Modeling the *In situ* Performance of Granular Materials Stabilized with Cement

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ABSTRACT

Since COS current design methods do not directly incorporate stabilization materials, this study used a three dimensional non-linear orthotropic computational road structure model to measure the performance of pavement structure stabilized base course layers. The objective of this project was to investigate the effects of cement stabilization for granular material and subgrade soil, within a typical City of Saskatoon road structure.

The cross section used in this study was a typical City of Saskatoon local road structure, composed of 45 mm hot mix asphalt concrete (HMAC) on 225 mm granular base, built directly on top of *in situ* subgrade. The cross section was analysed with two percent cement stabilization added to the granular base layer and three percent cement stabilization added to the top 300 mm of the *in situ* subgrade. Gyratory compaction and triaxial frequency sweep analysis of the materials were conducted at realistic field state conditions to determine the mechanistic material constitutive properties used in the structural road model.

The cement stabilized granular base layer examined in the study showed improved shear strain and horizontal strain behaviour when compared to the unstabilized granular base layer. This improvement confirms that cement stabilization of granular base materials has an enhanced primary response. This study demonstrated that COS pavement designs are highly dependent on subgrade type and condition state and that cement stabilization of subgrade materials can improve the structural primary response of the subgrade layer.

INTRODUCTION

The City of Saskatoon (COS) is faced with many challenges with regards to its pavement materials, *in situ* subgrade conditions, and road design. Heavy traffic loading, severe climatic conditions of extreme temperatures and increased precipitation due to climate change, poor subgrade conditions, and the aged state of road infrastructure all contribute to the accelerated degradation of roads. Granular material stabilization offers a solution to improving the performance of granular materials in a road structure.

In Saskatchewan, cement stabilization has been used to improve the durability, stiffness, and frost-susceptibility of granular base and subbase layers, as well as *in situ* subgrades. The City of Saskatoon has used cement stabilization, which is often combined with asphalt emulsion stabilization, in pilot full depth reclamation projects using granular materials, as well as numerous recycled projects using reclaimed asphalt pavement (*1,2*). Saskatchewan has investigated cement stabilization of granular base layers and *in situ* subgrades (*3,4,5,6*).

This paper examines the effects of cement stabilization in the granular base layer and subgrade of a typical local City of Saskatoon pavement structure. Research has found that traditional design methods are not applicable for new subdivisions, particularly when constructed in marginal soil conditions and often with marginal aggregates (*6,7*). This study employs a three dimensional (3D) non-linear orthotropic computational road model to measure the performance of a granular-stabilized pavement structure in terms of peak surface deflections, stresses, and strains.

Background

COS local roads have thinner structures than arterial and collector roadways. Local roads typically have a thin layer of hot mix asphalt concrete (HMAC) on top of a granular base layer, with or without a subbase layer, built on *in situ* subgrade. Local roads are low volume roads with less than 1,500 vehicles per day and very few large trucks. Local roads are used for accessibility. Local roads have marginal *in situ* subgrade conditions which result in premature surface distresses and structural failures.

COS roadways are constructed in variable subgrade conditions. Some City roadways are constructed on dry subgrades with no moisture problems, while other roadways are constructed on wet, low-lying subgrades. For example, roadways constructed in the central area of the City are located at a higher elevation than roadways on the outskirts of the City. These roadways perform well and have fewer issues with a wetting-up subgrade. Roadways constructed in low-lying areas are often subject to a high water table and wet field state conditions, especially with regards to the subgrade. In recent years, pavements have deteriorated far more quickly than anticipated due to marginal subgrades and poor, wet field state conditions.

