MECHANISTIC DESIGN:
A MODELING CASE STUDY FOR THE CITY OF SASKATOON

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ABSTRACT

A mechanistic roadway design methodology was employed for City of Saskatoon roadways as part of a pilot study. The mechanistic design methodology included Saskatoon field state conditions of subgrade materials, changing moisture contents, and alternative road building materials. This design methodology used is comprehensive and based on regulated standards, mechanistic materials testing, and modeling. A finite element method was used to conduct a mechanistic primary response analysis to determine road design pavement structure options.

This paper describes a road design case study for City of Saskatoon new subdivisions. Laboratory testing was conducted to assess the soil and aggregate material properties of sampled subgrade. Both conventional and mechanistic materials libraries were developed for subgrade and other pavement structure materials. The conventional materials library included material properties such as gradation, plasticity, and density and the mechanistic library included material properties such as dynamic modulus and Poisson’s ratio. The model used these material properties as inputs and the finite element method to perform simulations and generate model outputs. For this project, the outputs were different pavement structure design options based on maximum peak surface deflections allowed. The critical vehicle loads for City of Saskatoon collector and local roads is a vehicle loaded to primary weight limits.

For this new subdivision design case study, standard conventional pavement structures currently used for local roads and collector roads were modeled as a baseline and compared to alternative road structures with additional base material, a sand drainage layer, and a rock drainage layer for one subgrade type. For each resultant cross section generated by the model, the shear strains were analyzed and maximum peak surface deflections were used to assess which cross section was optimum for each subgrade type.

The results of this case study showed that the mechanistic model provided feasible alternative pavement structures for City of Saskatoon local and collector roadway design. This study illustrated that using the standard pavement structures for local roads currently used by the City’s design methodology may not be structurally appropriate for roads in new subdivisions with varying subgrade types.

INTRODUCTION

With an increase in population and continued economic growth forecasted for years to come, the City of Saskatoon (COS) has expanded to include many new subdivisions over the past few years, with more planned in the future. Strategic plans set forth by the City of Saskatoon back in 2000 recommended the city limits expand to include new urban residential neighbourhoods in the north-east, east, and west areas of the city (1).

Urban residential subdivisions constructed since 2000 include Willowgrove in the east, Evergreen in the north-east, Hampton Village in the north-west, Kensington in the west, Stonebridge in the south, and Rosewood in the south-east. While some of these subdivisions are nearly developed, many of them are still in a phased-construction stage. Land allocation for residential development east and north-east of the city was established just two years ago. Figure 1 illustrates these land allocation alterations made to COS' boundaries, which were effective August 1, 2010. The boundary alteration provides the COS the opportunity to grow to the north and north east, which is consistent with the *Future Growth of Saskatoon Study*. These areas provide new neighbourhoods, employment areas, and amenities (2).

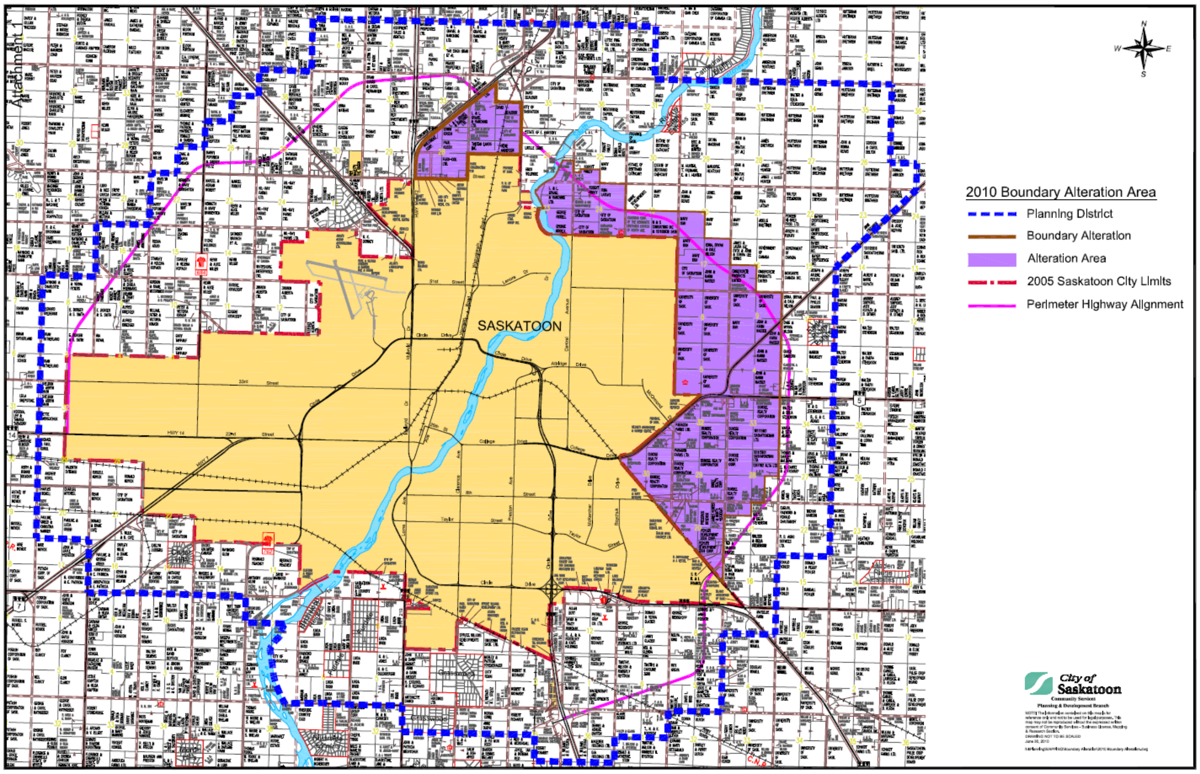


Figure 1 Boundary Alteration Map (2)

