City of Saskatoon Mechanistic Pavement Structure Modeling

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ABSTRACT
Road agencies worldwide are faced with unprecedented challenges with regards to managing diverse and aging road infrastructure assets. Given the modern day challenges of structurally upgrading in-service road infrastructure assets in diverse field state conditions, there is a need for a more fundamentals-based road design methodology with the ability to incorporate new innovative materials, road structure systems, and field state conditions directly into the design process. This project demonstrated the use of computational engineering mechanics for structural road modeling to provide a reliable pavement design process and validation for City of Saskatoon field state conditions.

The mechanistic analysis method employed in this study modeled peak surface deflection under critical state load spectra conditions. The structural road modeling framework was found to concur with non-destructive structural measurements of conventional pavement structures and recycled pavement field test sections. The structural road modeling framework provides a method to measure the in-field performance of various road structures in field state conditions, in addition to verifying pavement structure design.

INTRODUCTION

The City of Saskatoon, like many urban centres, is challenged with rehabilitating, maintaining, and operating several thousand lane kilometers of roads. A history of reduced preservation budgets and maintenance has increased the City's infrastructure deficit (*1*). Keeping up with the rehabilitation and maintenance of existing road assets in combination with the expansion and construction of new roads in the city has proved to be a difficult task for the City of Saskatoon. Determining optimal rehabilitation solutions for in-service road structures in varied field state conditions is of primary concern. Given the modern day challenges of structurally upgrading in-service road assets in diverse field state conditions, there is a need for a fundamentals based road design methodology with the ability to incorporate new innovative materials, road structures, and severe Saskatchewan field state conditions.

PSI Technologies has developed a mechanistic model that calculates the fundamental mechanistic primary response principles known to be directly related to long term pavement performance. The PSIPave™ road model provides a pavement design process and validation using non-destructive heavy weight deflection (HWD) structural asset management measures, mechanistic material properties, and long term performance prediction.

Background

Conventional Saskatchewan road design methods use the modified California Bearing Ratio (CBR) Shell Design Curves. This method of pavement design is empirical-based and does not account for realistic present-day field performance of road materials. This design method is generally based on the layered linear elastic primary response criterion of vertical compressive stress/strain at the top of the subgrade for permanent deformation, and horizontal tensile stress/strain at the bottom of the asphalt layer for fatigue cracking (*2*). Developed in 2002, AASHTO's mechanistic-empirical pavement design guide (MEPDG) applies principles of engineering mechanics and uses inputs including traffic, climate, pavement layer thickness, and material properties to predict pavement performance (*3*). While the City of Saskatoon (COS) has not adopted the MEPDG in its new road construction or road rehabilitation, the value of using mechanistic materials properties for design and rehabilitation purposes is recognized.

COS, like the rest of Saskatchewan, is highly dependent on subgrade type for the purpose of pavement structural design. The CBR Shell Design Curves use subgrade type to dictate HMAC surfacing, granular base layer, and subbase layer thicknesses. Moreover, often a history of "typical" preservation treatments developed within a jurisdiction are used despite the fact they may not account for changing field state conditions or alternative materials. For example, conventional methods are not applicable for alternative road structures and recycled materials.

Typical City of Saskatoon arterial, local, and collector roadways are constructed in an urban cross section, including curb and gutter. Conventional urban cross sections typically include up to 200 mm granular base on top of subgrade, with 50 mm to 150 mm hot mix asphalt concrete (HMAC) surfacing. City of Saskatoon roadways are constructed on subgrade materials of variable *in situ* conditions. For example, some Saskatoon roadways are constructed on high-and-dry subgrades with no moisture problems while other Saskatoon roadways are constructed on wet, low-lying subgrades subject to a high water-table issues. The latter is becoming increasingly common in jurisdictions such as Saskatoon that have seen an increase in new-home construction in areas of poor subgrade conditions and increasing water table as well as field state conditions in ageing areas (*4,5*). Also, in recent years, Saskatchewan has experienced increased precipitation and spring flooding in areas throughout the city (*6*). There has been more City of Saskatoon roads failing structurally due to poor subgrades (*4,5*). Conventional attempts to mitigate poor subgrade materials include full-depth remove and replace reconstruction with additional granular base thickness.

