Impact of Effective Layer Thicknesses on the Structural Performance of In-Service Roads

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ABSTRACT

Over the in-service life of a road, the structural layers are subjected to environmental effects such as freeze-thaw, moisture migration and fines translation into the structural layers. These processes affect the mechanical properties of the layers and reduce the structural life cycle of a road. These effects are known to increase in areas of higher moisture susceptibility.

This study focuses on the use of a comprehensive field road condition data collection and post-survey analysis integrated with non-linear structural finite element modeling to assess the current moisture migration condition of an in-service road structure, mechanistic materials characterization and numerical modeling was used to quantify the impact on the structural integrity of the road and the effective remaining layers.

Results from non-linear finite element analysis and non-destructive pavement condition data collection show that moisture infiltrated layers contribute to pavement deterioration as the effective layer thickness is reduced, therefore compromising structural integrity of the overall structure.

The three-dimensional structural model results show higher peak surface defections for the compromised structures, as expected. Strains, both orthogonal and shear, also increased in the case of thinner effective layer thickness. This study shows three-dimensional modeling calculated shear strains were found to yield a higher rate of increase as the road deteriorates. As well, the induced shear strains were found to be significantly higher than traditional orthogonal strains used to predict pavement performance. Therefore, true three-dimensional modeling and non-linear orthogonal materials characterization better captures shear strains state which is known to be the primary failure mechanism of road structural performance.

INTRODUCTION

Over the in-service life of a road, structural layers are subject to environmental effects such as freeze-thaw, moisture migration and fines translation. These processes affect the mechanical properties of the layers and reduce the structural life cycle of a road. These effects are increased in areas of higher moisture susceptibility. As roads age, these effects alter the structural capacity and effective thickness of the road structural layers.

In order to understand risk and responsibility in the case of roadway performance, agencies can use finite element modeling as a roadway structural design and management tool. Roadway analysis using finite element modeling requires non-linear orthogonal mechanistic tests to be performed on each road layer under realistic field state conditions. The material constitutive properties can then be input into a finite element model to provide insight into the expected road performance as an operational structural system (Figure 1). This study focuses on the use of comprehensive field road condition data collection and analysis integrated with finite element modeling and materials analysis to assess the in-situ field state structural performance condition of road structures as well as predict the structural performance of these roads over their lifetime.

Objective

The objective of this study was to demonstrate the ability to evaluate the structural capacity of aged roads subjected to moisture infiltration overtime (effective layers) through the use of advanced materials testing and non-linear three-dimensional numerical modeling.

Mechanistic Numerical Analysis

Conventional road design has traditionally utilized empirical methods or a combination of mechanistic-empirical methodologies that typically employ inelastic orthogonal strains for calculations and predict field performance (1, 2). Roadway design and life cycle management can significantly benefit from advanced numerical modeling techniques and non-linear inelastic material constitutive theory (3, 4, 5). In particular, shear strains are known to be highly correlated to structural failure criterion of road structure materials and provide more accurate predictions than simple orthogonal strains (6). Shear strain predictions provide realistic correlation with unusual and hard-to-predict scenarios, such as off-ramps, slow moving traffic lanes, bus stops and others.

Advanced mechanistic materials characterization and numerical modeling were performed on a typical Saskatchewan highway for this paper. Similar methods have been used previously (7, 8). The road model used in this study has been validated by comparing model-generated peak deflections to field-measured peak deflections using non-destructive failing weight deflectometer (FWD) testing (9). Material properties were obtained from dynamic mechanistic laboratory tests and used as inputs into the finite element model. The model was then able to predict deflection responses based on a simulated truck load as well as strains in the pavement structure (10, 11, 12).

Numerical modeling is a complex tool with many unknown material properties variables to be assessed and encoded for the model to accurately simulate reality. Given the limited materials properties available for the analysis contained herein, the authors acknowledge that additional materials analysis should be performed and utilized in the model to improve the design and performance prediction capabilities. For this paper, a few assumptions were regarding materials and loads. Static critical loading was analyzed on an isotropic non-linear elastic stress dependent material model. The goal of this analysis was to understand the behavior of effective layer thickness under critical state loading, therefore details of fatigue over long term performance were not included. For this analysis, the layers are considered perfectly bonded.

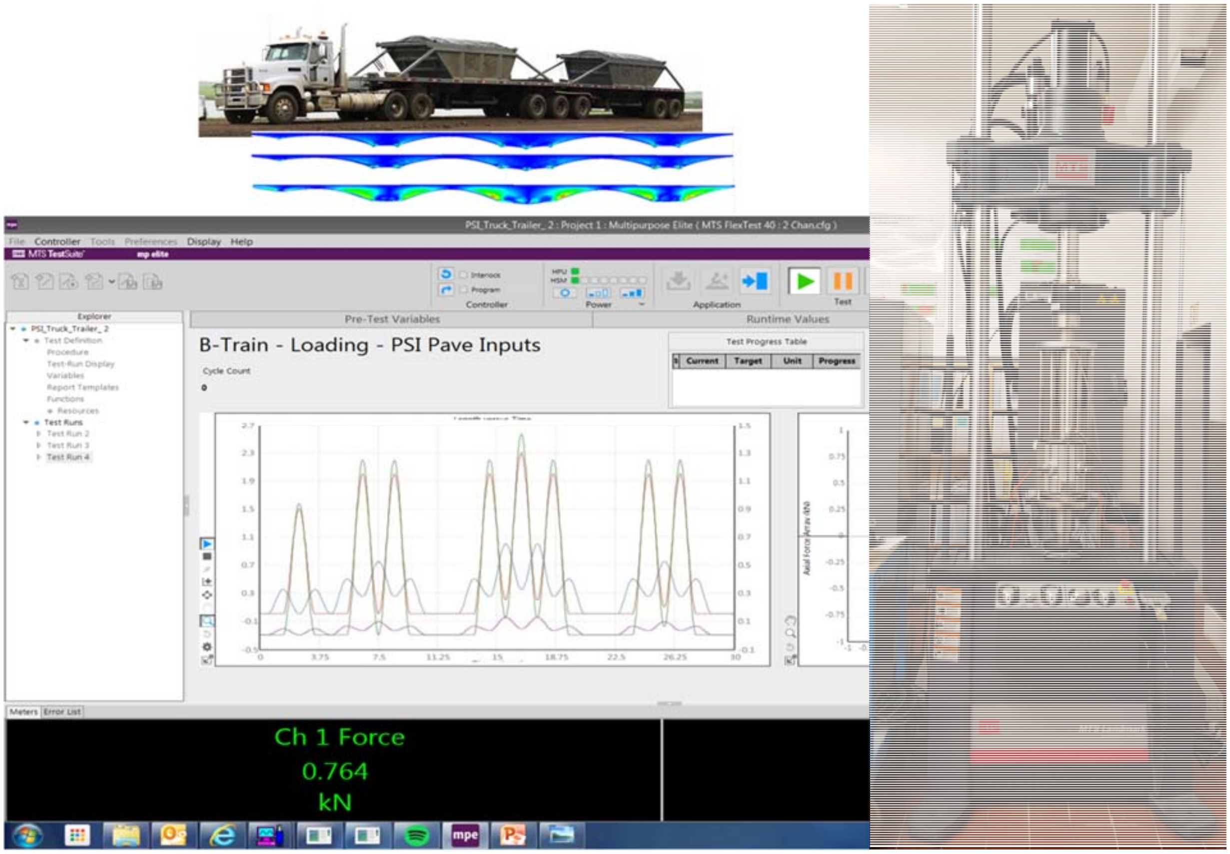


Figure 1 Dynamic Mechanistic Material Testing Setup and Protocol under B-Train Loading