Currently, 12 percent of existing roadways in the COS are built on what are considered marginal soil conditions, while 70 percent of new road construction in the new residential subdivisions is planned to occur in marginal soil conditions. In addition, locally available quality aggregate resources are substantially depleted, which has resulted in the use of marginal base aggregates for road construction. In recent years, roads that are less than ten years old have failed in urban residential subdivisions due to marginal subgrade conditions, marginal base aggregates, and increased heavy construction traffic (3). Figure 2 illustrates photos of typical urban residential failures within 10 years of initial construction.

a) Failure of a 7-Year-Old Road **b) Failure of a Road Patch in 2001**

Figure 2 Photos of Urban Residential Failures within 10 Years of Initial Construction

COS pavement structure life cycle performance is highly dependent on subgrade type (3,4). Subgrade structural failure is a predominant concern due to thin local and collector structures, prevalent high moisture conditions, and marginal soil condition in new subdivisions.

A study by Prang et al. showed that the subgrade material properties can dictate the structural performance of COS roads (3). This study used non-destructive falling weight deflectometer testing measurements to compare a 30-year-old residential area with a till subgrade to a 10-year-old residential area with a clay subgrade. Using a rating system developed to rate the peak surface deflection of COS roadways, the local and collector roads in the 'high-and-dry' clay-till subgrade area performed 'good' structurally while the roads in the low lying and wet clay subgrade area performed 'poor' to 'fair' structurally.

Presently, City of Saskatoon road designs are based on the Saskatchewan Highways' modified California Bearing Ratio (CBR) Shell Design Curves (5). This method is founded on statistical regression analysis of the layered linear elastic primary response of road structures constructed at the AASHTO road test (6). CBR Shell Curves determine hot mix asphalt concrete (HMAC), granular base, and subbase layer thicknesses based on the *in situ* CBR of the subgrade and traffic ESALs over the design life of the pavement structure. Also, this design method is specifically developed for a rural cross-section.

In practice, road structural designs are often based on historical preservation treatments and materials. Neither the CBR Shell Curve method nor the historical typical preservation treatments effectively account for changing field conditions – including climatic and traffic loading effects or aged pavement structures – or allow for the design of road structures with recycled materials.

Figure 3 illustrates City of Saskatoon current standard design cross sections for local roadways. Local roads have thinner granular structures compared to collector and arterial roads – only 225 mm granular base thickness. Changes may occur to the design standard when field conditions do not allow for the conventional structure to last through construction of the subdivision.

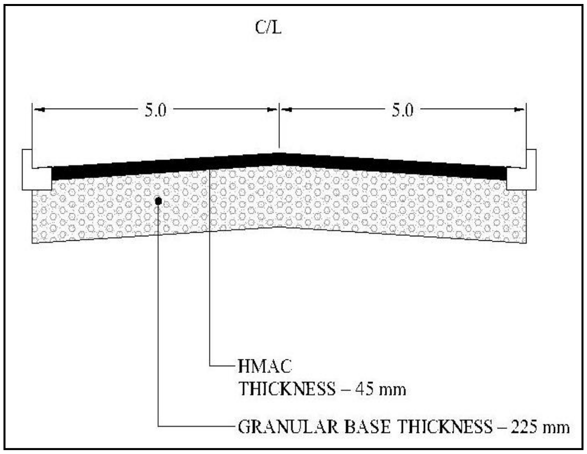


Figure 3 **City of Saskatoon Current Standard Design Cross Sections – Local Roads**

Road modeling has demonstrated COS roads' subgrade-dependency with regards to primary pavement response (4,7). 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. The road model also showed the significance of the effect of constructing urban roads in a 'clay box' relative to conventional highway design with free draining shoulders.

This paper summarizes a study undertook for the City of Saskatoon by PSI Technologies to develop a comprehensive and scientifically defendable design methodology for local roadways based on field state conditions of proposed new neighbourhoods. This study utilized a mechanistic roadway design methodology that included Saskatoon field state conditions of subgrade materials, changing moisture contents, and alternative road building materials. This design methodology used was comprehensive and based on regulated standards, mechanistic materials testing, and modeling. A finite element method was used to conduct a mechanistic primary response analysis to determine road design pavement structure options.

PROJECT SCOPE, LAYOUT, & METHODOLOGY

The design methodology for this study was split in four phases: preliminary testing, materials library development, PSIPave3D™ Road Modeling, and road design options. For purposes of this paper, not all study results are presented. This paper is limited to presenting the results for one subgrade type and for local roads only.

As part of the first phase, PSI Technologies sampled subgrade materials from four (4) new subdivisions under development and construction in the City of Saskatoon (COS) and conducted preliminary testing on the sampled material. Subgrade soil sampling was targeted to characterize the soils found in areas where new subdivisions will be constructed or are currently under construction. Gradehole subgrade samples were extracted from up to ten locations in each subdivision, as illustrated in Figure 4. Evergreen (EG) is located in the north east area of the city; Rosewood (RW) is located in the south east area of the city; Stonebridge is located south of Saskatoon; and Kensington (Ken) is located directly west of the city. Each sample was mechanically excavated to an average depth of 1.2 m after stripping the topsoil.

Conventional laboratory preliminary characterization was performed on the targeted *in situ* subgrade material samples and included grain size distribution (ASTM D6913), unified soil classification system (USCS) (ASTM D2487), and Atterberg limits characterization (ASTM D3282). This study is limited to presenting the results for one subgrade type and local road structures only.