Materials used in Saskatoon road construction include *in situ* subgrade, crushed granular base and sub base, and HMAC. Typical subgrades in Saskatoon include clay till subgrade and plastic clay subgrade. Finding high quality aggregate materials in Saskatchewan is challenging because quality aggregate sources are becoming increasingly depleted, especially near urban areas (*1-6*). With a dwindling aggregate supply, granular base materials may be considered marginal with increased fines and fine sand content, and decreased aggregate angularity (*8*). HMAC is the most expensive layer in a pavement structure and Saskatchewan typically constructs pavement structures with very thin HMAC surfaces.

As a result, agencies are faced with considering more cost effective alternatives to mitigate reliance on marginal granular materials and poor *in situ* subgrade conditions. Cement stabilization can enhance the materials properties, moisture susceptibility, and field performance of marginal granular and subgrade materials (*1-6,9*). Research has found that cement stabilization can substantially improve the mechanical behaviour and climatic durability of marginal and poorly graded granular materials (*1-6,9*).

Presently, COS road designs are based on the Saskatchewan Highways' modified California Bearing Ratio (CBR) Shell Design Curves (*10*). This design method is empirically-based, founded on the layered linear elastic primary orthogonal strain response of the road structure (*7,8,12*). CBR Shell Curves determine HMAC, granular base, and subbase layer thicknesses based on the *in situ* subgrade CBR. This design method was also initially developed for highway cross sections comprised of high quality materials. Therefore, the CBR Shell Curve design method is not directly applicable to urban road structures under current field state conditions because it does not account for urban cross sections, urban climatic and traffic loading effects, aged pavement structures, marginal aggregates or recycled materials. It also cannot account for the effect of stabilized granular materials.

A more recent development in pavement design is American Association of State Highway and Transportation Officials (AASHTO)'s mechanistic-empirical pavement design guide (MEPDG); MEPDG applies principles of engineering mechanics and uses performance transfer factors to account for traffic and climate to predict pavement performance (*12*). However, the MEPDG was developed with several assumptions that do not hold true for Saskatoon field state conditions.

PSIPave3D™ is a non-linear orthotropic road model used to calculate fundamental mechanistic responses across diverse road materials, structures, and field state conditions for both road structural analysis and design. The model is encoded into a user-friendly software package created for routine road designs. The deflection as well as 3D-strain behavior of a road structure is spatially calculated by the model incorporating road layer thicknesses, load spectra, climatic conditions and material constitutive properties into the design and analysis of any given road structure.

In the face of COS empirical based road design and field state condition challenges, PSIPave3D™ offers many benefits to road designers over traditional road design practices. The model can be used for new construction as well as rehabilitation designs. PSIPave3D™ incorporates complex geometry and pavement structure cross sections in addition to an array of materials including diverse virgin aggregates, recycled PCC and RAP aggregates, reclaimed *in situ* material, and various HMAC mixes. PSIPave3D™ accounts for all subgrade types across a full spectrum of *in situ* moistures and densities, including marginal soil conditions and stabilization systems.

Objective

The objective of this project was to investigate the effects of cement stabilization for granular material and subgrade soil, within a typical City of Saskatoon road structure using a 3D road structural computational mechanics model to determine the primary deflection response.

Scope

The cross section used in this study was a typical City of Saskatoon local road structure, as illustrated in Figure 1, composed of 45 mm hot mix asphalt concrete (HMAC) on 225 mm granular base, built directly on top of *in situ* subgrade.

Figure 1 Typical City of Saskatoon local road cross section

The effect of cement stabilization was examined using the PSIPave3D™ model. Two percent cement stabilization was added to the granular base layer. Three percent cement stabilization was added to the top 300 mm of the *in situ* subgrade. The PSIPave3D™ road model was used to predict strain contour profiles and peak deflections of the pavement structure with and without cement stabilization. The loading is based on a dual-tire axle load at primary weight limits, simulative of a loaded city garbage truck or transit bus. Mechanistic materials properties were determined in the laboratory using rapid triaxial frequency testing and include dynamic modulus, radial microstrain, phase angle and Poisson's ratio.

