MECHANISTIC DESIGN SENSITIVITY ANALYSIS FOR

CITY OF SASKATOON PAVEMENT STRUCTURE DESIGN

Prepared by:

Duane Guenther, Roberto Soares, Rielle Haichert, Farukh Sharipov, and Curtis Berthelot

PSI Technologies Inc., Saskatoon, SK

221 Jessop Avenue, Saskatoon, SK, Canada, S7N 1Y3

Phone: (306) 477-4090, Fax: (306) 477-4190, dguenther@pavesci.com

Paper prepared for presentation at the

Characterization of Soils and Pavement Materials for Mechanistic Empirical Pavement Design Session
2014 Annual Conference of the

Transportation Association of Canada

Montreal, Quebec

ABSTRACT

Currently, City of Saskatoon (COS) pavement structure designs are based on Saskatchewan Ministry of Highways and Infrastructure (MHI) design protocols for roadways in addition to the *City of Saskatoon New Neighbourhood Design and Development Standards Manual*. The MHI design protocols use California bearing ratio (CBR) modified Shell design curves, which are based on the American Association of State Highway Officials (AASHO) road test.

In new Saskatoon subdivisions, many of the *in situ* subgrade soaked CBR measurements are less than 5.0. In those cases, the City's *New Neighbourhood Standards Manual* calls for the pavement structure design to be conducted on an individual basis, with drainage layers, weeping tile, and geosynthetics. Neither the *New Neighbourhood Standards Manual* nor the MHI design protocols account for the use of drainage layers, weeping tiles, and/or geosynthetics in the design processes. A new design methodology is needed.

Given observed premature structural failures of relatively new pavements in Saskatoon in areas of poor soils and/or wet conditions, a mechanistic roadway design methodology for Saskatoon roadways was conducted as part of a pilot study in 2013. The design methodology that was used employed mechanistic materials testing and three dimensional road structural modeling. This pilot study showed that the standard City of Saskatoon pavement structures for roadways were not structurally appropriate for roadways in subdivisions with marginal subgrade types. Mechanistic modeling provided an alternative design methodology based on peak surface deflection critical state criteria and *in situ* material properties specific to actual traffic loadings and moisture conditions.

This paper examines the sensitivity of peak surface deflection model response relative to granular base thickness with and without drainage layers. Using results of the mechanistic pavement structure design study, these pavement structures were evaluated into three levels of risk based on modeled peak deflections: low risk of failing, some risk of structural failure, and high risk of structural failure. Levels of risk were established for thickness of granular base layer as well as construction costs. This allows the pavement designer to determine the optimum pavement structure using desired layer thickness or budgetary requirements, all based on modeled structural primary response under field state conditions typically encountered in the Saskatoon's new subdivision areas.

INTRODUCTION

Currently, City of Saskatoon (COS) pavement structure designs are based on Saskatchewan Ministry of Highways and Infrastructure (MHI) design protocols for roadways in addition to the *City of Saskatoon New Neighbourhood Design and Development Standards Manual* (1). The MHI design protocols use California bearing ratio (CBR) modified Shell design curves, which are based on the American Association of State Highway Officials (AASHO) road test (2). In practice, road structural designs are often based on historical preservation treatments and materials. However, neither the CBR Shell Curve method nor the historical typical preservation treatments effectively account for climatic and urban traffic loading effects on subgrade materials or pavement structure drainage layers (3). Figures 1 and 2 below illustrate typical residential road failures in Saskatoon roads as a result of inadequate roadway design based on subgrade type.

Many of Saskatoon's new subdivisions are constructed in locations with marginal subgrade conditions (1). In these locations, the *in situ* subgrade soaked CBR measurements are less than 5.0 (1). It is estimated that up to 70 percent of new road construction in the Saskatoon's residential subdivisions will occur in marginal soil conditions. In this case, for a soaked CBR less than 5.0, Saskatoon's *New Neighbourhood Standards Manual* requires the roadways to be designed on an individual basis using information from the geotechnical investigation and traffic analysis. Also, the manual calls for the pavement structure design to be conducted on an individual basis, with drainage layers, weeping tile, and geosynthetics. Neither the *New Neighbourhood Standards Manual* nor the MHI design protocols account for the use of drainage layers, weeping tiles, and/or geosynthetics in their design processes (1,2,3). A new design methodology is needed and the City of Saskatoon is presently undergoing an evaluation of its current pavement design standards.