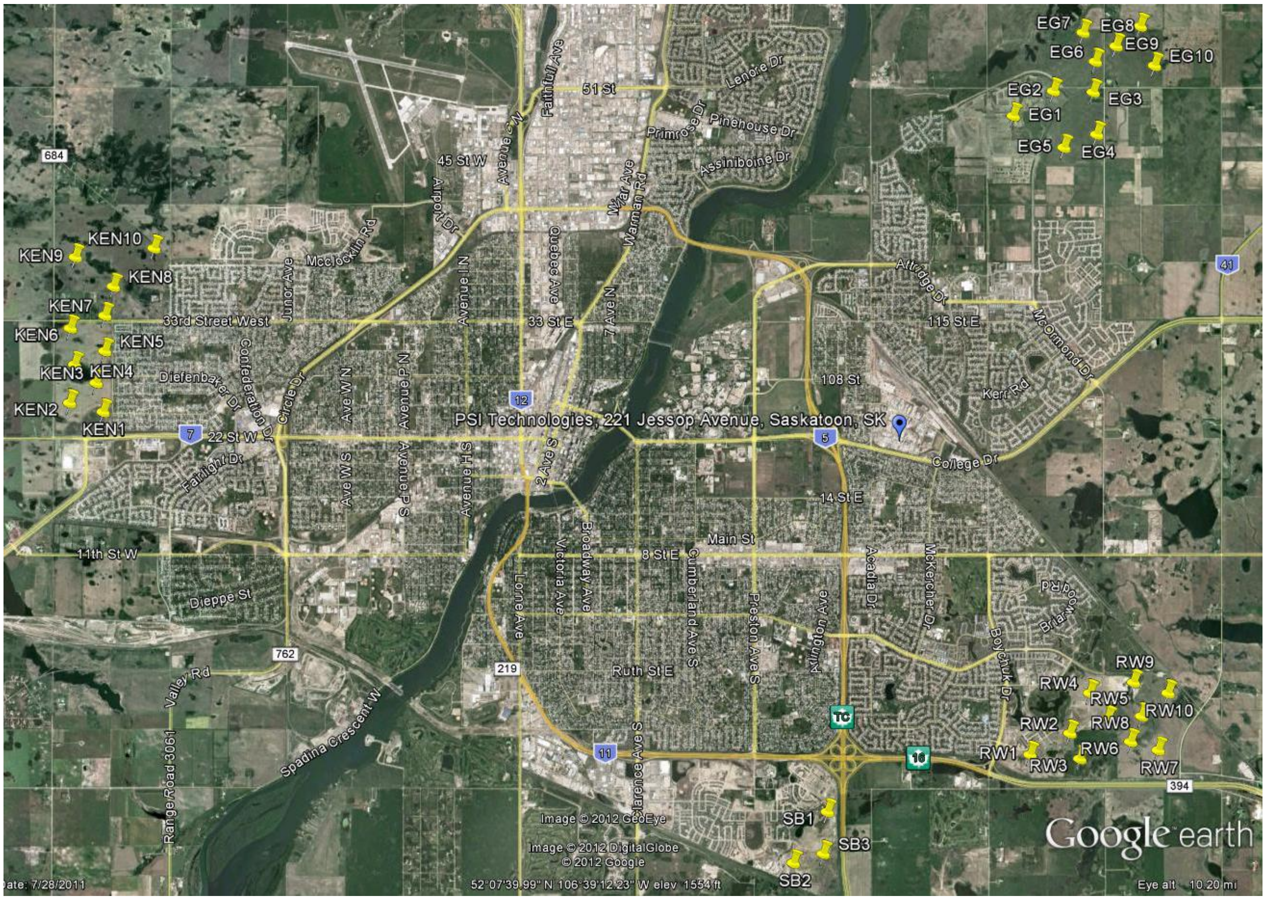


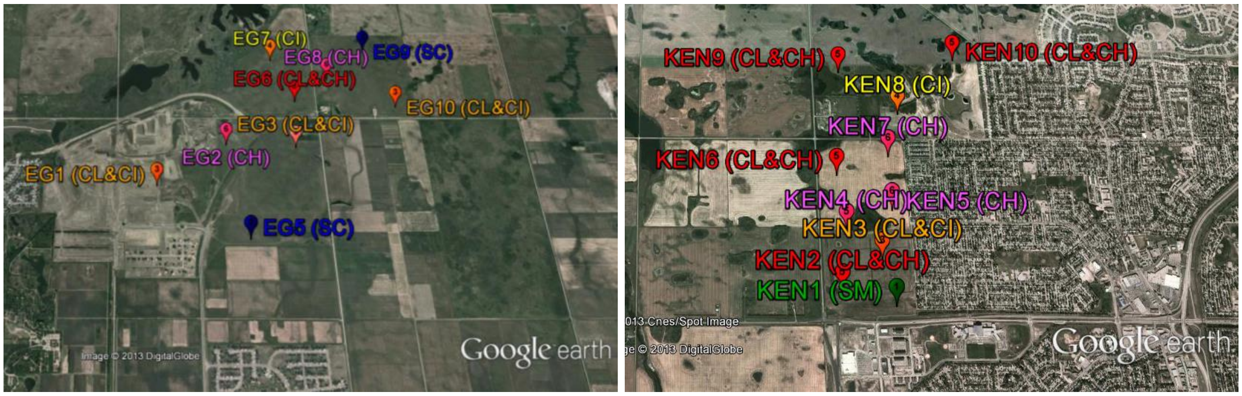
Figure 4 **Gradehole Locations – Saskatoon**

PRELIMINARY LABORATORY TESTING RESULTS

Based on preliminary subgrade material characterization results, it was found that subgrade material properties were variable within the subdivisions. Figure 5 illustrates the different subgrades present in each subdivision (each colour represents a different subgrade type). For example, Rosewood (RW) had five (5) different subgrades present, ranging from silty sand (SM) to intermediate/high plastic clay (CL-CH). Therefore, one design for each subdivision would not be optimal, since the subgrade material properties vary within each subdivision area. A total of six (6) subgrade types identified were determined based on having like-properties.