PSIPAVE3D™ MODELING RESULTS

Figure 2 illustrates the model-predicted peak surface deflections across a load spectra of primary weight limits for each pavement structure. Primary weight limits represent a loaded garbage truck, which is typical for local COS roadways. The City of Saskatoon structural asset management system has established heavy weight deflectometer (HWD) condition state thresholds for good, fair, and poor structural condition ratings.

The unstabilized pavement structure had a peak surface deflection under primary weight limits of 1.57 mm, which is within the poor deflection threshold for local roads. Stabilizing the base layer with two percent cement improved the average peak surface deflection of the road structure to 1.28 mm. Stabilizing the subgrade layer with three percent cement further improved the peak surface deflection of the pavement structure, reducing the peak surface deflection to less than 1.00 mm, which is considered to be within the good deflection threshold.

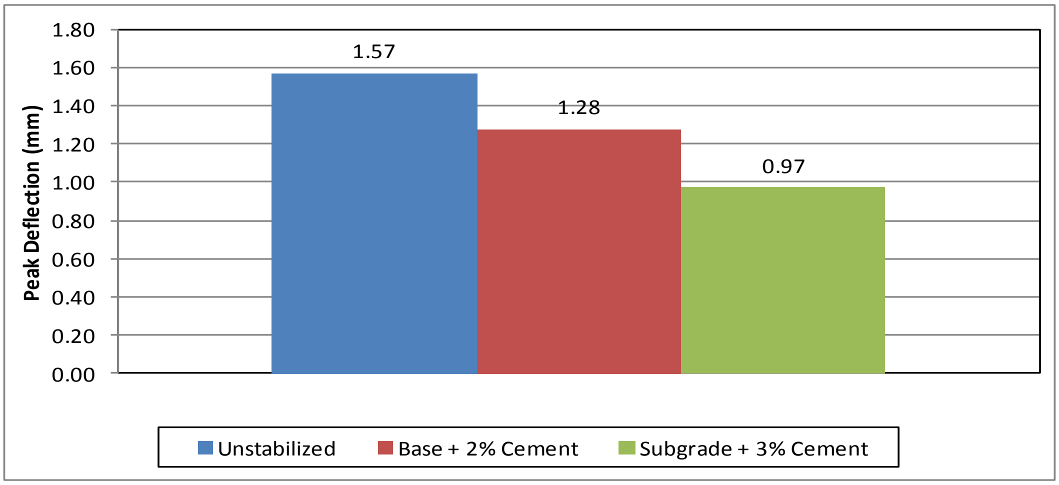


Figure 2 Model predicted peak surface deflections (mm) at primary weight limits

Vertical compressive strain at the top of subgrade and horizontal strain at the bottom of the HMAC layer have been traditionally used in the pavement design process to correlate pavement design to rutting and fatigue performance in the field. Figure 3 summarizes the peak horizontal tensile strain and Figure 4 summarizes the peak vertical compressive strain in each layer for each stabilization system.

Figure 3 shows that cement stabilization of the granular base layer resulted in a greater reduction in horizontal tensile strain than cement stabilization of the subgrade layer. The peak horizontal strain in the granular base is measured at the granular base-HMAC surface interface.