In recent years, the City of Saskatoon has explored drainage systems as an integral component to mitigating the effect of poor subgrades (*5*). Under the "Green Streets" Infrastructure Program, the City of Saskatoon rehabilitated roads experiencing structural failures due to poor subgrade conditions using reclaimed asphalt pavement (RAP) and crushed Portland cement concrete (PCC) materials. The crushed PCC materials were used in a drainage layer installed between the subgrade and base layer. Drainage layers were constructed with geotextile fabric between the layers to separate and promote drainage and were be tied into the city's storm-drainage system using weeping tile. Crushed PCC drainage rock provides a less expensive alternative to using conventional pit run rock (*4*).

Like most jurisdictions, the City of Saskatoon employs an infrastructure asset management system to delegate budgetary expenditures of new construction and rehabilitation and maintenance strategies (*1)*. Innovative rehabilitation strategies have included ultra-thin overlays, drainage layers, and PCC and RAP used as an aggregate replacement. With regards to managing transportation infrastructure such as road assets, the City of Saskatoon has historically relied on surface distress measurements and roughness to characterize the condition of road assets (*7*). Using surface distresses and roughness to characterize road assets at the network-level is limited such that they do not accurately characterize the structural integrity of a pavement structure (*7*).

Non-destructive structural asset management heavy weight deflection (HWD) measurements are used to determine the structural integrity of a pavement structure by measuring the peak deflection of the road under a spectra of commercial truck loads. HWD measurements compliment visual distress surveys and automated distress surveys by providing detailed road structure information. HWD measurements remove speculation of a road's structure prevalent in visual distress surveys. The City of Saskatoon has investigated the use of non-destructive HWD measurements as part of its road asset management system in conjunction with its surface distress measurements. Over the past eight years, as part of a pilot study, the City of Saskatoon has collected HWD measurements for a number of its arterial, collector, and local roads. Based on HWD measurements, the City of Saskatoon has established HWD peak surface deflection measurement thresholds that may be used to determined the condition of a road (*7,8*).

PSI Technologies has developed a mechanistic road model to calculate fundamental mechanistic primary response principles known to be directly related to long term pavement performance. The model uses computational mechanics to calculate the stress-strain behaviour of a road structure across road structure composition, load spectra, climatic conditions and mechanistic material properties. The PSIPave™ road model uses mechanistic material properties and road geometry to predict and verify field performance. Figure 1 illustrates the capabilities of the model to determine pavement response under various field state conditions.

Objective
The objective of this project was twofold. First, the objective was to demonstrate the use of structural road modeling computational engineering mechanics to determine the primary deflection response of typical City of Saskatoon pavement rehabilitation systems in field state conditions. Second, the objective was to use structural road modeling to validate pre and post construction field HWD-measured deflections for an actual road rehabilitation project.

Scope
This project used mechanistic materials characterization and computational road modeling to examine the performance of conventional pavement structures and recycled pavement structures in City of Saskatoon. Peak deflections were predicted for different City of Saskatoon pavement structures using the PSIPave™ road model.

The performance of conventional pavement structures and recycled pavement structures in the City of Saskatoon was examined across typical cross sections. For example, the typical conventional pavement structure examined had a 60 mm hot mix asphalt concrete (HMAC) surface on 200 mm granular base, on top of subgrade. The typical recycled pavement structure examined had 60 mm HMAC surfacing on 200 mm *in situ* reclaimed HMAC and granular base material with a drainage layer of 300 mm crushed Portland cement concrete (PCC) material, on top of subgrade.

To account for the variable subgrade conditions present in Saskatoon, two types of typical subgrades were identified: a good subgrade and a poor subgrade. A good subgrade was defined as a high-and-dry self-draining subgrade that is not susceptible to moisture issues. A poor subgrade was defined as a wetted-up subgrade susceptible to moisture issues.

Using a field example from the 2009 road rehabilitation of 8th Street East in Saskatoon, the model was validated using mechanistic materials properties, HWD peak surface deflections, and layer thicknesses constructed in the field for both pre and post construction right turn lane pavement structures. The driving lane and median lanes were rehabilitated using other recycled pavement structures and are not modeled in this paper.