- Subgrade Type 1 (green) – Silty Sand (SM)
- Subgrade Type 2 (blue) – Clayey Sand (SC)
- Subgrade Type 3 (orange) – Low to Intermediate Plastic Clay (CL & CI)
- Subgrade Type 4 (yellow) – Intermediate Plastic Clay (CI)
- Subgrade Type 5 (red) – Intermediate to High Plastic Clay (CL & CH)
- Subgrade Type 6 (pink) – High Plastic Clay (CH)

a) Rosewood (RW) and Stonebridge (SB)



b) Evergreen (EG) **c) Kensington (KEN)**

Figure 5 Subgrade Types in each Subdivision

Using mechanistic modeling results, design recommendations for each subgrade type were determined. For the purposes of this paper, the following details the results of Subgrade Type 6 (CH).

MATERIALS LIBRARY DEVELOPMENT

The materials library used for this mechanistic modeling study included City of Saskatoon granular base, crushed rock, drainage sand, and the six (6) subgrade types. This study is limited to one subgrade type, a high plastic clay (CH). The conventional materials testing results and the mechanistic testing results for the high plastic clay (CH) subgrade type are provided in Table 1 and Table 2, respectively.

Pavement structure design options were determined for subgrade types under both wet and dry subgrade conditions and include conventional pavement structures and pavement structures with a drainage layer. For the purposes of this study, a dry subgrade is defined as a subgrade at optimum moisture content. A wet subgrade is defined as a subgrade wet of optimum moisture content (above optimum). In the case of the wet subgrade, it is also assumed that the granular base is wet of optimum moisture. These assumptions were used at the input stage of the PSIPave3D™ road model.

Table 1 Conventional Materials Library – High Plastic Clay (CH)

Subgrade Material	Moisture Content (%)				Density	Liquid Limit	Plasticity Index
	Optimum	1/6th Below Optimum	1/6th Above Optimum	1/3rd Above Optimum			
High Plastic Clay (CH)	22.4	18.7	26.1	29.9	1575	54-64	33-38

Table 2 lists the mechanistic materials properties including dynamic modulus and Poisson's ratio for the highplastic clay (CH) subgrade under four (4) moisture contents representative of typical field state subgrade conditions, over five stress states (SS). The moisture contents analyzed were optimum moisture content, 1/6th below optimum moisture content, 1/6th above optimum moisture content, and 1/3rd above optimum moisture content. Five stress states (SS) were used in this analysis to capture the materials' behavior under a broad range of induced stresses.

Table 2 Mechanistic Materials Library – High Plastic Clay (CH)

Subgrade Material & Moisture Content	Dynamic Modulus (MPa)					Poisson's Ratio				
	Stress State (SS)					Stress State (SS)				
	SS1	SS2	SS3	SS4	SS5	SS1	SS2	SS3	SS4	SS5
CH (1/6th Below Optimum)	170	139	118	91	68	0.38	0.34	0.27	0.20	0.17
CH (Optimum)	105	86	78	63	49	0.50	0.41	0.33	0.28	0.23
CH (1/6th Above Optimum)	51	53	47	36	22	N/A	0.38	0.34	0.30	0.27
CH (1/3rd Above Optimum)	N/A	35	28	20	16	N/A	0.49	0.37	0.34	0.56