Given observed premature structural failures of relatively new pavements in Saskatoon areas of poor soils and/or wet conditions, a mechanistic roadway design methodology for Saskatoon roadways was conducted as part of a pilot study in 2013 (4,5). The design methodology employed materials testing and three dimensional road structural modeling. The model evaluated four pavement structures with different drainage layers: edge drain, drainage sand, drainage rock, and Saskatoon granular base only. All pavement structures included a hot mix asphalt surface, granular base, and woven geosynthetics if a drainage layer was present. The design vehicle load was specified at Saskatchewan primary weight limits. This pilot study showed that the standard City of Saskatoon pavement structures for roadways were not structurally appropriate for roadways in constructed in new subdivisions with weak subgrade types. Mechanistic modeling provided an alternative design methodology based on peak surface deflection critical state criteria and *in situ* material properties specific to field state conditions. Mechanistic modeling has also shown that Saskatoon roadway life cycle performance is highly dependent on subgrade type (4,5,6,7).

This paper is a continuation of a study conducted last year for the City of Saskatoon. A paper titled *Mechanistic Design: A Modeling Case Study for the City of Saskatoon* was presented at the 2013 Annual Conference of the Transportation Association of Canada (3).

The objective of this study presented herein is to measure and assess the sensitivity of peak surface deflection model response relative to granular base thickness and construction costs with and without different drainage layers using a mechanistic finite element analysis approach.

Figure 1 Typical Moisture Problems in Saskatoon Streets

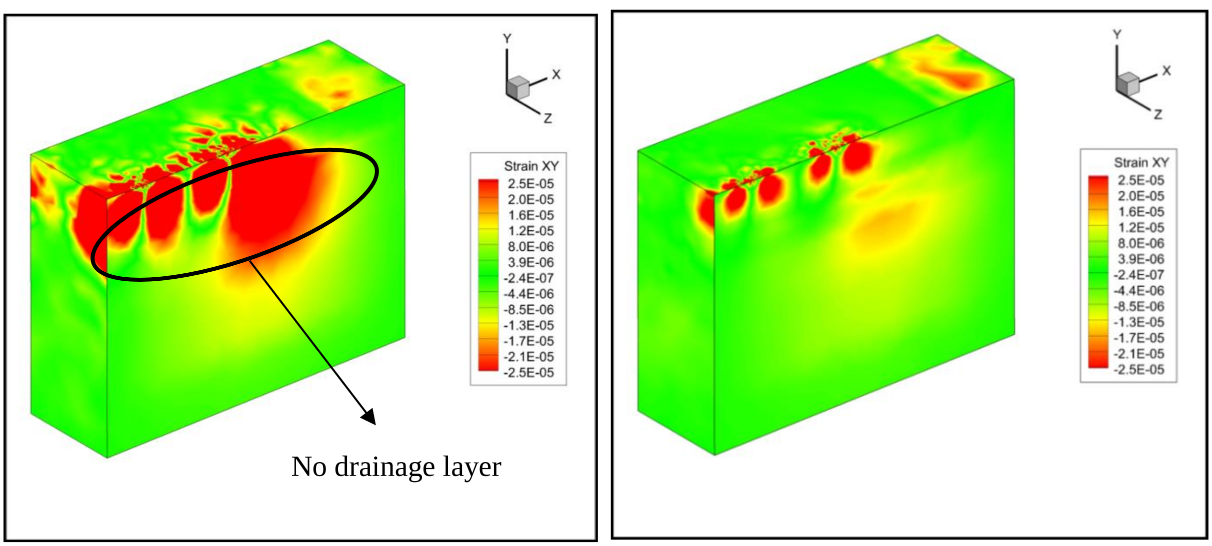
Figure 2 Typical City of Saskatoon Roadway Structural Failure

Mechanistic Finite Element Analysis Approach

A finite element numerical model was used to predict the mechanical behavior and performance of various pavement structures under different stress states. This methodology uses material properties for the pavement layer materials, applies a simulated load, and predicts a deflection response on the surface. The road model uses dynamic modulus and Poisson's ratio of pavement structure materials, along with a given set of loads and geometries to calculate the stresses, strains, and deflection in the pavement structure. The subgrades are differentiated based on the Unified Soil Classification System (USCS) and moisture content (optimum moisture content, wet of optimum, etc.).