MECHANISTIC MATERIALS CHARACTERIZATION

Triaxial frequency sweep testing was performed on continuum samples prepared at optimum moisture and density as well as dry/low density and wet/low density conditions representative of the observed *in situ* range of each material within the road. The mechanistic characterization was performed across stress states and load frequencies as per the specified load limits, posted traffic speed and structural layer thicknesses. B-Train loading simulative of two B-Trains passing each other, as shown in Figure 2 was used in the model calculations. Each B-Train was loaded to primary load (tandem 17,000 kg and tridem 23,000 kg) with equal load distribution across tires in each axle. In addition, the tire inflation pressure was 100 psi and tire width 30 cm. Test loading frequencies ranged from 0.1 Hz to 25 Hz.

The materials showed considerable sensitivity in mechanical behaviour relative to *in situ* moisture content and density when subject to *in situ* field state loading conditions. This sensitivity is evident across the high variability of the non-linear dynamic modulus. Non-linear dynamic modulus was characterized across the full range of field stress states and load frequencies representative of the design field state conditions; results are provided in Table 1 below. The dynamic modulus is a measure of the stiffness of a material. All subgrade materials exhibited a decrease in dynamic modulus with increasing moisture content, as expected.

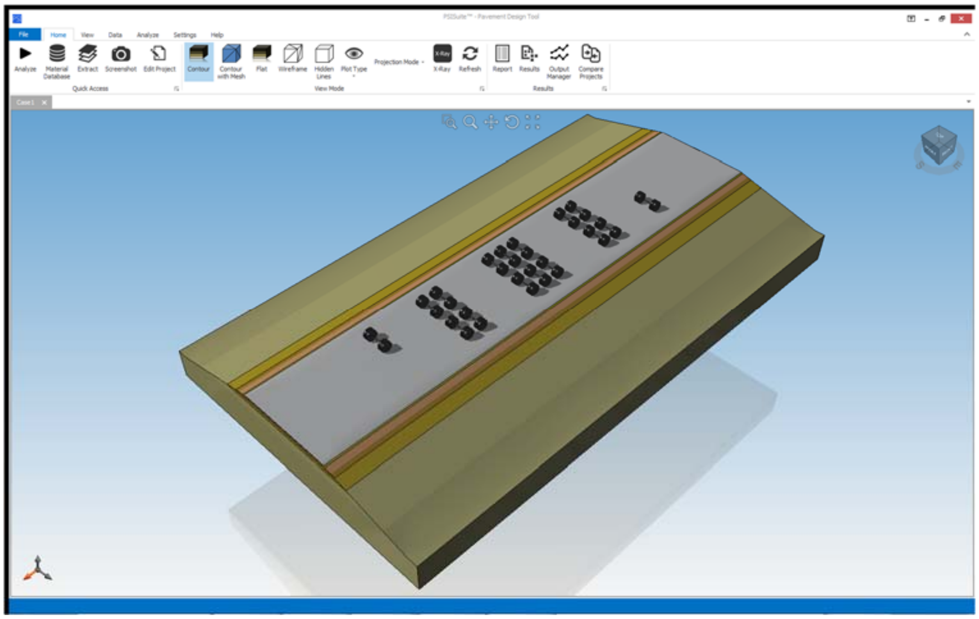


Figure 2 Example of Numerical Model Mesh Illustrating Two B-Trains Passing

Table 1 Non-Linear Dynamic Modulus Range

Material Type	**Material Condition Description**	**Range of Dynamic Modulus (MPa) Across Stress State and Load Frequency**	
		Min	**Max**
HMAC	MHI Type 71, New Pavement	394	3501
Base	MHI Type 33, Low Fines, Optimum Moisture	112	532
	High Fines, Wet of Optimum Moisture	58	314
Subbase	MHI Type 6, Low Fines, Optimum Moisture	109	416
	High Fines, Wet of Optimum Moisture	55	208
Subgrade	Clay Till at Optimum Moisture and Density	130	248
	Clay Till at Wet of Optimum Moisture	30	83

Non-linear Poisson's ratio was characterized across the full range of field stress states and load frequencies representative of the design field state conditions, as seen in

Table 2 below. Poisson's ratio is a ratio of the vertical to lateral strain translation. Poisson's ratio is a critical input into three-dimensional numerical modeling simulations when evaluating true shear strain conditions and exhibits non-linear behavior as a function of stress state and load rate.

Table 2 Non-Linear Poisson's Ratio Range

Material Type	Material Condition Description	Range of Poisson's Ratio Across Stress State and Load Frequency	
		Min	Max
HMAC	MHI Type 71, New Pavement	0.16	0.49
Base	MHI Type 33, Low Fines, Optimum Moisture	0.16	0.47
	High Fines, Wet of Optimum Moisture	0.38	0.49
Subbase	MHI Type 6, Low Fines, Optimum Moisture	0.29	0.49
	High Fines, Wet of Optimum Moisture	0.35	0.49
Subgrade	Clay Till at Optimum Moisture and Density	0.12	0.34
	Clay Till at Wet of Optimum Moisture	0.28	0.49

Non-linear phase angle was characterized across the full range of field stress states and load frequencies representative of the design field state conditions, as seen in Table 3 below. Phase angle is an indication of the viscoelastic behavior of the materials; higher phase angles indicate increasing permanent strain is occurring in a material, relative to recoverable strain for a given field state loading condition.