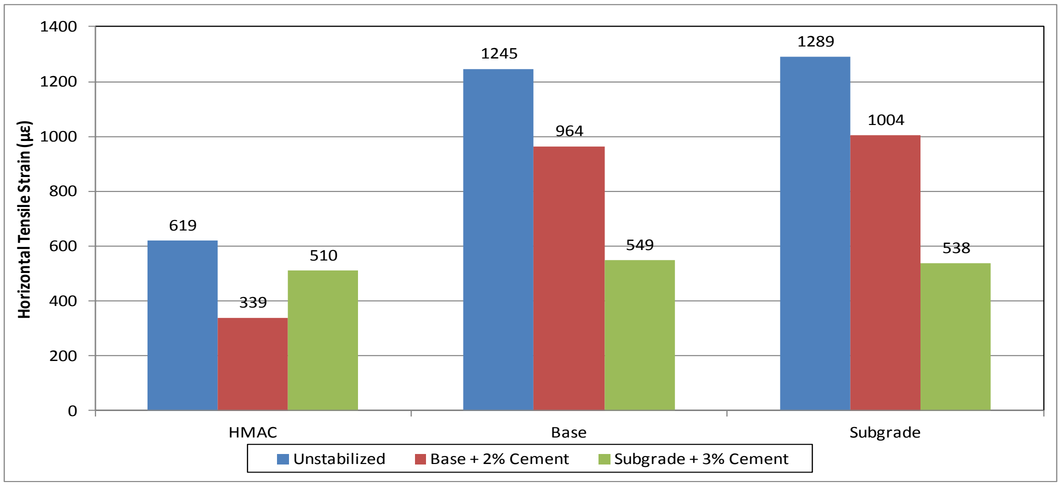


Figure 3 Model predicted horizontal shear strain at primary weight limits

Figure 4 shows that cement stabilization of the subgrade layer resulted in greater reduction in vertical compressive strain than cement stabilization of the granular base layer. By designing and constructing a subgrade layer with reduced vertical compressive strains at the top of the subgrade layer, structural failures due to subgrade failures are less likely. The base layer showed minimal reductions in vertical compressive strains for both stabilized layers, demonstrating the effect that the pavement structure's subgrade has on the road's structural integrity.

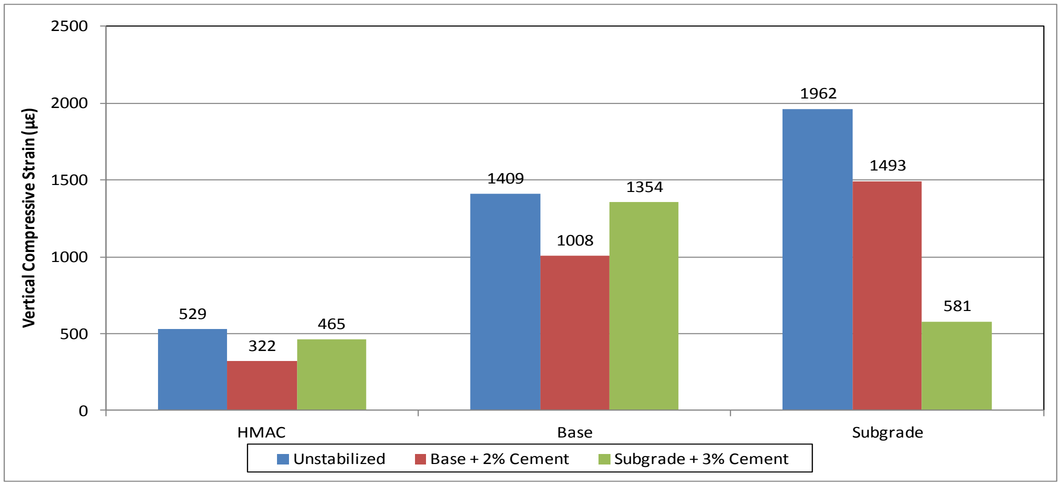


Figure 4 Model predicted vertical compressive strain at primary weight limits

This research examined shear strain behaviour of unstabilized and stabilized pavement layers. Shear strain structural failures have been observed in many Saskatchewan road structural failures. Figure 5 summarizes the maximum shear strains in each layer for each stabilization system. Figure 6 and Figure 7 illustrate the contour profiles for both unstabilized and cement stabilized granular base and subgrade layers, respectively.