Research has shown that urban roadways are highly dependent on the subgrade and are more likely to fail in critical state loading before reaching the designed number of traffic loading repetitions (4,5,6,7,8). Previous research completed in Saskatoon has concluded that a drainage layer can mitigate weak subgrades and pavement structure moisture infiltration in urban settings (7). The road model outputs orthogonal strains, which conventional road design methodologies typically calculate and empirically correlate to field performance. The road model also outputs shear strains, which truly dictate the structural performance and failure criterion of a pavement structure.

Figure 3 illustrates an example of the model's three dimensional shear strain results for a roadway cross section, comparing a local Saskatoon roadway without a drainage layer (i.e. granular base layer only) to the same structure with a crushed rock drainage layer and reduced granular base layer thickness. (Note the pavement structures with a drainage layer modeled with geosynthetics are in place to separate the material; the geosynthetics modeled were woven geotextiles and biaxial geogrids.) The red color indicates a high shear strain while the green indicates reduced shear strain in the pavement structure's subgrade. Saskatchewan road structures are highly subgrade dependent due to the relatively thin asphalt concrete and granular base layers, and the modeled shear strain results reflect that. By installing a drainage layer using crushed rock, the shear strains in the high plastic clay subgrade are dissipated which reduces high strain concentrations in the granular base layer as well.



a) No Drainage (existing specification) **b) Drainage Rock**

Figure 3 3D Shear Strain Results – Local Roadways, (CH Subgrade, High Risk of Moisture) (4)

The three dimensional model was used to conduct the finite element analysis that determined the road design pavement structure deflections, measured in millimetres (mm), based on critical state loading. For the purposes of this study, critical state loading is defined as Saskatchewan primary weight load and was used to determine failure instead of conventional equivalent single axle load (ESAL) accumulation. Also, for the purposes of this study, all pavement structures with drainage layers (i.e. sand, crushed rock) were modeled with the assumption that geosynthetics are in place between the subgrade and a drainage layer as well as between the granular layer and drainage layer to maintain material separation, to allow pore water pressure dissipation, and to provide structural stiffness during construction. The geosynthetics modeled were woven geotextiles and biaxial geogrids. Geosynthetics offer structural stiffness during construction in order to bridge weak subgrades. The geosynthetics that were modeled herein were conservatively assumed for the sole purpose of material separation properties.

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. A study was conducted to validate the structural road modeling deflection response by field falling weight deflectometer testing (7). The study found that the field deflection measurements were accurately validated across four different road structures and various load spectra with most model predicted peak surface deflections being within the range of -2 to 13 percent of the field measured peak surface deflections (7). This study demonstrated the dependency of a pavement structure on its subgrade with regards to primary pavement response (4,7). This study also demonstrated the effect of a drainage layer on the structural performance of urban roads (7). Previous studies using PSIPave3D™ have shown that *in situ* subgrades in marginal or wet conditions do not provide the necessary structural capacity for traffic loads, especially in wet subgrade conditions (4,5,6,7,8). The road model has also showed the effect of constructing urban roads in a 'clay box' relative to conventional highway design with free draining shoulders (8).

RESULTS AND DISCUSSION

Granular Base Thickness Comparisons for Varying Drainage Layer Types

Past research identified design curves for local and collector roadways across different subgrade types in order to capture the broad range of subgrades found in the new neighborhoods surrounding the City of Saskatoon (4). Figure 4 a) and b) illustrate the granular thicknesses required to meet the deflection requirements for local and collector roadways, respectively, when the risk of the granular base increasing in moisture content to greater than optimum moisture is high for a high plasticity clay subgrade (CH). Figure 4 a) and b) assume an asphalt thickness of 45 mm for local roadways and 80 mm for collector roadways, respectively, and investigate the structural response of the pavement structures with varying drainage layer types: an edge drain, sand drainage layer, and crushed rock drainage layer. Pavement structures with a granular base layer only are also presented as a baseline.

The peak deflection of each pavement structure was compared to a maximum peak deflection criteria determined at Saskatchewan primary weight limit (9). The maximum peak deflection criteria were 1.0 mm for local roadways, 0.65 mm for collector roadways and 0.50 mm for arterial roadways (9). This deflection criterion was determined based on deflection measurements taken in Saskatoon over a number of years as part of an asset management study that compared the deflection in roads that were not showing damage at the end of their service life to the deflection experienced in areas where roads had to be replaced before the end of their service life (9). Previous studies have identified that peak deflection criteria induces high strains in the pavement structure (4,5,6,7,8). These strains are above the materials' strain limits, causing cracking and rutting initiation and subsequently pavement failure. The structures were then color coded into three levels of risk, as illustrated in Figure 4.