Table 3 Non-Linear Phase Angle Range

Material Type	Material Condition Description	Range of Phase Angle (Degrees) Across Stress State and Load Frequency	
		Min	Max
HMAC	MHI Type 71, New Pavement	20.3	31.8
Base	Type 33, Low Fines, Optimum Moisture	6.0	14.4
	High Fines, Wet of Optimum Moisture	5.6	15.1
Subbase	MHI Type 6, Low Fines, Optimum Moisture	4.8	15.0
	High Fines, Wet of Optimum Moisture	4.3	15.7
Subgrade	Clay Till at Optimum Moisture and Density	5.1	15.2
	Clay Till at Wet of Optimum Moisture	8.8	31.2

ROAD MODELING RESULTS

Numerical modeling was conducted using material property inputs from the mechanistic characterization of road materials and the structural design geometry specified in the road design. The three-dimensional numerical modeling uses non-linear material constitutive properties, across both stress state and load frequencies. Simulations of three moisture conditions states of the road structure were evaluated including:

1) **Deep Subgrade Wetting Up**: optimum design structural layers, wetted up deep *in situ* subgrade but prepared subgrade at optimum;
2) **Initial Bottom Up Moisture Infiltration in Prepared Subgrade**: Prepared subgrade wet of optimum, structural layers in good condition, at optimum moisture (short-term bottom up moisture infiltration); and,
3) **Advanced Bottom Up Moisture Infiltration into Upper Structural Layers**: Bottom up moisture infiltration, with subgrade, subbase and bottom of base above optimum moisture (long-term bottom up moisture infiltration).

To capture true three-dimensional effects, the numerical modeling mesh contained over 5 million finite elements in a full three-dimensional simulation of a roadway (as shown in Figure 2), with layer thicknesses and side slope geometric measurements are captured by the road condition survey van Figure 3 and provided by Roadoctor™ analysis as shown in Figure 4. PSIPave3D™ utilized actual measured material properties retrieved from field samples. The high number of elements and level of mesh details add to computational cost, where each simulation takes about 20 CPU hours to model.

Figure 3 Surveying van with GPR, Lidar and Video Camera

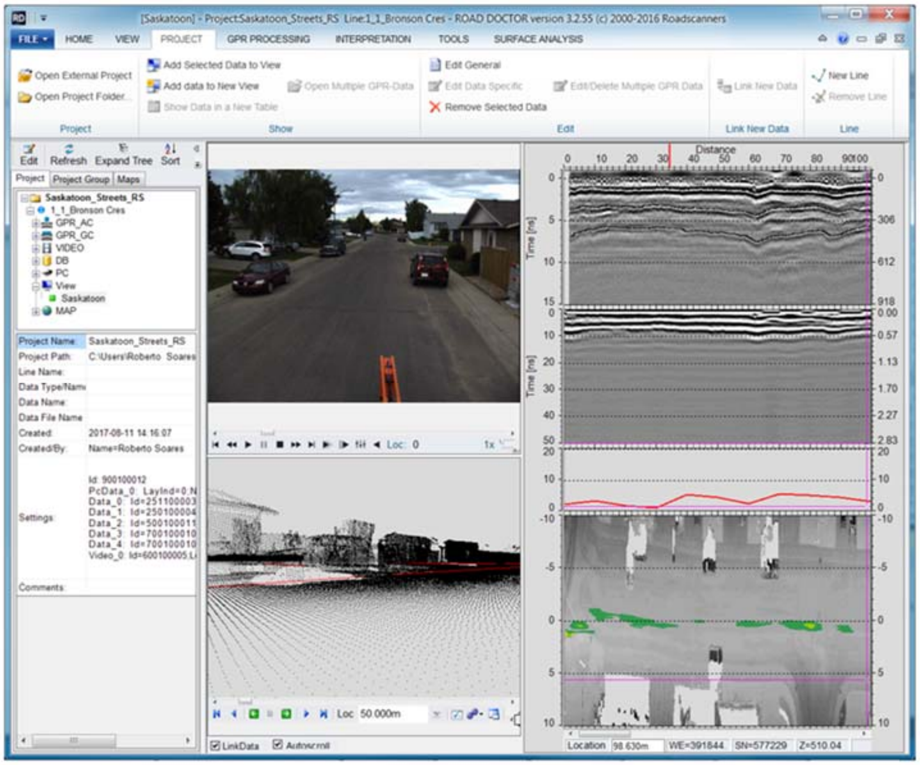
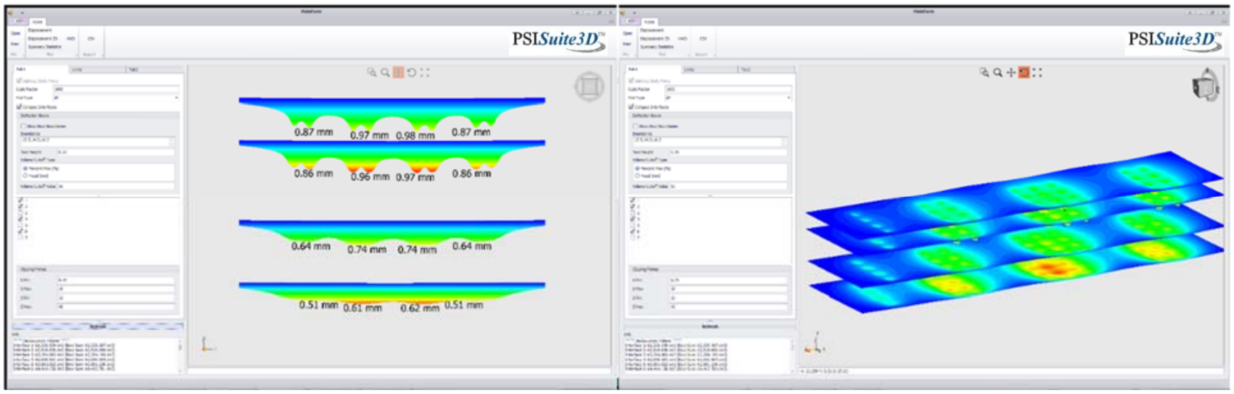


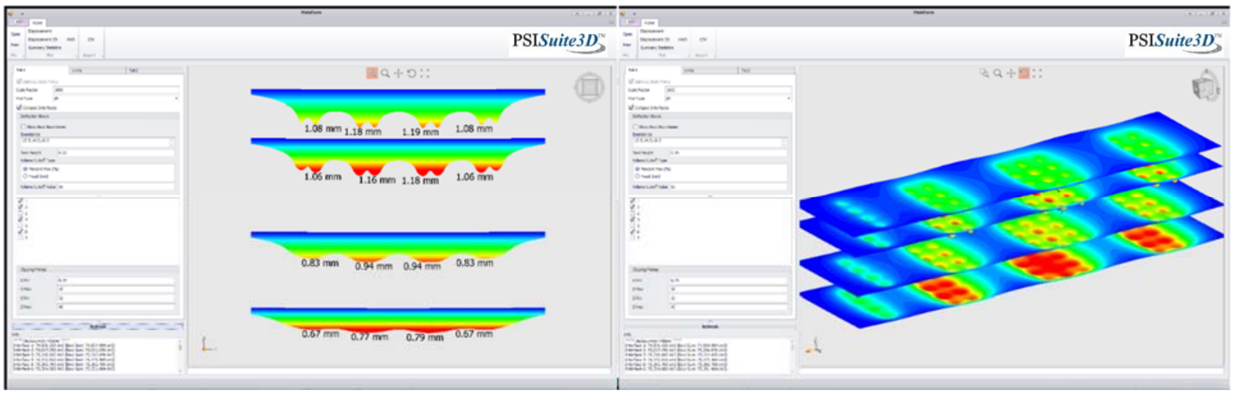
Figure 4 Roaddoctor^{TM} **road survey analysis screenshot**

Figure 5 illustrates the numerical road structural modeling using field state material properties, structural cross section, and traffic loading conditions. The analysis was conducted to determine the response of the road structure using standard accepted construction practices (optimum conditions) and compare this to the range in measured conditions on the roadway under increasing bottom up moisture infiltration over time representative of the effective layer concept. Figure 5 shows deflection contours from a front and oblique view of the two B-Trains and its effect on each pavement layer interface.