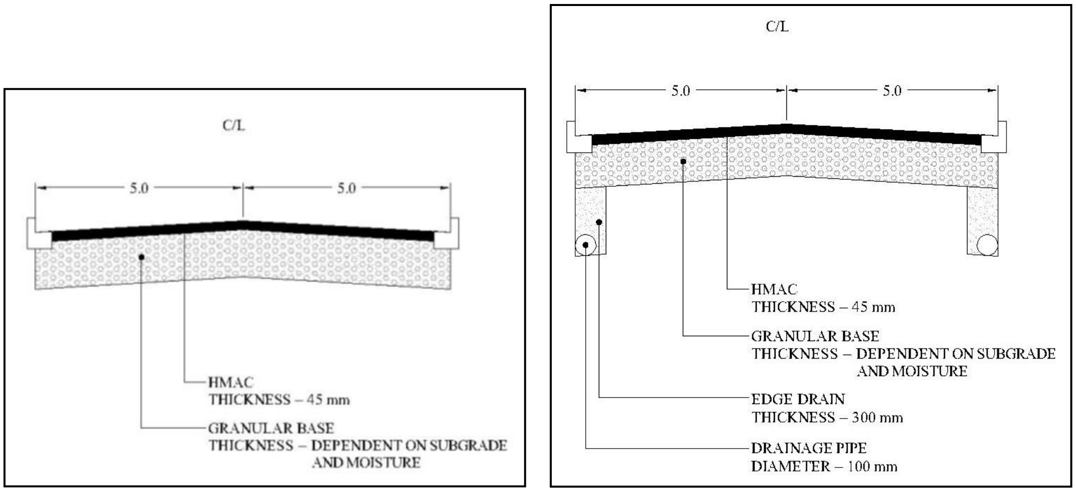
N/A = Sample Failed

ROAD MODELING RESULTS

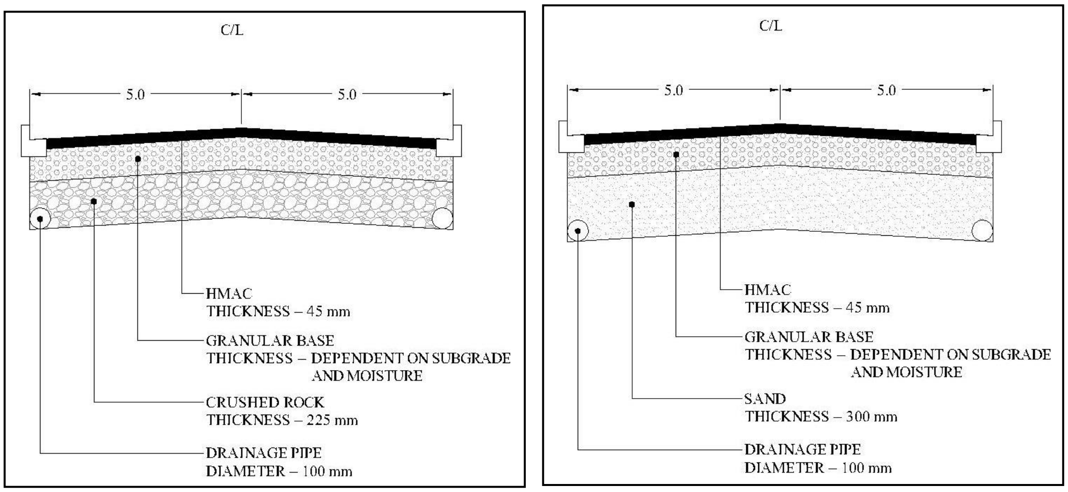
PSI Technologies' mechanistic road model, PSIPave3D™, was used to conduct the finite element analysis (FEA) that determined the road structure design options. Recommended pavement structure design options were determined based on peak surface deflection, measured in millimetres (mm). Modeled structures included the existing typical structure and four new, proposed structures. The following pavement structures and drainage alternatives were analyzed using the model under both wet and dry conditions:

- No drainage structure (existing specification);
- Granular base only with no drainage structure (Figure 6a);
- Granular base and edge drains (Figure 6b);
- Granular base and crushed rock layer (Figure 6c); and
- Granular base and sand drainage layer (Figure 6d).

For each pavement structure, the asphalt concrete (AC) thickness and drainage layer thicknesses were kept consistent. The granular base thickness was varied depending on the subgrade and moisture conditions.



a) Granular Base Only **b) Granular Base & Edge Drain**



c) Granular Base & Crushed Rock Drainage Layer **d) Granular Base & Sand Drainage Layer**

Figure 6 Local Road Design Options

All structures with drainage layers were modeled with the assumption that geosynthetics are in place to separate the materials and provide structural strength during construction. The geosynthetics modeled were woven geotextiles and biaxial geogrids.

A conventional road structure and three (3) road structures with different types of drainage layers were generated for each moisture and subgrade case, for local roads. The conventional road structure is composed of HMAC surfacing with granular base and subgrade material. A road structure with a drainage layer incorporates a drainage layer in between the granular base and subgrade layers. The purpose of the drainage layer is to mitigate moisture within the pavement structure.

Pavement structural design was based on the criterion that peak surface deflection at primary weight limits (44.6 kN) shall be less than 1.00 mm for local roads. Recommended pavement structure design thicknesses were determined for each pavement structure and drainage alternative when the peak surface deflection under primary weight limits was reduced to 1.00 mm or less.

For local roads, the granular base design thickness was limited to a maximum of 700 mm and a minimum of 150 mm. These limits were set since a base is rarely constructed thinner than 150 mm and a base thickness greater than 700 mm in not an economical option. While some alternatives would meet the deflection criteria with thinner granular base structures, a granular base minimum thickness of 150 mm was used and the corresponding deflections are noted.

Figure 7 illustrates the peak surface deflections across proposed design options for local roadways and Figure 8 illustrates corresponding granular base thickness – except in the case of the existing specification (no drainage) data. For the existing specification, the peak surface deflection was determined using a granular base thickness of 225 mm. For the proposed pavement structures and drainage systems, the granular base thickness was determined iteratively, once the peak surface deflection was reduced to 1.00 mm or less. An effort to reduce the peak surface deflection of the structure with no drainage structure resulted in a peak surface deflection of 1.71 mm (see below), which in turn resulted in a granular base thickness of 700 mm

For example, with a high risk of moisture (wet conditions), a pavement structure designed for a Subgrade Type 6 (CH) with the existing specification (no drainage) has a peak surface deflections greater than the 1.00 mm threshold for local roadways. By constructing the local roadway pavement structure with an edge drain, drainage rock, or drainage sand, the peak surface deflection meet the 1.00 mm threshold for all Subgrade Types.