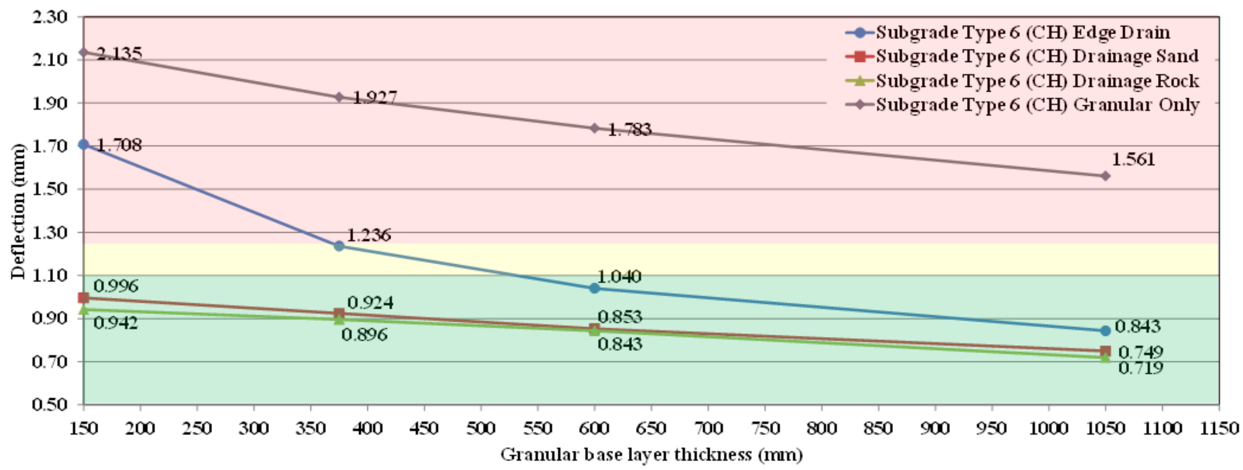
- Green signifies structures that are at low risk of failing due to meeting the deflection criteria or being within 10% of the maximum allowable deflection.
- Yellow signifies structures that have some risk of structural failure and have deflections between 10% and 25% greater than the maximum allowable deflection.

- Red signifies structures that have a high risk of structural failure as the peak deflection is greater than 25% over the maximum allowable deflection.

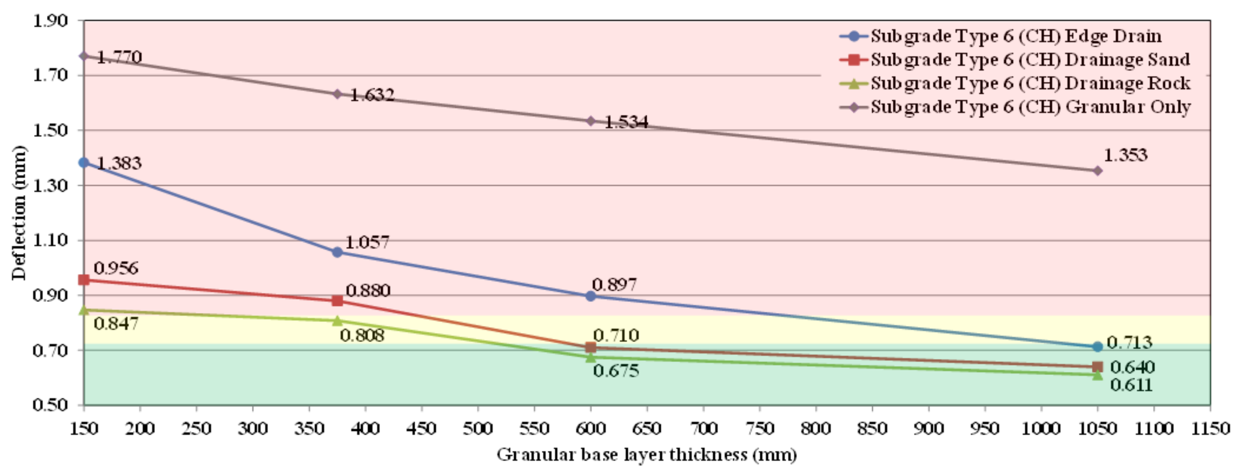
These design curves (Figure 4) were completed assuming:

- A wet of optimum high plastic clay (CH) subgrade; and
- A low fracture drainage rock layer (COS specifications call for minimum of 50% fracture, one face).