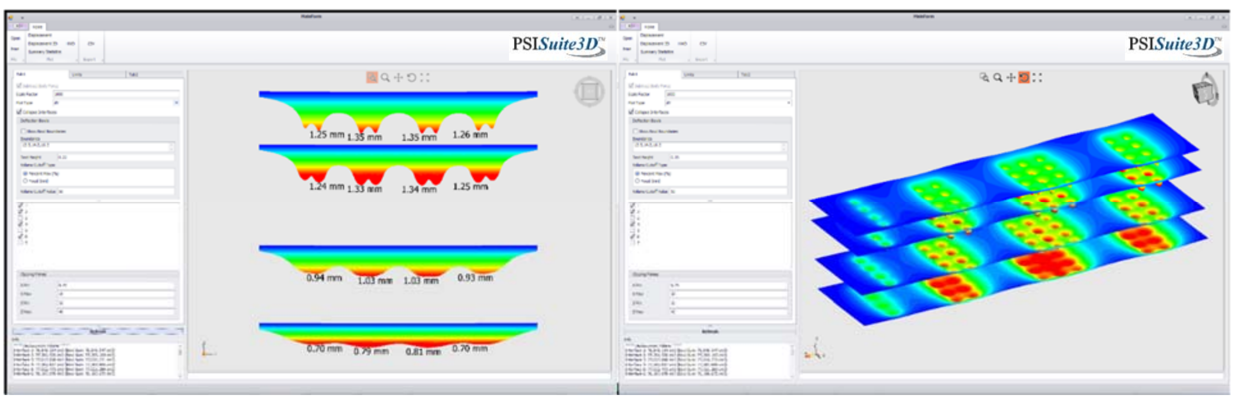
Deflection Profiles



a) Deep Subgrade Wetting Up



b) Initial Bottom Up Moisture Infiltration in Prepared Subgrade



c) Advanced Bottom Up Moisture Infiltration into Structural Layers

Figure 5 Numerical Model Deflection Profiles

Figure 6 shows the peak deflection under the three different modeled scenarios and it illustrates how they increase with increased moisture infiltration. It also compares with the initial design condition, a given target structural design peak surface deflection of 0.75mm at primary load limits for initial design of roadways in Saskatchewan.

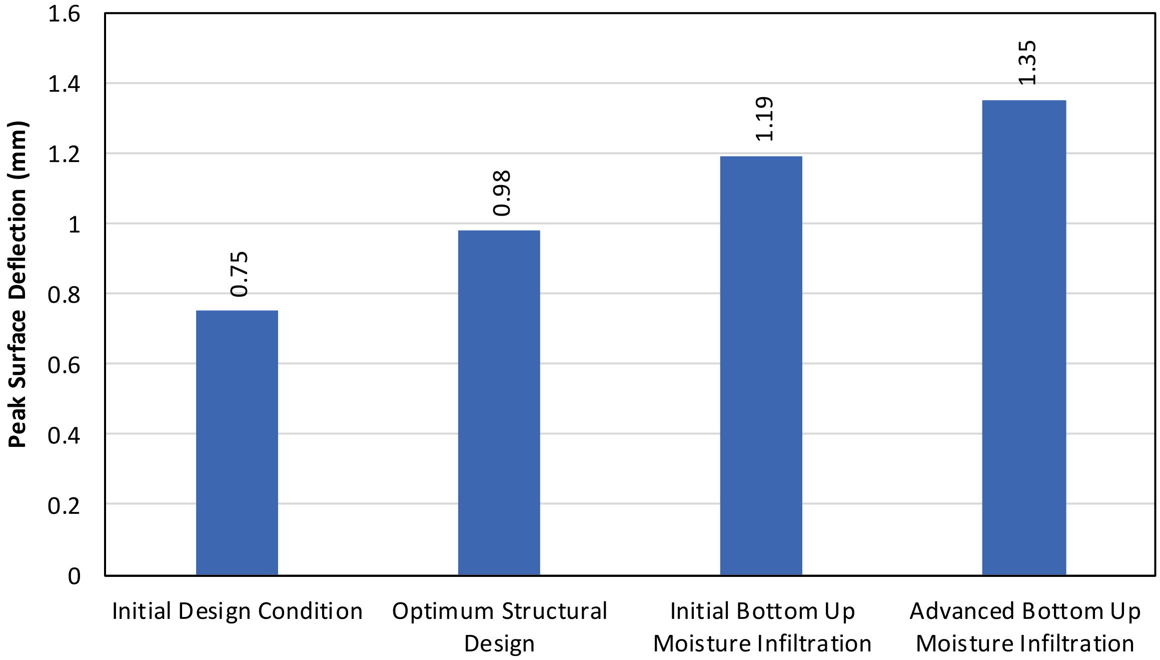


Figure 6 Numerical Model Peak Surface Deflection – Summary

Horizontal Tensile Strain at Bottom of Asphalt

Horizontal tensile strain at the bottom of the asphalt layer has traditionally been used to characterize the rigidity of the hot mix asphalt concrete (HMAC) layer. A significant difference in stiffness in the interface between the top layer and the base layer induces a strain discontinuity and strain concentrations. Flexing phenomenon causes the asphalt layer to flex as a beam, where high tensile and shear strains/stresses occur under and adjacent to the loading, tending to cause cracks from the bottom up as well as parallel immediately adjacent to the wheel paths. The increase in tensile orthogonal strain at the bottom of the asphalt layer as a function of increasing moisture content is seen in Figure 7.

Vertical Compressive Strain at Top of Subgrade

Compressive strain at the top of the subgrade has traditionally been used to evaluate the competence of the road structure and the subgrade material as an integral system. High compressive strains at the top of the subgrade signify the applied loads are not being dissipated by the structural layers. As the subgrade gets compressed, the entire structural layers deform vertically, causing "deep dish" rutting. A wet subgrade, as seen in the results from Figure 7 below, has a significant impact on compressive strains at the top of the subgrade.