MODELING OF TYPICAL CITY OF SASKATOON URBAN CROSS SECTIONS

To satisfy the first objective of this paper, two typical cross sections constructed in COS were modeled to predict peak deflections for each structure. Typical material properties and layer thicknesses were used to model these cross sections in typical COS field state conditions.

Conventional Urban Cross Sections
Figure 2 illustrates two conventional urban cross sections recently constructed in Saskatoon. Figure 2 a) illustrates a conventional pavement structure on a good subgrade. Figure 2 b) illustrates a conventional pavement structure on poor subgrade. Wetting-up of the granular base layer is common in typical Saskatoon urban roadways with poor subgrade as fines content from the subgrade layers migrates up into the granular base layer, increasing its moisture content and subsequently reducing the road structure's integrity.

Road Model Results

The PSIPave™ road model was used to predict the peak deflection of City of Saskatoon urban cross sections using pavement structure layer depths and mechanistic material properties. The two conventional pavement structures described in the previous section were modeled using respective typical material properties and typical cross section layer thicknesses, as illustrated in Figure 1. The mechanistic materials properties were determined using rapid triaxial frequency testing and include dynamic modulus, radial microstrain, phase angle and Poisson's ratio.

Figure 3 illustrates the resultant model-predicted peak surface deflections across a load spectra of secondary weight limits, primary weight limits, primary plus 25 percent weight limits, and primary plus 50 percent weight limits for each pavement structure. The City of Saskatoon structural asset management system has established HWD condition state thresholds for good, fair, and poor roads. Poor thresholds for local and arterial roads were set at 1.50 mm and 2.00 mm, respectively.

As seen in Figure 3, the conventional cross section on good subgrade had the lowest peak surface deflections. Although this is the ideal situation, it is not the most common field state condition in Saskatoon. Peak deflections for the conventional cross section on poor subgrade are more representative of typical City of Saskatoon field state condition. Figure 3 shows the highest peak surface deflections across all weight limits were observed for a conventional cross section on poor subgrade.

MODELING A ROAD REHABILITATION PROJECT

To satisfy the second objective of this paper, the road model was validated using mechanistic materials properties, layer thicknesses, and HWD peak surface deflections for both the pre and post construction of a section of 8th Street East in Saskatoon.

In 2009, a 540 m section of 8th Street East was rehabilitated under the COS "Green Streets" Infrastructure Program. 8th Street East consists of three lanes. The right hand turning lane was exhibiting structural failure pre construction due to drainage issues which included a poor, wet subgrade. The right turn lane was rehabilitated using a recycled pavement structure design. The driving lane and median lanes were rehabilitated using other recycled pavement structures and are not modeled herein.

Road Rehabilitation Urban Cross Sections

Figure 4 illustrates the pre and post cross sections for the right turn lane of 8th Street East. Figure 4 a) illustrates the pre construction cross section and shows the poor subgrade causing the granular base to become wet. Figure 4 b) illustrates the post construction cross section. The post construction recycled pavement structure was constructed with a 300 mm crushed PCC drainage layer to mitigate moisture issues.

Road Model Results

The PSIPave™ road model was used to predict strain contour profiles of the pavement structures and to determine the peak deflection of 8th Street both pre and post construction using pavement structure layer depths and mechanistic material properties, as illustrated previously in Figure 1. The mechanistic materials properties were determined using rapid triaxial frequency testing and include dynamic modulus, radial microstrain, phase angle and Poisson's ratio.

Figure 5 and Figure 6 illustrate the shear strain profiles and vertical strain profiles, respectively, for the pre and post construction 8th Street East right turn lane pavement structures under primary weight limits plus 25 percent. The loading is based on a two-tire load exceeding primary weight limits by 25 percent.

Figure 5 illustrates the shear strain profiles for 8th Street East's right turn lane pre and post construction under primary plus 25 percent weight limits. For the shear strain contours, a cross section of the shear strain profile is also provided to demonstrate the shear strains occurring within the road structure. Figure 5 shows an improvement in shear strain behavior post construction. Pre construction, poor shear strain behavior was observed in all layers of the pavement structure, but was specifically prevalent in the subgrade (bottom portion of the contour). Post construction, the shear strains in the subgrade were reduced, thus reducing the potential for shear failure in the subgrade which is a common pavement structure failure mechanism.