While these systems will perform as designed, an optimized structure is desirable given the excessive granular thicknesses required to minimize the pavement structures' peak deflections. The drainage layers add additional thickness to the total road structure – at 300 mm for the sand drainage layer and 225 mm for the crushed rock drainage layer. The edge drain system adds a partial 300 mm thick granular layer at the edge of the roadway. When comparing the peak surface deflection to the total road structure thickness, the drainage structures still have lower deflections than the granular only option. However, the deflections at similar total granular thicknesses show less difference between the drainage options than when examining only the granular base thicknesses.



a) Local Roadways



b) Collector Roadways

Figure 4 Granular Thicknesses versus Peak Surface Deflection (mm), Subgrade Type CH

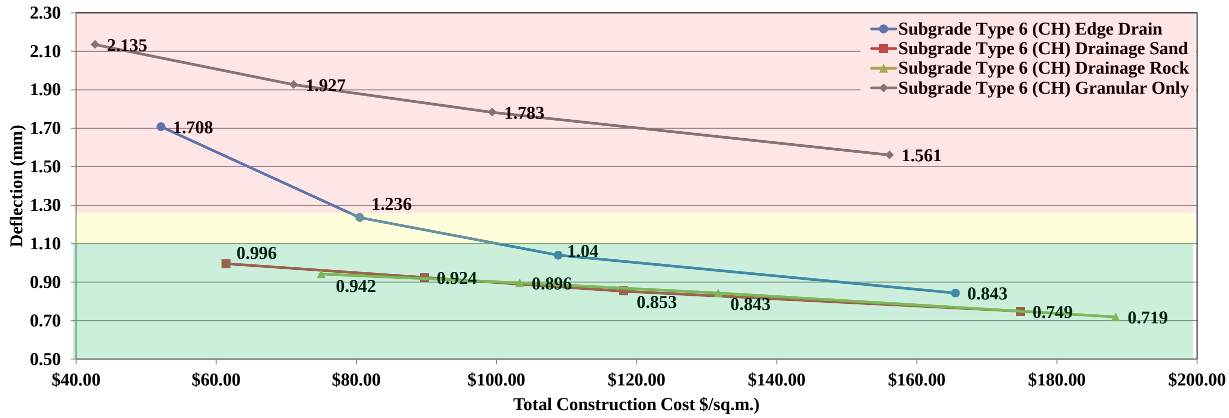
Peak Surface Deflections Cost Comparison for Varying Drainage Layer Types

Now that the peak surface deflections have been compared with the total road structure thicknesses for both local and collector roadways, a total construction cost versus peak surface deflection comparison can be made by assigning a unit cost to the road structure materials, including aggregate, geosynthetics, excavation, and miscellaneous items (i.e. drainage pipe). Table 1 identifies the roadway materials and unit prices that were used in this comparison. These costs were determined based on estimates from local construction agencies and suppliers.

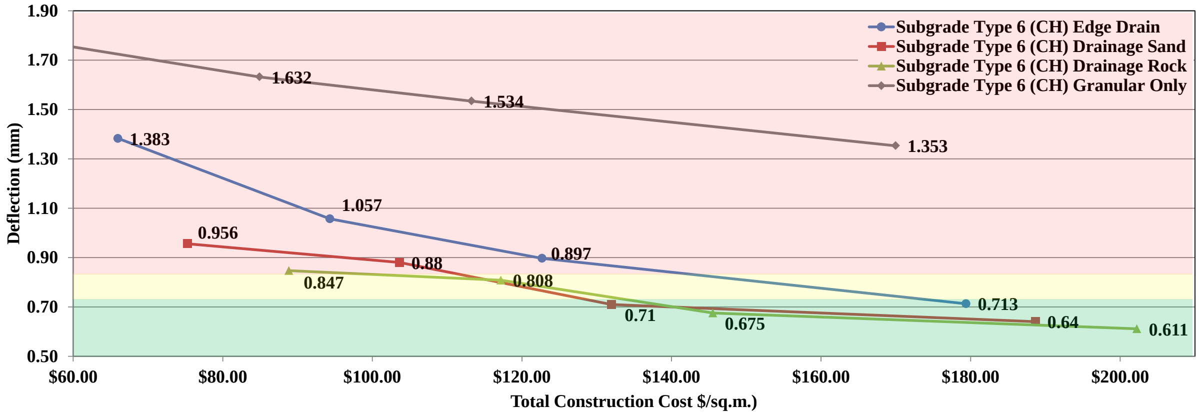
Figure 5 illustrates the total construction cost versus the peak surface deflection (at primary weights) for each of the four road structures, for a collector roadway with a high plasticity clay (CH) subgrade. To achieve a reduced peak surface deflection for all road structures, the cost per square meter increases. This corresponds to the increase in total road structure. The comparison provided in Figure 5 allows road designers to decide how much they want to spend per square meter of road construction and leverage the amount the road structure will structurally deflect.