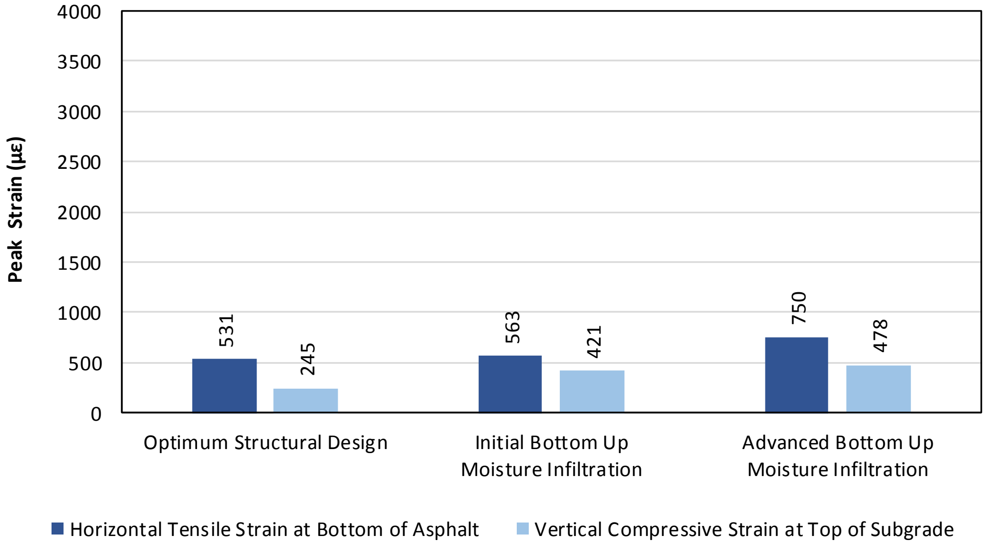


Figure 7 Peak Conventional Orthogonal Strains by Moisture Condition

Peak Shear Strain in Each Layer

Critical failure in most geotechnical material systems such as pavements commonly occurs due to high shear strain concentrations. Therefore, accurate prediction of the peak shear strains in a pavement structure is important in determining pavement performance. Shear strains are known to be directly related to dislocation of planes and particles with respect to each other. When a wheel load passes on a road surface, shear stresses are induced in the pavement layers at various magnitudes, wave lengths and principal orientation that changes as the tire rolls overs a fixed location. Therefore, quantifying shear strains as a function of traffic speed and structural primary response is required to assess three-dimensional strain states within the road structure. The numerical model employed in this analysis has the ability to encode all the aforementioned variables directly. Peak shear strains obtained from the numerical model for typical rural pavement application are identified in Figure 8 below.

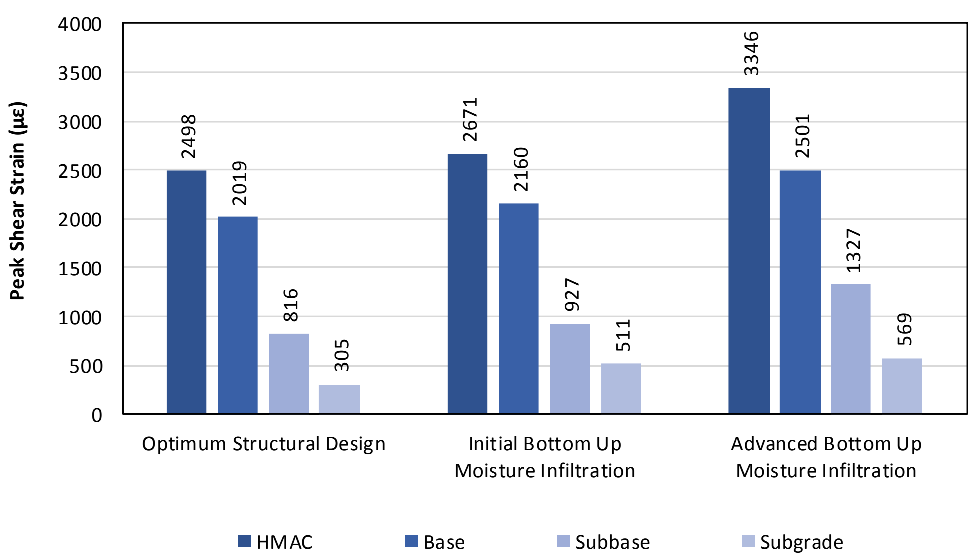
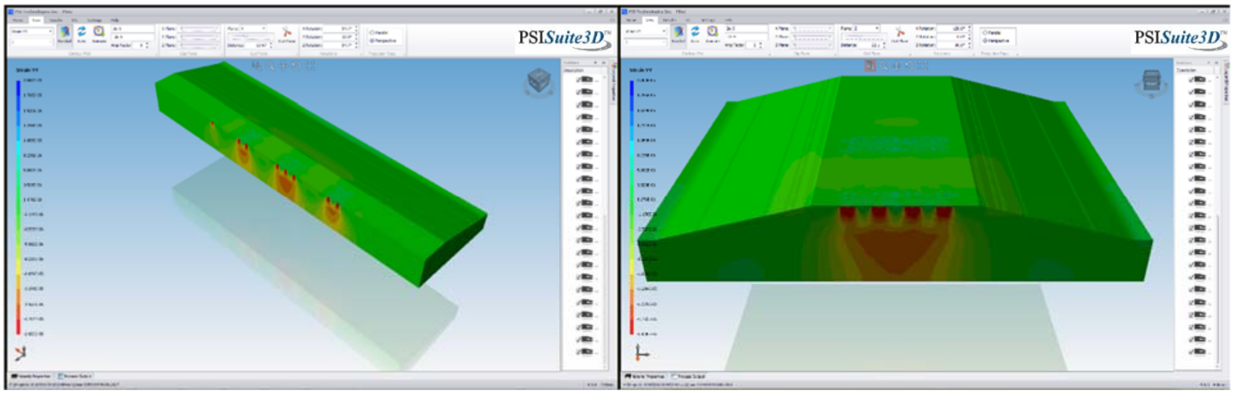
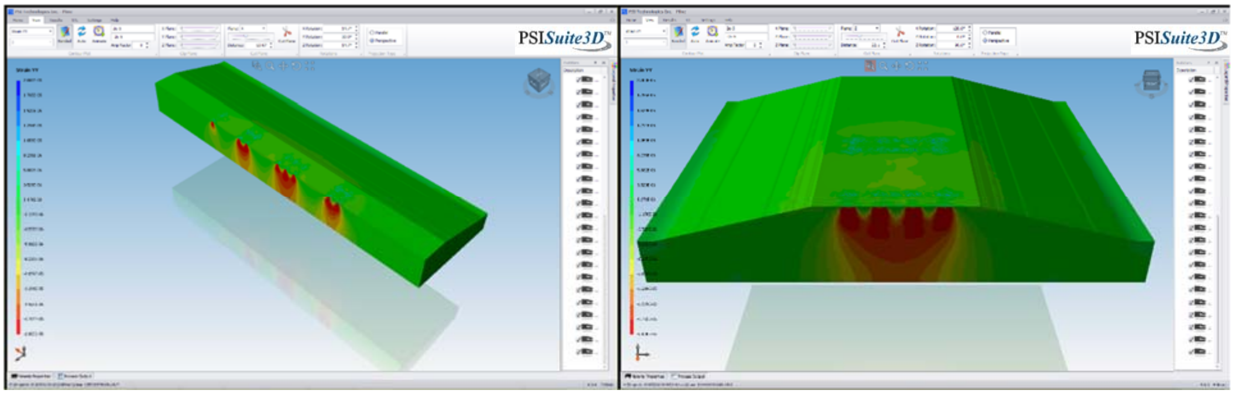