Figure 6 illustrates the vertical strain profiles for 8th Street East's right turn lane pre and post construction under primary plus 25 percent weight limits. For the vertical strain contours, a cross section of the vertical strain profile directly below the load is also provided to demonstrate the vertical strains occurring within the road structure. Figure 6 shows an improvement in vertical strain behavior post construction. Pre construction, poor vertical strain behavior was observed in all layers of the pavement structure. Post construction, the vertical strain behavior improved in the upper layers of the pavement structure, as well as in the subgrade.

Falling Weight Deflectometer Results

The road model predicted peak deflections were compared to HWD measured peak deflections determined in field using the HWD. Figure 7 illustrates the model predicted and HWD measured peak deflections for 8th Street East right hand turn lane, pre and post construction. As seen in Figure 7, the peak deflections predicted by the road model are in agreement with the HWD measured peak deflections. Pre construction, the difference between the road model and HWD peak deflections ranged from -0.02 mm to 0.02 mm. Post construction, the road model peak deflections were 0.04 mm to 0.06 mm greater than the HWD peak deflections. This demonstrates that the road model is capable of predicting peak surface deflections using material properties and layer thicknesses.

SUMMARY AND CONCLUSIONS

This project demonstrated the use of road structural modeling to determine the primary deflection response of various City of Saskatoon pavement rehabilitation systems in field state conditions. The PSIPave™ road model was used to predict the peak deflection of two conventional cross sections constructed in COS using typical pavement structure layer depths and mechanistic material properties. Peak surface deflections across a load spectra of weight limits were determined using the road model and showed the conventional cross section on poor subgrade had the highest peak surface deflections across all weight limits compared to the conventional cross section on good subgrade. This shows that the COS is highly dependent on subgrade type for the purpose of pavement structural design.

To satisfy the second objective of this paper, the road model was validated using mechanistic materials properties, layer thicknesses, and HWD peak surface deflections for both pre and post construction of the right turn lane on a section of 8th Street East in Saskatoon. The peak deflections predicted by the road model are in agreement with the HWD measured peak deflections; the road model is capable of predicting peak surface deflections using material properties and layer thicknesses.

The PSIPave™ road model was also used to predict strain contour profiles of the pavement structures and determine the peak deflection of 8th Street. Pre construction, poor shear strain behavior was observed in all layers of the pavement structure, but was specifically prevalent in the subgrade. Pre construction, poor vertical strain behavior was observed in all layers of the pavement structure. Post construction, the vertical strain behavior improved in the upper layers of the pavement structure and in the subgrade. Reducing shear and vertical strains in the subgrade eliminates potential for subgrade failure which is a common pavement structure failure mechanism.

The PSIPave™ road model was found to provide realistic performance prediction of conventional and recycled road structures. The road model was capable of providing peak deflections for various road structures which were confirmed by HWD field measured peak deflections. The road model was also used to predict the strain contours of pre and post construction pavement structures. This validated the reconstructed cross section as well as illustrated the effect the subgrade plays in the shear and vertical strain profiles within a Saskatoon road structure. It is recommended that the City of adopt computational mechanics modeling as part of the design process and design verification process in order to improve performance prediction of road structures.