Table 1 Roadway Material Unit Costs

Item	Unit	Unit Cost ($)
HMAC	tonne	$ 165.00
Base	tonne	$ 55.00
Geosynthetics (per layer)	sq.m.	$ 6.00
Excavation	cu.m.	$ 5.00
Sand	tonne	$ 20.00
Crushed Rock	tonne	$ 50.00
Drainage Pipe	lin.m.	$ 20.00
Sand Edge Drain	lin.m.	$ 16.50



a) Local Roadways



b) Collector Roadways

Figure 5 Total Construction Cost vs. Peak Surface Deflection – Subgrade Type CH

Granular Base Thickness Sensitivity Analysis Using Crushed Rock Drainage Layer with Varying Subgrade Moisture Conditions

Peak surface deflections were then modeled for Saskatoon roadway categories (local, collector, and arterial) with three different granular base thicknesses (150 mm, 375 mm, and 600 mm), different drainage layer thickness options (225 mm and 350 mm), and a high plasticity clay subgrade (CH) under varying moisture conditions. In addition, each roadway category was modeled with its design HMAC as specified by the City.

The design assumptions used in this study for the mechanistic modeled structures are:

- The subgrade immediately below and beside the granular structure will, over time, stabilize at optimum moisture since the drainage layer will remove any excess water.
- The drainage layer is composed of high fracture granular drainage rock with good aggregate interlock.
- The drainage rock is well confined with geosynthetics which add to its structural stiffness.

Modeled peak surface deflections for each roadways category and pavement structure scenario are illustrated in Figure 5 through 7. Figure 6 illustrates the peak surface deflections for local roadways with an HMAC thickness of 45 mm. Figure 7 illustrates the peak surface deflections for collector roadways with an HMAC thickness of 80 mm. Figure 8 illustrates the peak surface deflections for arterial roadways with an HMAC thickness of 110 mm.

For all roadway categories, with a high plasticity clay subgrade, using a granular base layer alone between the HMAC surface layer and the subgrade results in a high risk of structural failure as the peak deflection is greater than 25% over the maximum allowable deflection of each respective roadway category (1.0 mm for local roadways, 0.65 mm for collector roadways and 0.50 mm for arterial roadways). For all roadways categories, with a high plasticity clay subgrade at either optimum moisture content or wet of optimum, using a drainage layer reduces the peak deflections and the risk of failure.

