cause and effects of seasonal changes in pavement structural response. Guidelines and procedures for the collection of these data are also described in this report and are supplemented by LTPP SMP Directives.

Application/Use: The installation and data collection guidelines have been used by those interested in studying SMP data or in instrumenting pavements to monitor seasonal changes.

Contribution: Improvement in Knowledge; Advancement in Technology.

Present Benefit: The Seasonal Monitoring Program provided substantial advancement in technology and knowledge. Significant effort was expended by the LTPP team in developing a system to measure moisture content within the pavement structure using time domain refelectometry. The same holds true for the use of electrical resistivity in monitoring frost penetration.

The collection of temperature, moisture, and frost data has been instrumental in developing relationships between pavement response and in situ conditions. Pavement temperature prediction models have been developed based on the data. This has resulted more accurate FWD adjustments to account for temperature.

Correlations between pavement response and seasonal conditions have been useful in determining the proper time for applying load restrictions.

Future Benefit: SMP data will assist in understanding mechanistic properties of pavement structures and how those properties change through the seasons. The instrumentation applied to pavement monitoring will also be useful in evaluating new materials and pavement structures as they are developed. A thorough understanding of seasonal variations in material properties is fundamental in a mechanistic-empirical design.

Title: LTPP-SPS Automated Weather Station (AWS) Installation: Arizona DOT Open House

Date: 1994

Publisher: SHRP, Washington, DC

Abstract/Synopsis: This document is a compilation of multiple reports and provides an evaluation of various commercial weather data collection devices. Schematics on the layout of the weather station are included along with portions of manufacturer user manuals.

All necessary information required to install and collect climatic data from a weather station is provided.

This document is supplemented by LTPP AWS Directives.

Application/Use: Developing climatic information for LTPP sites has provided the data required to study the environmental impacts on pavement performance.

Contribution: Cost Savings; Advancement in Technology; Implementation/Usage.

Present Benefit: Automated weather stations provide substantial benefit to the pavement community, including the data needed to learn how climate contributes to pavement performance. With this knowledge, better rehabilitation and maintenance strategies can be developed resulting in a more cost-effective pavement management system.

LTPP weather stations have been utilized for avalanche control purposes, farming, crop dusting, flash flooding potential, and snow removal.

Future Benefit: The availability of climatic information for pavements with monitored performance data will be extremely useful in the calibration/validation of the M-E PEG.

Title: Development of the LTPP Climatic Database

Date: 1993

Publisher: FHWA, Office of Infrastructure Research and Development, McLean, VA

Abstract/Synopsis: This report summarizes the development of the Long-Term Pavement Performance (LTPP) program's climatic database, including the identification and sources of data, selection and verification of weather stations, actual data retrieval from available sources, and data quality assurance. The paper also discusses future activities such as updates and expansion of the database, and the collection of ground-truth data. The LTPP climatic data base is intended to provide the weather and climatic information needed to characterize the environment in which each LTPP test section has existed from the time of construction through the LTPP monitoring period.

Application/Use: Developing climatic information for every LTPP site has provided the baseline data necessary to study environmental impacts on pavement performance.

Contribution: Cost Savings; Improvement in Knowledge; Advancement in Technology.

Present Benefit: By providing the resources needed to learn how climate contributes to pavement performance, the data has a substantial benefit to the pavement community. The process in developing “virtual weather stations” can be applied to determine climatic characteristics at any location of interest. This environmental information can be useful in a variety of design applications.

Future Benefit: The availability of climatic information for pavements with monitored performance data will be extremely useful in the calibration/validation of the M-E PDG.

Title: How do Temperature and Moisture Affect Pavements? Strategic Highway Research Program Implementation

Date: 1993

Publisher: Arab Road Association

Journal Title: Arab Roads Vol. 42

Abstract/Synopsis: As the temperature and moisture content of paved roads change over the course of a day, and throughout the year, the structural characteristics of the pavement layers also change. Those changes affect how well the pavement responds to traffic loads, and thus how long the pavement lasts. The magnitude of those changes and the relationships involved are not well understood, making them difficult to address with any degree of confidence during the design and evaluation of pavements. To overcome this limitation, SHRP established a seasonal monitoring program within its Long-Term Pavement Performance (LTPP) program. The main objective of the monitoring program, to be conducted by FHWA, is to collect the data needed to attain a fundamental understanding of how variations in temperature and moisture affect pavement response.