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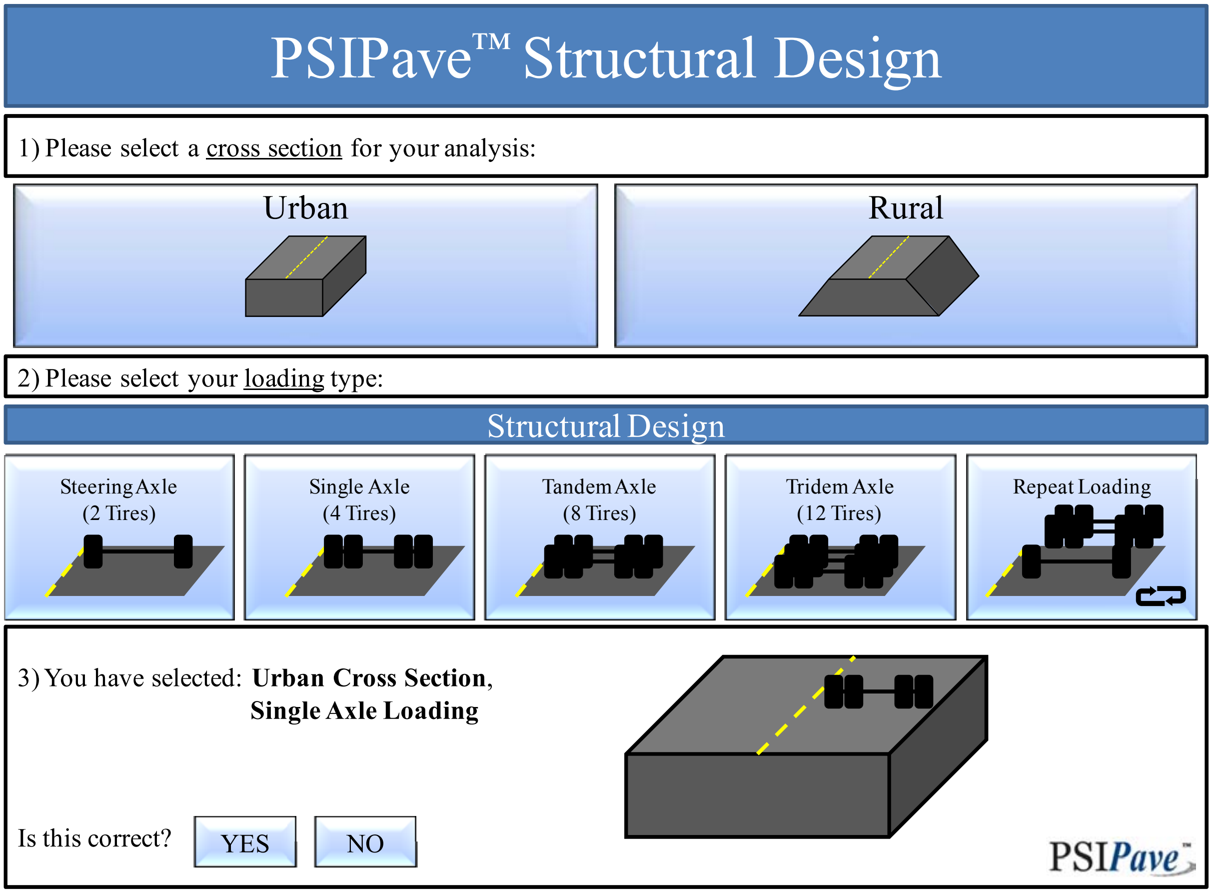
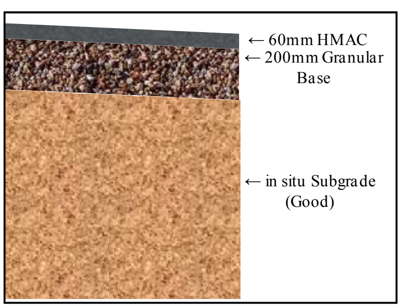
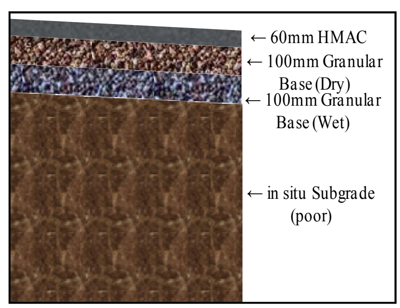


Figure 1 Mechanistic Design Road Model Process





a) Conventional (Good Subgrade) b) Conventional (Poor Subgrade)