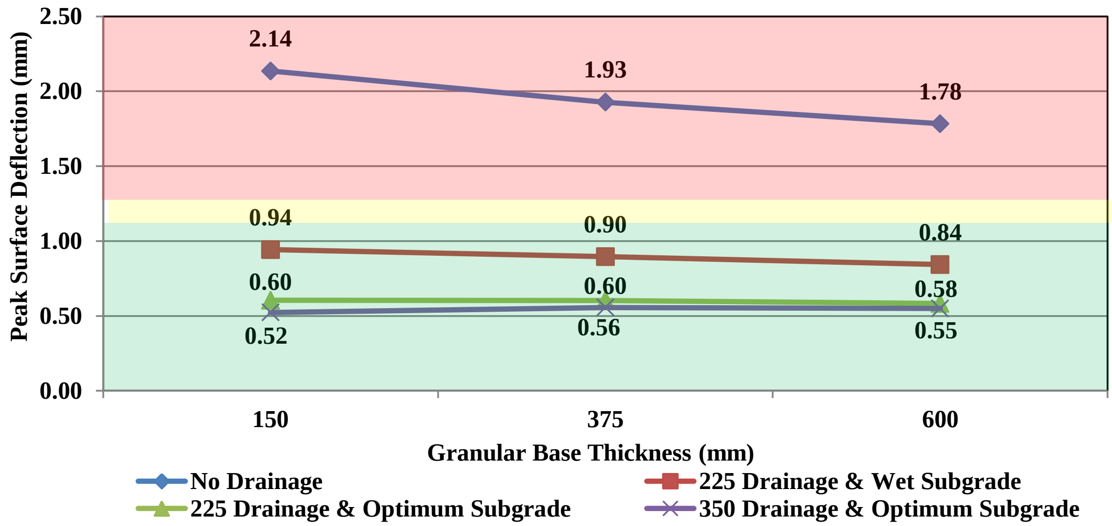


Figure 6 **Local Roadway Comparisons (45 mm AC, Type CH Subgrade)**

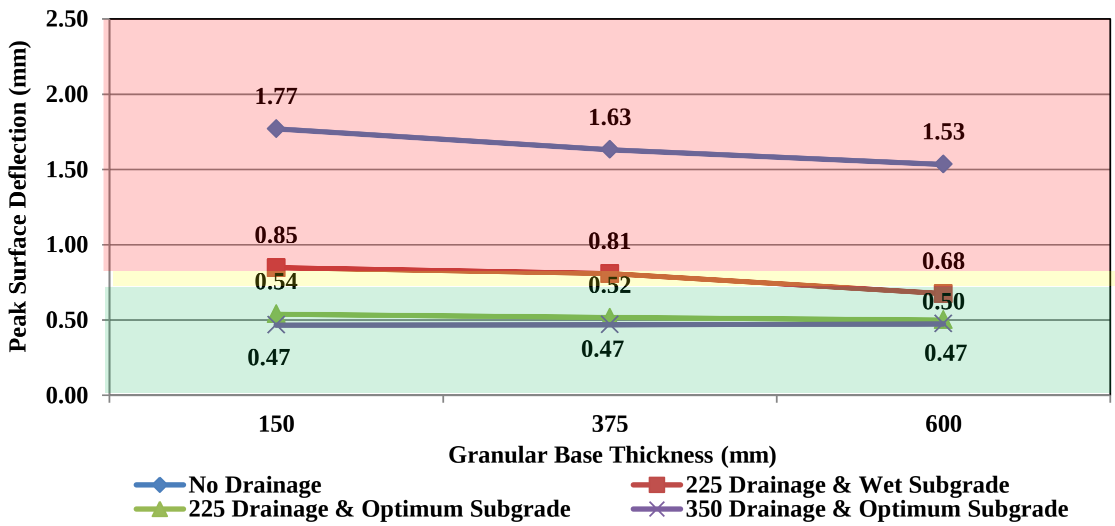


Figure 7 **Collector Roadway Comparisons (80mm AC, Type CH Subgrade)**

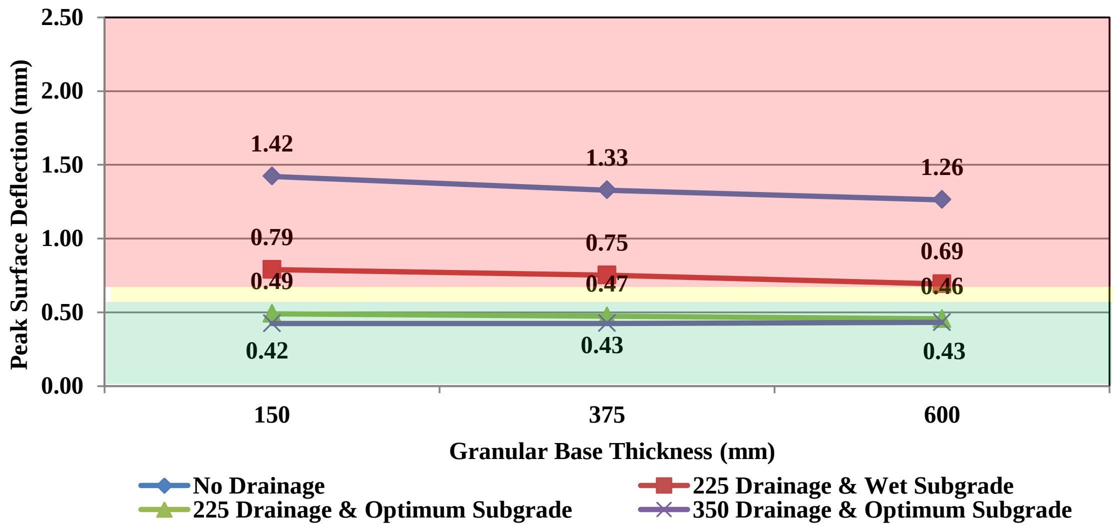


Figure 8 Arterial Roadway Comparisons (110mm AC, Type CH Subgrade)