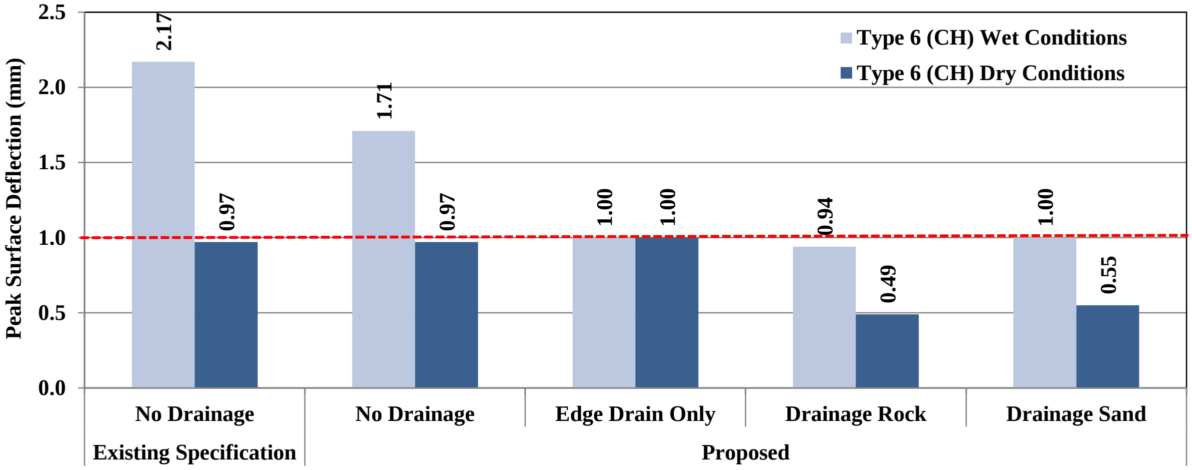


Figure 7 Peak Surface Deflections across Proposed Design Options – CH (Local Roads)

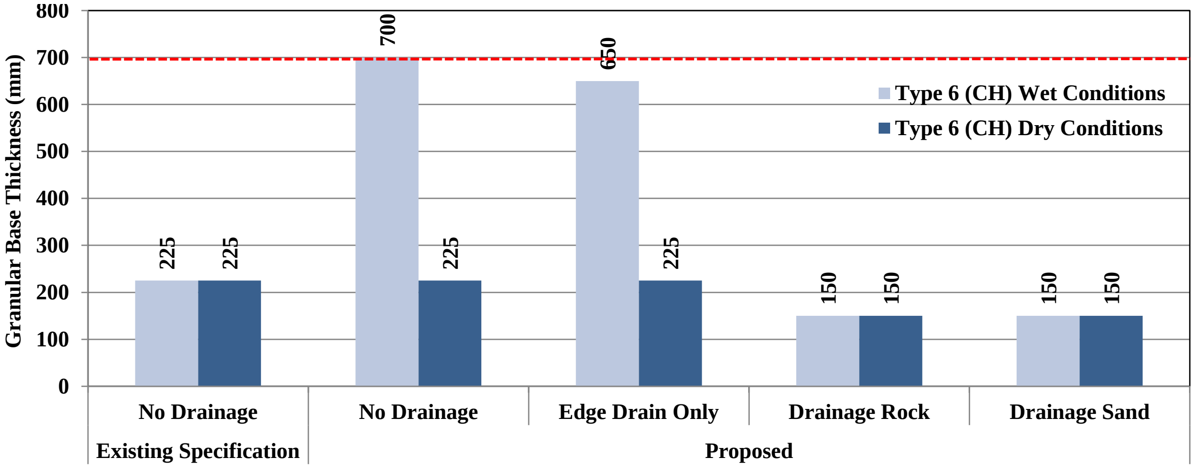
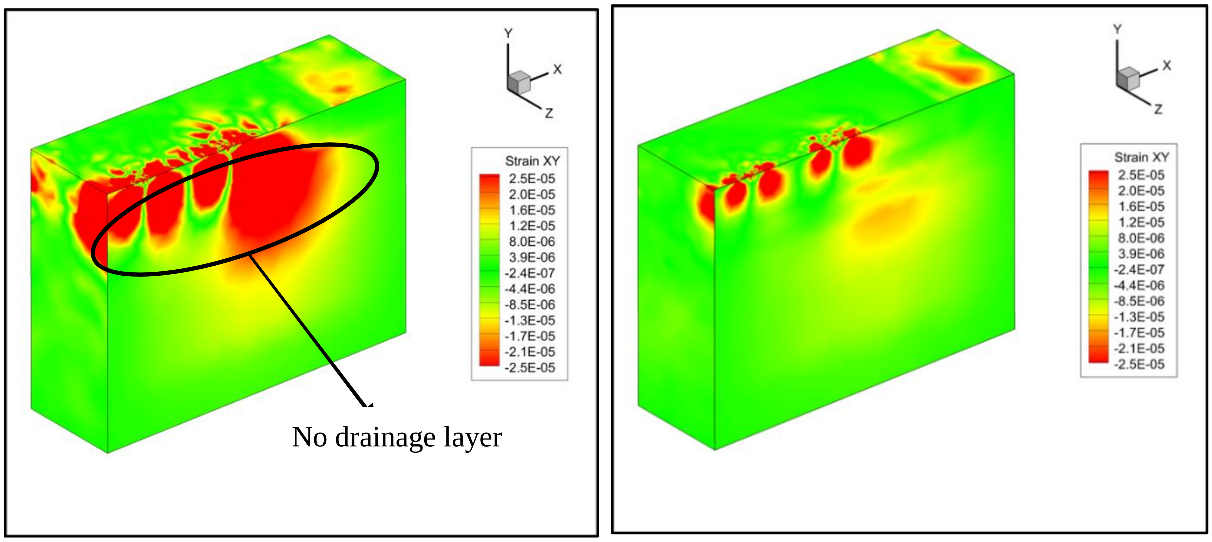


Figure 8 Granular Base Thickness across Proposed Design Options- CH (Local Roads)