Figure 8 Peak Shear Strain – by Layer by Moisture Condition

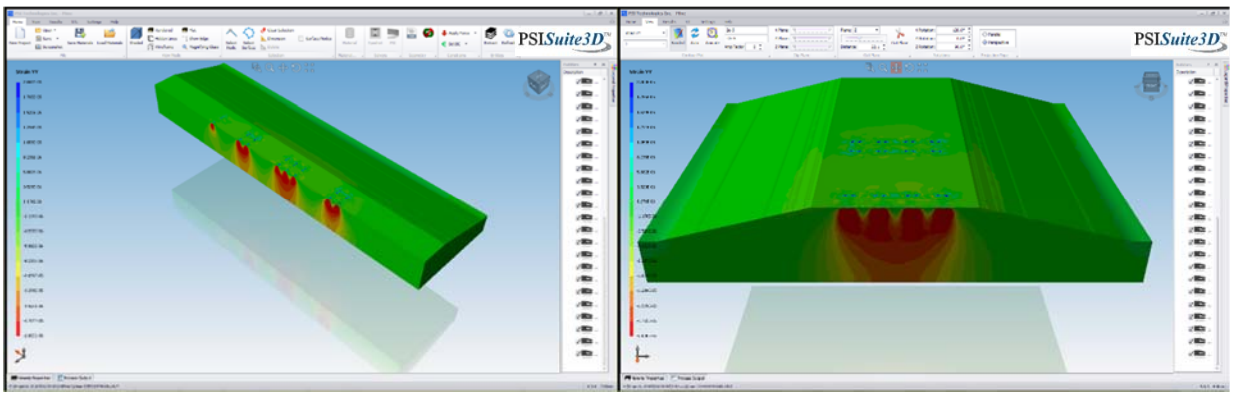
To further illustrate the strain profiles within the road structure, the numerical model was used to illustrate orthogonal as well as shear strain profiles occurring within the roads structure as shown in Figure 9, Figure 10 and Figure 11 respectively. Strain contours were plotted with respect to field state moisture condition.



a) Loading with Two B-Trains – Deep Subgrade Wetting Up

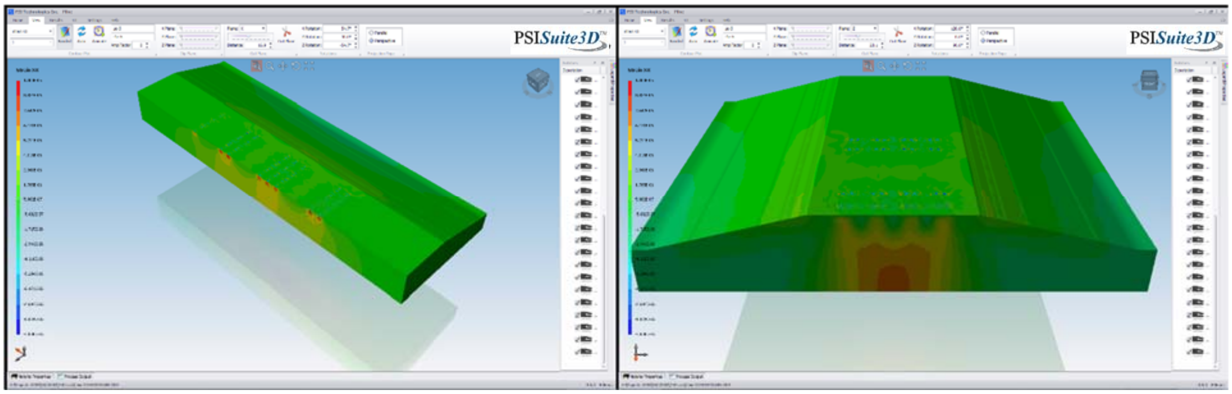


b) Loading with Two B-Trains – Initial Bottom Up Moisture Infiltration in Prepared Subgrade

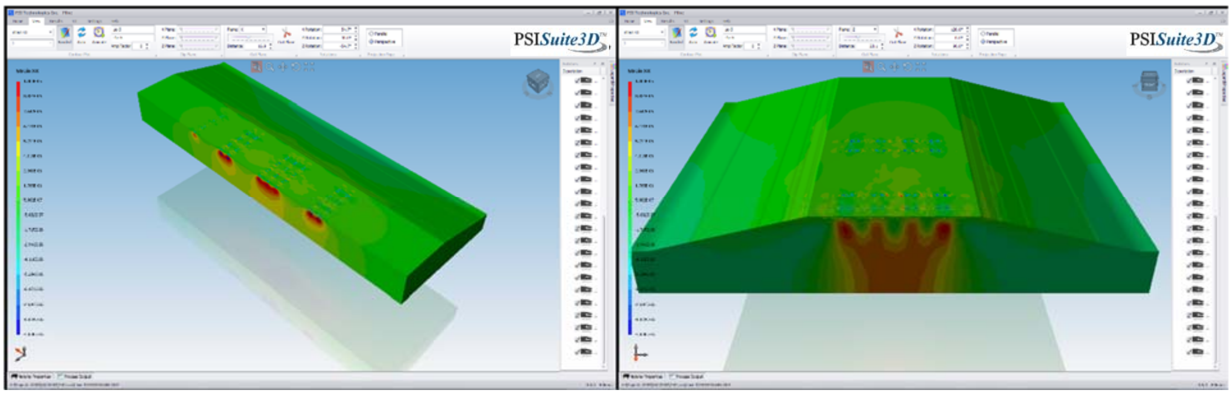


c) Loading with Two B-Trains – Advanced Bottom Up Moisture Infiltration into Structural Layers