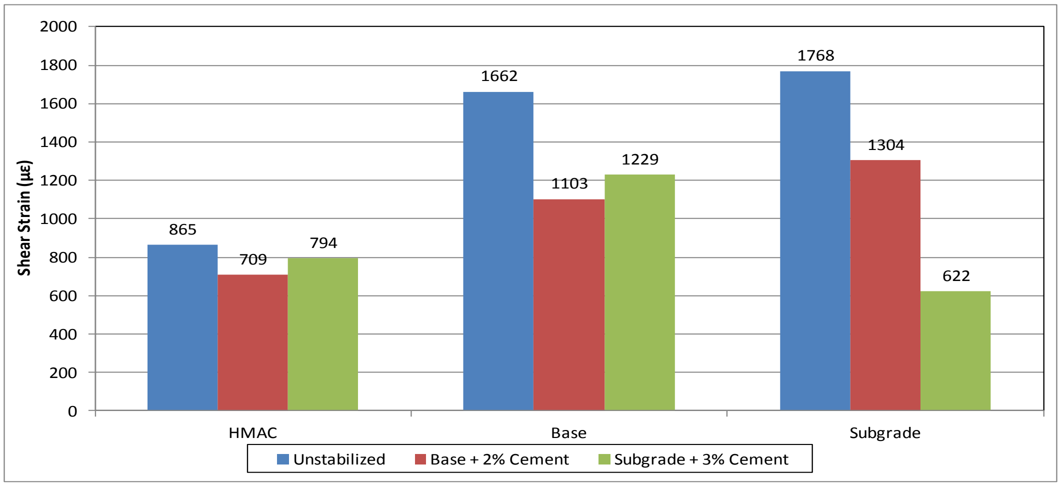
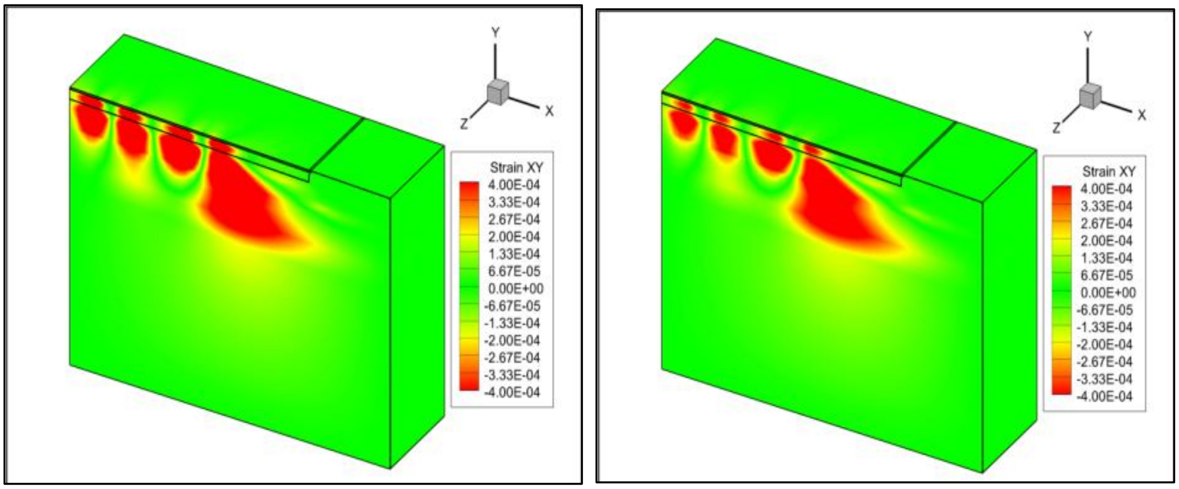