PSIPAVE3D™ ROAD MODELING

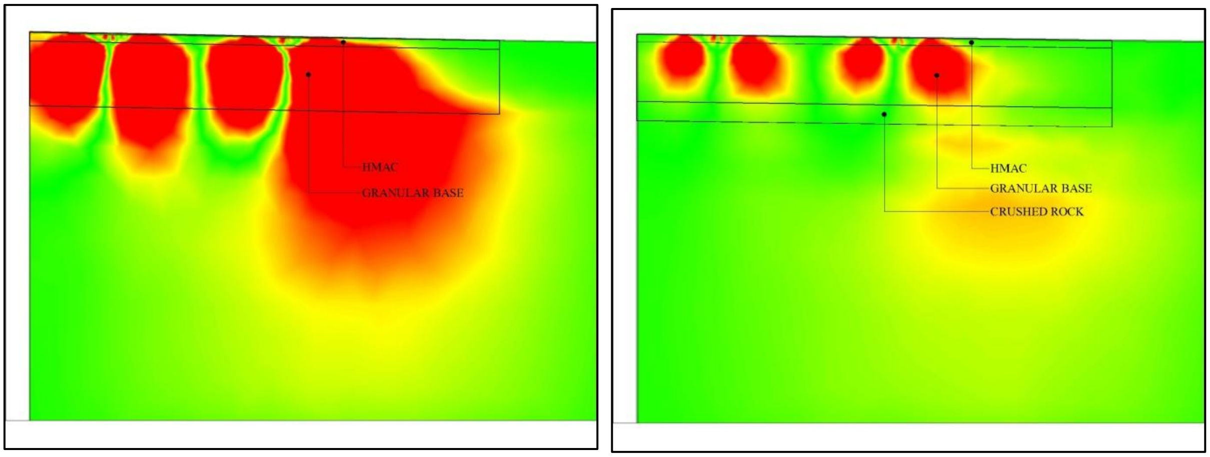
Using PSIPave3D™, the strains in the road structure were modeled as contours given the primary loading and the roadway material engineering characteristics.

Figure 9 illustrates the three dimensional shear strain contours of a local roadway under primary loading, both without a drainage layer (existing COS design) and with a drainage rock layer. For illustrative purposes, Figure 10 shows the two dimensional view with cross section layers identified. This example is of a local road structure on a wet Type 6 (CH) subgrade with a high risk of moisture; the cross section with no drainage layer has a granular structure of 700 mm while the drainage rock structure has a 150 mm granular base structure on top of a 225 mm rock drainage layer.



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

Figure 9 3D Shear Strain Results – Local Roadways (CH, High Risk of Moisture)

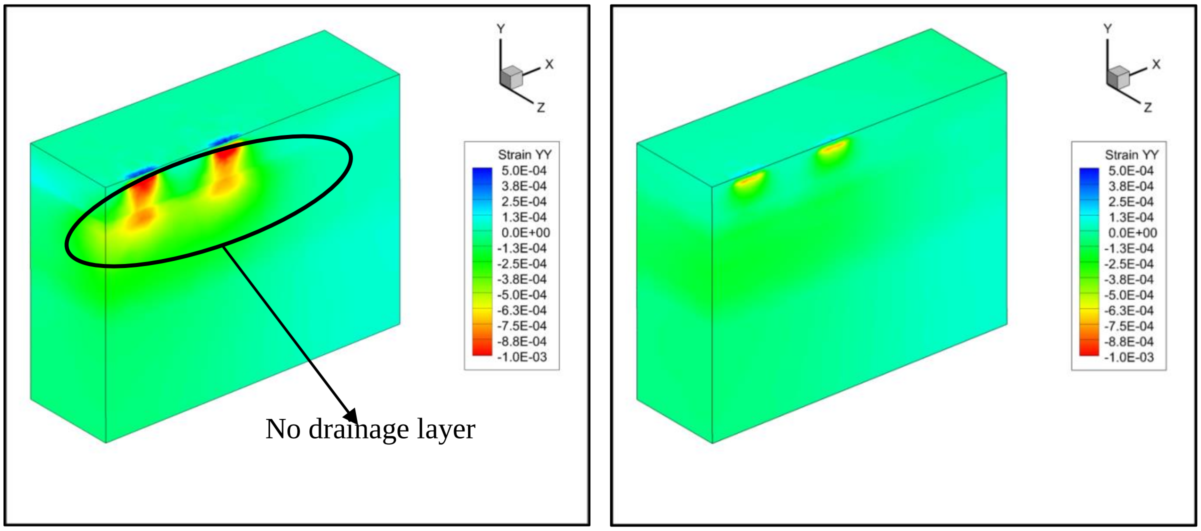


a) No Drainage (existing specification) **b) Drainage Rock**

Figure 10 2D Shear Strain Results – Local Roadways (CH, High Risk of Moisture)