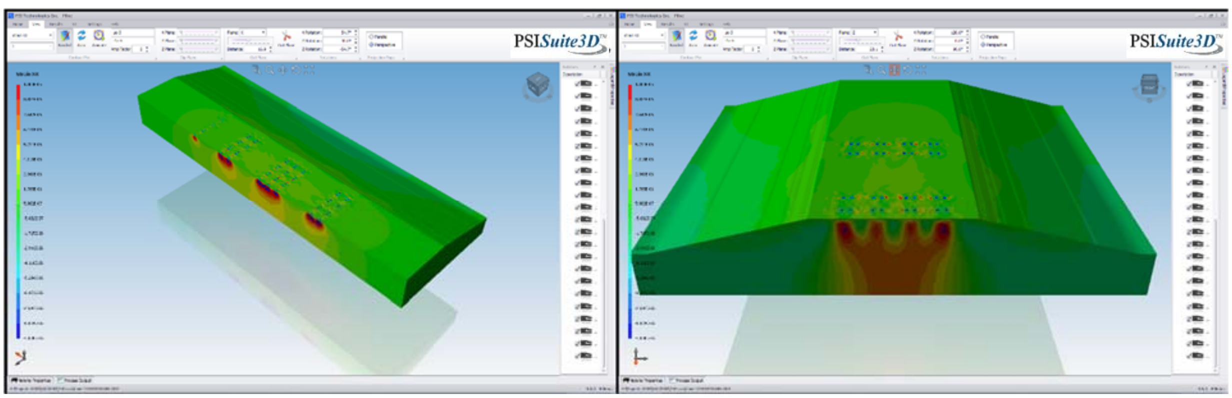
Figure 9 Vertical Compressive Strain Profile Across Road Length and Width by Moisture State



a) Loading with Two B-Trains – Deep Subgrade Wetting Up

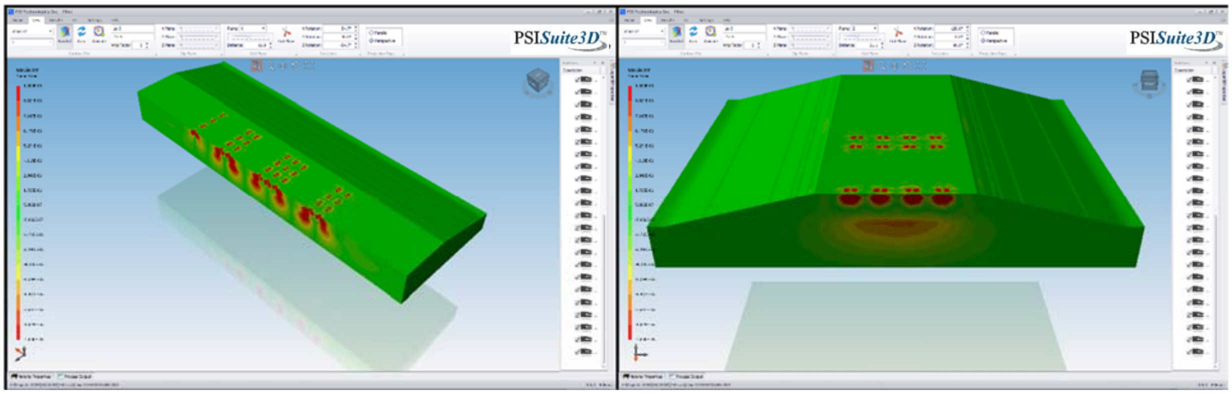


b) Loading with Two B-Trains – Initial Bottom Up Moisture Infiltration in Prepared Subgrade

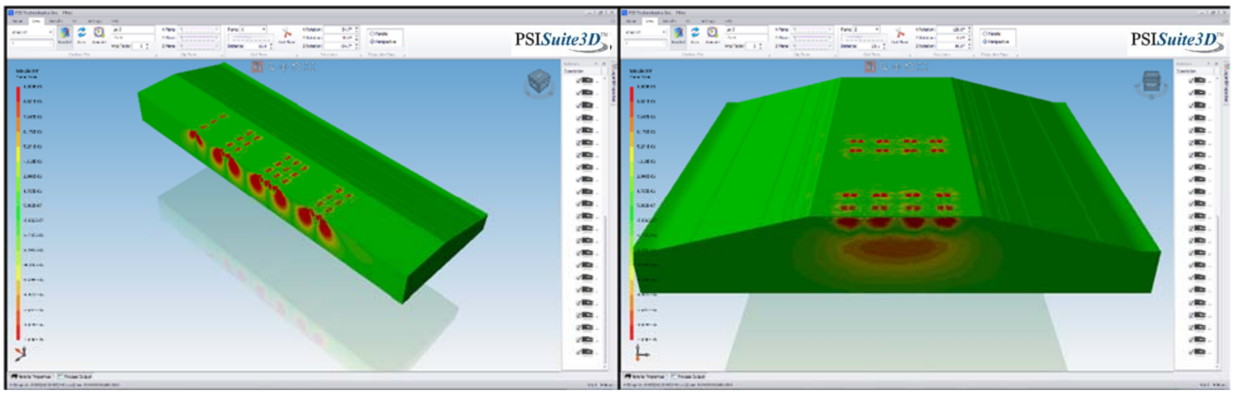


c) Loading with Two B-Trains – Advanced Bottom Up Moisture Infiltration into Structural Layers

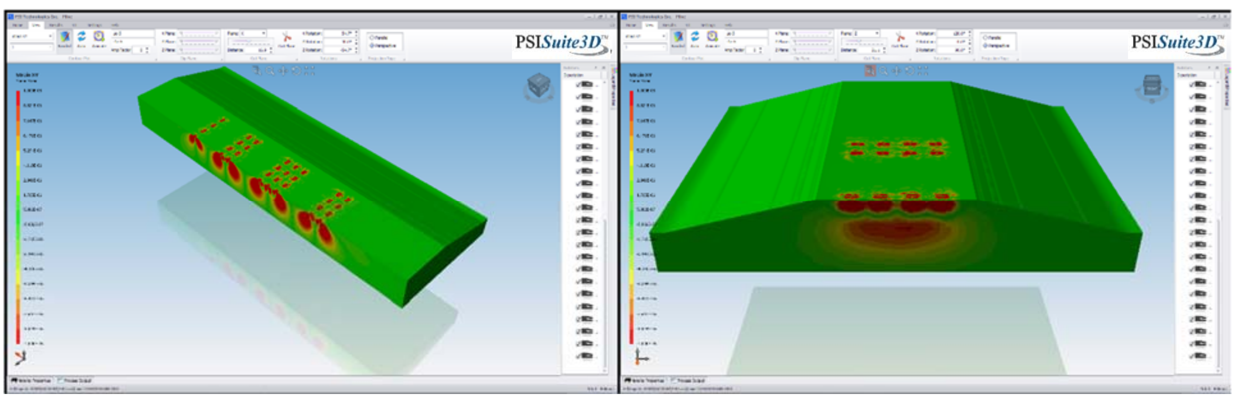
Figure 10 Horizontal Strain Profile Across Road Length and Width by Moisture State



a) Loading with Two B-Trains – Deep Subgrade Wetting Up



b) Loading with Two B-Trains – Initial Bottom Up Moisture Infiltration in Prepared Subgrade



c) Loading with Two B-Trains – Advanced Bottom Up Moisture Infiltration into Structural Layers