Application/Use: This paper can be used by those interested in the seasonal variation in pavement structures for analysis and design purposes.

Contribution: Improvement in Knowledge; Advancement in Technology.

Present Benefit: The LTPP program has devoted significant resources in establishing a data collection mechanism for subsurface moisture content, subsurface temperature, and frost penetration. The technologies utilized by the LTPP program can benefit in other applications. Additionally, the data collected at these sites provides valuable information on the daily or seasonal variation of in situ conditions, which is useful in pavement design.

Future Benefit: Understanding the changes in material properties through the seasons will be useful in refining design procedures to properly account for these variations. The SMP sites provide a link between in situ conditions and pavement response, which is a critical component to mechanistic-empirical analysis.

Title: Seasonal Monitoring Program, Workshop and Instrumentation Demonstration, Delta, Colorado, June 28 through July 2, 1993

Authors: Ardani, A.

Date: 1993

Publisher: Colorado Department of Transportation; Federal Highway Administration

Abstract/Synopsis: The Colorado Department of Transportation in cooperation with the LTPP Division of the Federal Highway Administration and LTPP Western Region Coordination Office sponsored a workshop and a field demonstration in Grand Junction and Delta, Colorado, for the Seasonal Monitoring Program. The purpose of the workshop and the field demonstration was to train and familiarize the LTPP Strategic Highway Research Program (SHRP) Coordinators with the Seasonal Monitoring Program's concept, equipment installation, operation, and data collection. Altogether there are 64 sites for the Seasonal Monitoring Program across the country which cover four environmental zones (wet-freeze, wet-no freeze, dry freeze, dry no freeze). The matrix that constitutes this program also includes pavement type (flexible vs. rigid), thickness, and subgrade type (coarse vs. fine). With all these factors in mind the Colorado site is located in the zone of dry-freeze with fine subgrade and thin flexible pavement surface. The primary objective of the SHRP's seasonal monitoring program is to evaluate and monitor the impact of seasonal variations in moisture and temperature on pavement response. This program will attempt to establish a relationship between pavement response and deflection measurements taken at different times of the year for a given climatic zone. The ultimate goal of this program is to rationally use the acquired deflection data for evaluation, analysis and design. The instrumentation consisted of the following: 1) TDR (Time Domain Reflectometry) sensors, for moisture; 2) Resistivity sensors, to monitor frost penetration; 3) Thermistors, to measure temperature of the subgrade; 4) Observation well, to monitor depth of ground water; 5) Tipping Bucket Rain Gage, to measure rainfall; and 6) Ambient Temperature probe, to monitor the air temperature. The SHRP seasonal monitoring site at the Delta site will be tested on a two year cycle; i.e., testing in years 1, 3, 5, etc. The data collected from this site will be entered into the National Information Management System (NIMS), along with data from 63 other sites across the United States and Canada. Interim results cam be expected in 5 years, and final results within the next 10 years.

Application/Use: This report documents the instrumentation and installation activities conducted at a SMP workshop in Colorado. It can be used by those interested in using SMP data or instrumenting pavements to monitor seasonal changes.

Contribution: Improvement in Knowledge; Advancement in Technology.

Present Benefit: The Seasonal Monitoring Program provided substantial advancements in technology and knowledge. Significant effort was expended by the LTPP team in developing a system to measure moisture content within the pavement structure using time domain refelectometry. The same holds true for the use of electrical resistivity in monitoring frost penetration.

The collection of temperature, moisture, and frost data has been instrumental in developing relationships between pavement response and in situ conditions. Pavement temperature prediction models have been developed based on the data. For example, this has resulted more accurate FWD adjustments to account for temperature. Additionally, correlations between pavement response and seasonal conditions have been useful in determining the proper time to apply load restrictions.

Future Benefit: The data collected as part of SMP will assist in understanding mechanistic properties of pavement structures and how those properties change through the seasons. The pavement monitoring instrumentation will also be useful in evaluating new materials and pavement structures as they are developed. A thorough understanding of seasonal properties is fundamental in mechanistic-empirical design.