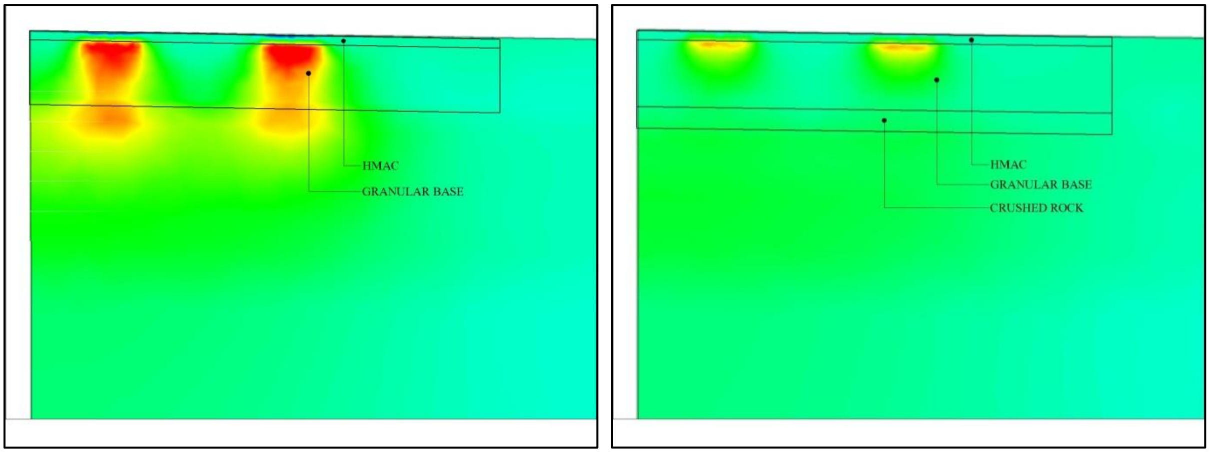
The red color indicates a high shear strain while the green indicates reduced shear strain. As City of Saskatoon roadway structures are subgrade dependent, when moisture is introduced into the structure, especially a highly plastic clay subgrade (such as Subgrade Type 6), the resulting shear strains cause the roadway to fail. The drainage layers were necessary to reduce the strain on the subgrade [Figure 9 b) and Figure 10 b)]. By constructing a rock drainage layer in this pavement structure for this subgrade type, shear strains were dissipated prior to reaching the subgrade, reducing high strain concentrations in the granular layers as well.

Similar results are shown when comparing the vertical compressive strain in the same structures as shown in Figure 11 and Figure 12. The vertical compressive strain is an indication of structural rutting likelihood. By reducing the amount of compressive strain, the amount of structural rutting is likewise reduced. The structural drainage layer will reduce the strain in the structure so that very little strain will be evident in the subgrade.



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

Figure 11 3D Vertical Compressive Strain Results – Local Roadways (CH, High Risk of Moisture)



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

Figure 12 2D Vertical Compressive Results – Local Roadways (CH, High Risk of Moisture)

MECHANISTIC PAVEMENT STRUCTURE DESIGN METHODOLOGY

This section describes the mechanistic pavement structure design methodology developed as part of this project. The first step is listed in Table 3. The first step to designing a pavement structure for a local or collector roadway using the mechanistic PSIPave3D™ Road Modeling methodology is to determine the subgrade type. For this case study, the subgrade type examined is classified as high plastic clay (CH).

Once the subgrade type is determined, the risk of excess moisture is examined qualitatively. The following is considered:

- Is the road built in a high-and-dry location?
- What is the water table? Is it high?
- Is irrigation present near the roadway?

There are two options for moisture risk: yes, there is a risk of moisture (high water table, presence of irrigation, etc.) or none (high-and-dry, no high water table or irrigation).

Table 3 PSIPave3D™ Road Modeling Methodology: Step 1 – Local Roads

Decision 1 - Determine Subgrade Type (Atterberg Limits, Gradation)			
High Plastic Clay (CH)			
Decision 2 - Determine Risk of Excess Moisture (high water table, presence of irrigation)			
Yes, Risk of Moisture		None	
Decision 3 - Determine the Drainage Alternative			
Drainage Rock	Drainage Sand	Edge Drains only	No Drainage Structure

Based on the subgrade type and risk of excess moisture, the designer will then choose the drainage structure (step 2, Table 4). There are four pavement structures and drainage alternatives:

- Granular base only with no drainage structure;
- Granular base and edge drains;
- Granular base and crushed rock layer; and
- Granular base and sand drainage layer.

Table 4 shows the local road design options for the high plastic clay (CH) subgrade. If there is a high risk of moisture present, then a drainage layer such as rock, sand, or edge drains is recommended. If there is a low risk of moisture, then any of the four pavement structures are recommended. The thickness of the granular base layer is reduced with the presence of a drainage layer. The "no drainage structure" option (conventional COS design structure) is not recommended for areas with a high risk of moisture.

Table 4 PSIPave3D™ Road Modeling Methodology: Step 2 – Local Roads

Subgrade Soil High Plastic Clay (CH)					
		Drainage Alternative			
		No Drainage Structure	**Edge Drains Only**	**Drainage Sand**	**Drainage Rock**
HMAC		45	45	45	45
Granular Base	**High Risk of Moisture**	Option Not Recommended	650	150	150
	Low Risk of Moisture	225	225	150	150
Drainage Layer		N/A	300	300	225

CONCLUSION

This study showed that there are six different subgrade types across four new subdivisions in different areas of Saskatoon. Standard design cross sections for local and collector roads have not been performing well in some of the new construction areas. Up to five different subgrades ranging from silty sand to high plastic clays are present in any one subdivision. Since City of Saskatoon roadway performance is highly dependent on subgrade and moisture conditions, this study set out to develop a design methodology that accounted for varying subgrade and moisture conditions.

Four pavement structures and drainage alternatives were analyzed and compared with the City's conventional design pavement structure including: granular base only with no drainage structure; granular base and edge drains; granular base and crushed rock layer; and granular base and sand drainage layer. For each structure, the asphalt concrete layer and the drainage layer (if applicable) was kept constant and the granular base thickness was varied to achieve required peak surface deflection criterion of 1.00 mm or less.

Using PSIPave3D™, this study showed that mechanistic modeling provides feasible alternative pavement structures for City of Saskatoon local and collector roadway design. A design methodology was developed to provide road designers with structural layer options for varying subgrade types and moisture conditions. This study illustrated that using the standard pavement structures for local roads currently used by the City's design methodology may not be structurally appropriate for roads in new subdivisions with varying subgrade types.

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