Figure 2 Typical Urban Pavement Structures

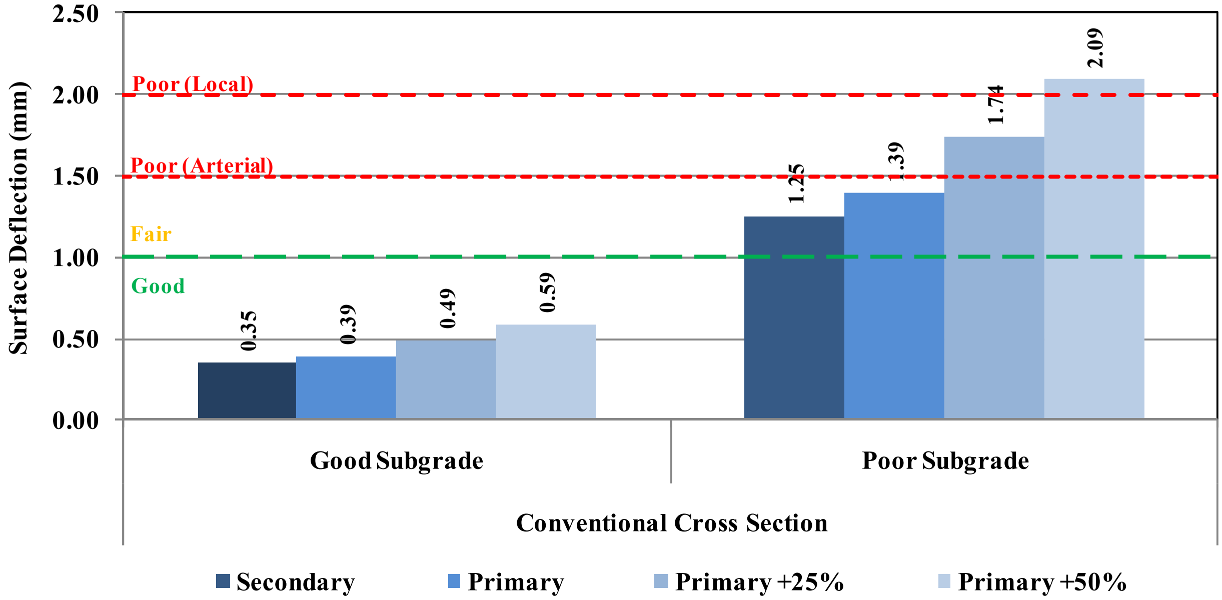
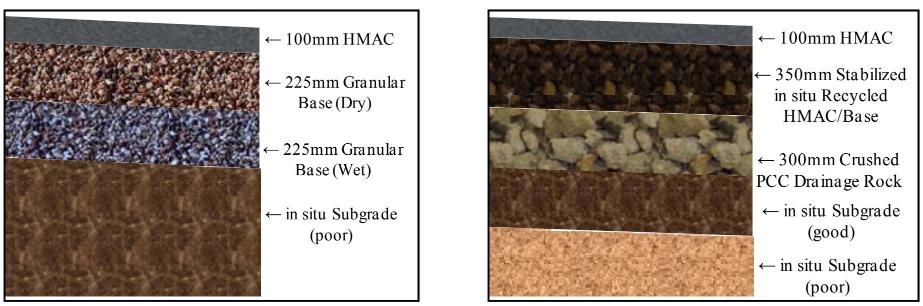
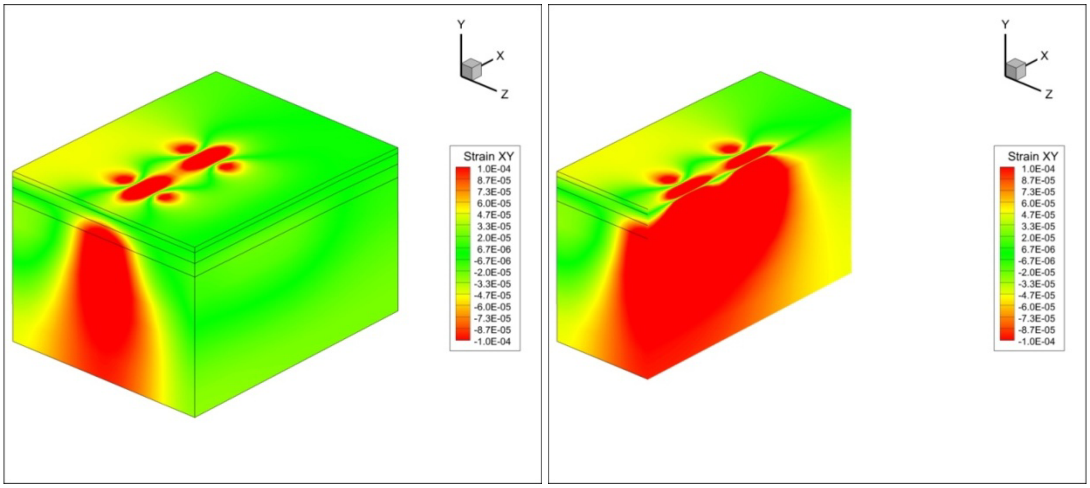