Figure 11 Shear Strain Profile Across Road Length and Width by Moisture State

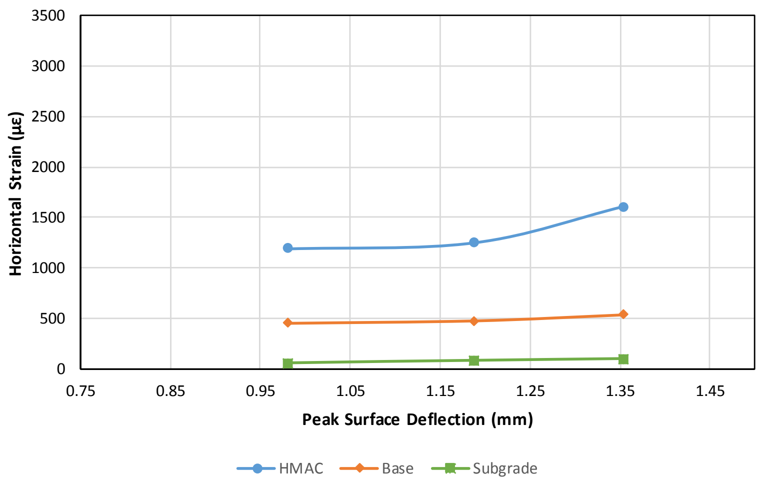


Figure 12 Peak Horizontal Tensile Strain versus Peak Surface Deflection

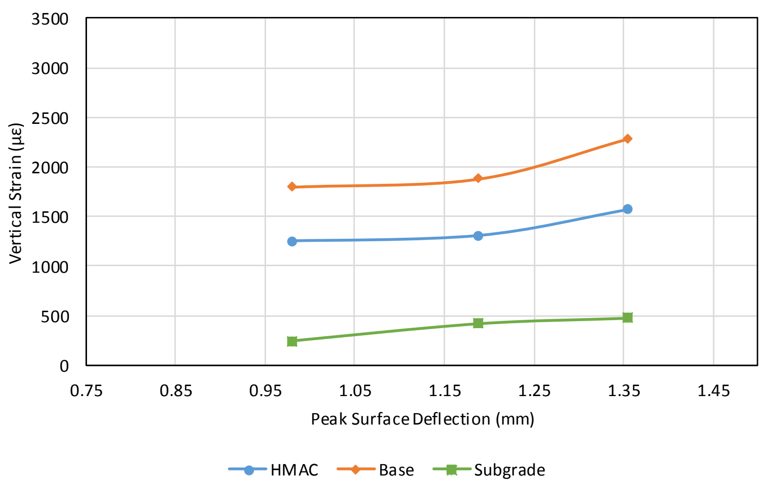


Figure 13 Peak Vertical Compressive Strain versus Peak Surface Deflection

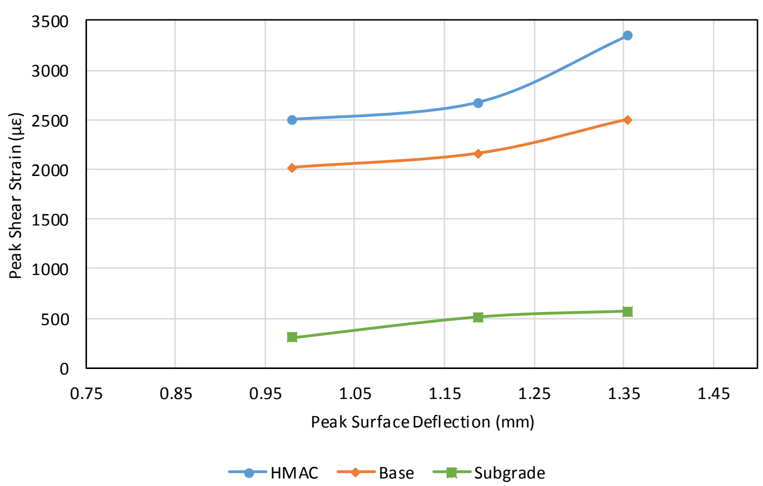


Figure 14 Peak Shear Strain versus Peak Surface Deflection

Based on the horizontal tensile, vertical compressive and shear strain contours presented in Figure 9, Figure 10 and Figure 11 respectively, the peak strain value within each road structural layer was identified in Figure 12, Figure 13 and Figure 14 illustrate a comparison of the trend of peak surface deflection versus peak horizontal tensile, vertical compressive and shear strains, respectively across field state moisture content.

As seen in Figure 12 through Figure 14, the normal orthogonal strains commonly used to predict road performance were observed to be much lower in magnitude relative to shear strain. In addition, the relative increase in magnitude of shear strains with progressively wetting up of the road structure was observed to be significantly higher relative to the orthogonal strains within the road structural layers of base and HMAC.

CONCLUSION

The finite element model characterized the effect of the *in situ* variability under typical B-Train truck loading specified for the analyzed heavy haul road in Western Canada as well as climatic conditions typical of the area. Shear strain modeling was the focus of this analysis as this variable is rapidly becoming recognized as a unique measurement of roadway performance. Orthogonal strains need to be applied in conjunction with shear strain to obtain a more accurate roadway performance. The results of the modelling investigation showed significant variation in peak surface deflection, tensile and compressive strain profiles. Based on the numerical modeling with PSIPave3D™ presented herein, using material property inputs from the mechanistic characterization, and the structural design geometry the following was observed:

- The effective layer, or layer deterioration has a significant impact on measured/simulated variables such as shear and orthogonal strains and deflections.
- Shear strains were shown to be of higher magnitude and to increase at a higher rate than deflection, indicating that deflection alone does not truly indicate roadway performance condition.
- Three-dimensional contours indicated the levels of strains through each scenario modeled. It highlights the importance of characterizing two B-Trains side-by-side and how each truck magnifies the effect of induced strain into the deep pavement layers.
- GPR analysis combined with numerical modelling can be a powerful tool to predict roadway performance as it enables roadway engineers to pinpoint deficient locations affected by moisture infiltration.

Based on the results obtained herein, three-dimensional non-linear orthogonal road structure modeling provides the ability to quantify shear strains occurring within road structures. Given geo-materials are known to fail primarily in shear in the field, it is hypothesized that road structural performance prediction formulations should be based on shear strain formulations as opposed to orthogonal strains.

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