CONCLUSION

This study measured and assessed the sensitivity of peak surface deflection model response relative to granular base thickness and construction costs with and without different drainage layers. The mechanistic design process, using modeling software, was able to determine adequate granular base thickness and crushed rock drainage layer thicknesses for the Saskatoon roadways based on critical state loading and actual material properties. The mechanistic design is able to accurately represent the effect of the crushed rock drainage layer surrounded by geosynthetics and its benefits to the pavement structure.

Peak surface deflections were modeled for three Saskatoon roadway categories with three different granular base thicknesses, two different drainage layer thickness options, and a high plasticity clay subgrade (CH) under varying moisture conditions. The study found that for all roadways categories, with a high plasticity clay subgrade at either optimum moisture content or wet of optimum, using a drainage layer reduces the peak deflections and the risk of failure.

Using a road model, this study was able to establish levels of risk for thickness of granular base layer as well as construction costs. Pavement designers will now be able to determine the optimum pavement structure using desired layer thickness or budgetary requirements, all based on modeled structural primary response under field state conditions typically encountered in the Saskatoon's new subdivision areas.

This study is a true mechanistic analysis based on deflection performance. The road model used in this mechanistic analysis generates peak strains and stresses in a pavement structure. However, peak surface deflections are used to present the results in this study. The mechanistic analysis is flexible and incorporates any given geometry, loading and loading configuration, and more importantly, material properties such as dynamic modulus and Poisson's ratio that have been characterized using a mechanistic approach. These material properties are captured over a broad range of temperatures which simulate climatic effects; different load magnitudes which simulate different field state loading conditions, such as for truck traffic; as well as frequencies which simulate vehicle speeds. Together, a given set of loads, geometry, and material properties representing one pavement structure will result in peak deflections coupled with stress and strain distribution along the entire structure. These additional variables allow pavement design engineers to identify weak areas and make optimal pavement structure design decisions.

REFERENCES

1. City of Saskatoon (COS). 2012. *City of Saskatoon New Neighbourhood Design and Development Standards Manual.* Saskatoon, Saskatchewan.
2. Saskatchewan Ministry of Highways and Infrastructure (MHI). 2009. *Surfacing Manual*. Saskatoon, Saskatchewan.
3. Classed, A., Edwards, J., Sommer, P., and P. Uge. Asphalt Pavement Design – The Shell Method. 4th International Conference, Structural Design of Asphalt Pavements. Ann Arbor, Michigan, 1977, pp.39-74.
4. Guenther, D., Haichert, R., Soares, R., and Berthelot, C. 2013. Mechanistic Design: A Modeling Case Study for the City of Saskatoon. Transportation Association of Canada (TAC) Annual Conference, Winnipeg, MB.
5. Prang, C., Podborochynski, D., Kelln, R., Berthelot, C. 2012. City of Saskatoon's Pavement Management System: Network Level Structural Evaluation. Submitted to Journal of the Transportation Research Board of the National Academies, TRB 91sth Annual Meeting, January 22-26, 2012, Washington, D.C. USA. (Paper #12-1369)
6. Berthelot, C., Haichert, R., Soares, R., Podborochynski, D., Guenther, D. 2011. City of Saskatoon Mechanistic Pavement Structure Modeling. 2011 Transportation Association of Canada (TAC) Annual Conference. Edmonton, AB.
7. Berthelot, C., Soares, R., Haichert, R., Podborochynski, D., Guenther, D., Kelln, R. 2012. Modeling the Performance of Urban Structural Sub-Surface Drainage Systems. Transportation Research Record: Journal of the Transportation Research Board of the National Academies, Washington, D.C. USA. Vol. 2282. p.p.34-42.
8. Soares, R., Berthelot, C., Podborochynski, D., Haichert, R. 2012. Quantifying the Impact of Truck Axle Groups on Rural and Urban Pavement Structure Performance. Transportation Association of Canada (TAC) Annual Conference. (Podium)
9. Prang, C. Integration of Structural Information into an Urban Asset Management System. 2012. Masters of Science Thesis, University of Saskatchewan. Saskatoon, Saskatchewan.