Figure 3 PSIPave™ Predicted Peak Surface Deflection

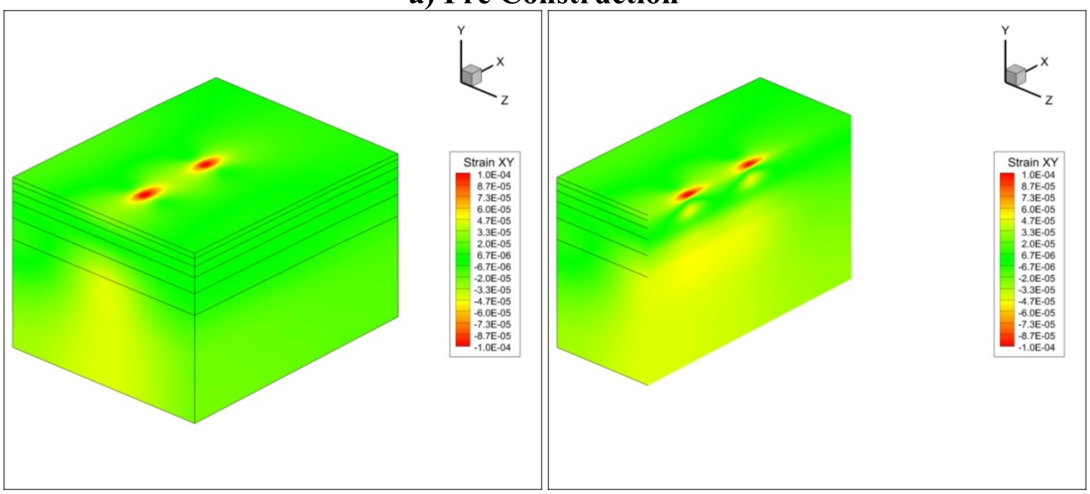


a) Pre Construction b) Post Construction

Figure 4 Road Rehabilitation Pavement Structures – 8th Street East (right turn lane)

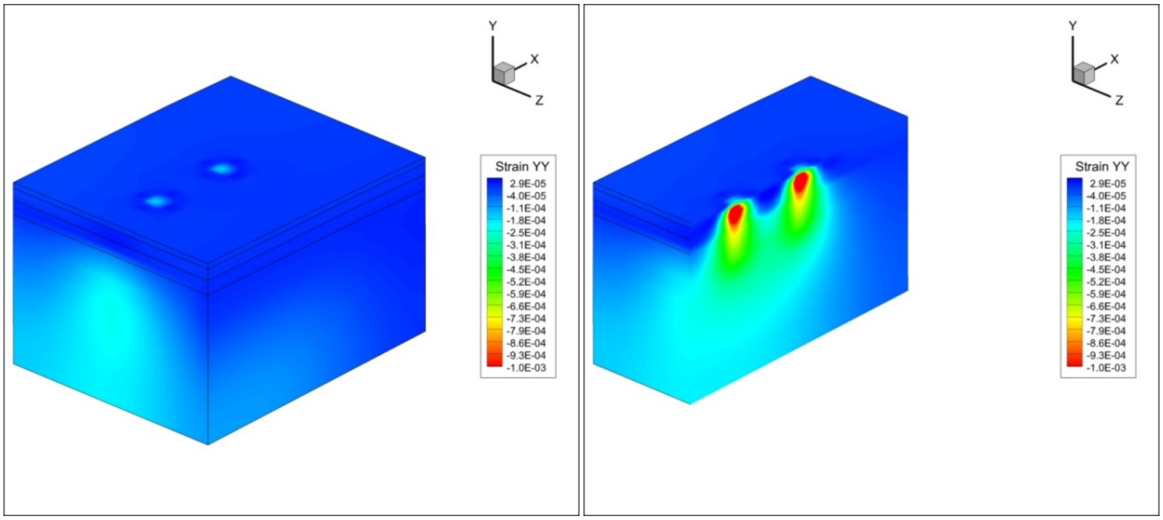


a) Pre Construction

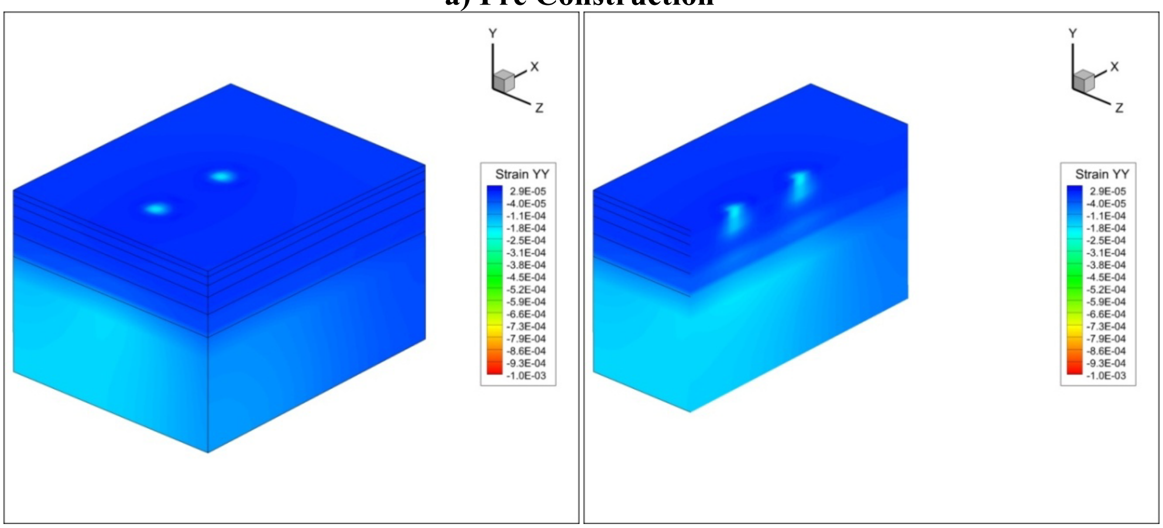


b) Post Construction

Figure 5 Shear Strain Profiles under Primary +25% Weight Limits – 8th Street East (Right Turn Lane)



a) Pre Construction



b) Post Construction

Figure 6 Vertical Compressive Strain Profiles under Primary +25% Weight Limits – 8th Street East (Right Turn Lane)

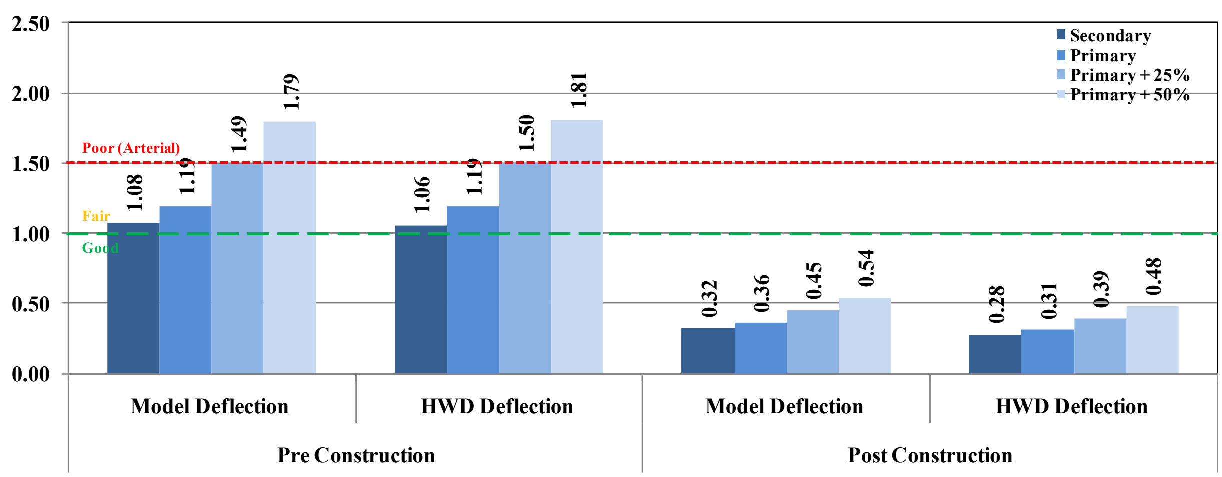


Figure 7 PSIPave™ Predicted Peak Surface Deflection