Figure 5 Model predicted shear strain at primary weight limits

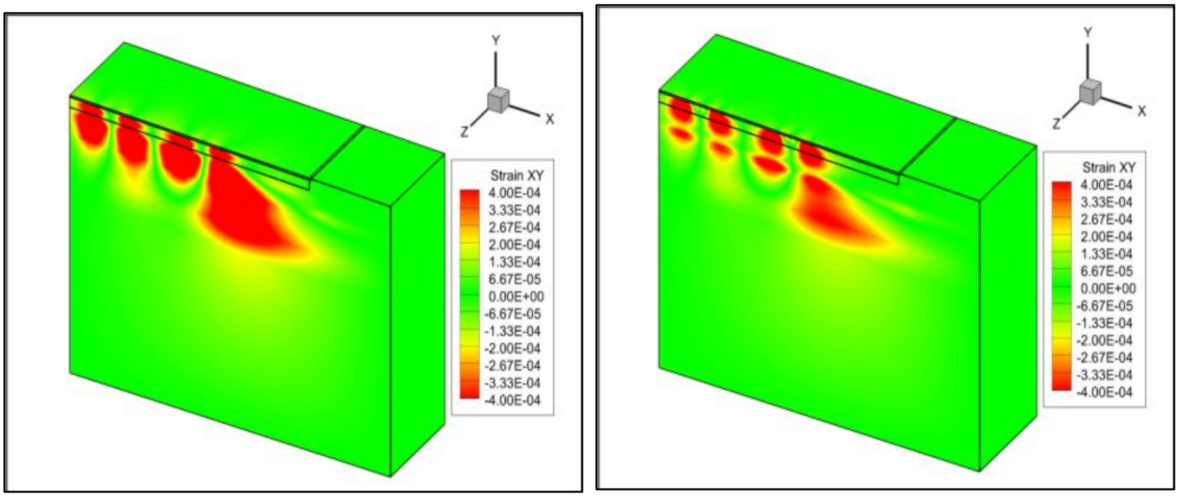
As seen in Figure 5, the peak shear strain in the unstabilized subgrade is greater than the other layers or stabilization systems. Overall, the unstabilized pavement structure has the highest peak shear strains in all layers of the pavement structure, including HMAC, granular base, and subgrade layers. Stabilizing the granular base layer with two percent cement reduced the peak shear strains in all pavement layers. Likewise, stabilizing the subgrade soil with three percent cement has similar effects.

As seen in Figures 6 and 7, cement stabilization reduced the shear strains in the subgrade layer more so than any other pavement layer, compared to an unstabilized, *in situ* subgrade. Cement stabilized granular base materials had reduction in shear strains compared to the unstabilized granular base materials, but not to the extent of the subgrade layer. The contours show a prevalence of shear strains near the edge of the road structure. This reflects typical ‘clay box’ road construction in COS. A ‘clay box’ refers to urban road structure constructed in the confines of a curb and gutter, on top of a clay subgrade.



a) Unstabilized **b) Cement Stabilized**

Figure 6 Contours of model predicted shear strain at primary weight limits – Base Layer



a) Unstabilized **b) Cement Stabilized**

Figure 7 Contours of model predicted shear strain at primary weight limits - Subgrade

CONCLUSIONS

The City of Saskatoon (COS) is faced with many challenges with regards to its pavement materials, *in situ* subgrade conditions, and road design. COS local roads have thinner structures than arterial and collector roadways, are used primarily for accessibility, and often have marginal *in situ* subgrade conditions which result in premature surface distresses and structural failures. For example, some City roadways are constructed on dry subgrades with no moisture problems, while other roadways are constructed on wet, low-lying subgrades. Thus, pavements are deteriorating far more quickly than anticipated due to marginal subgrades and poor, wet field state conditions. Cement stabilization of granular materials can mitigate reliance on marginal granular materials and poor *in situ* subgrade conditions. Cement stabilization can enhance the material properties, moisture susceptibility, and field performance of marginal granular and subgrade materials.

This paper demonstrated the use of a 3D non-linear orthotropic computational road structural model to characterize the structural behaviour of cement stabilized granular base and subgrade soils. The model was used to model peak surface deflections, as well as normal and shear strains under field state load conditions. Primary weight limits were used as the design load to emulate a loaded garbage truck, which is typical for local COS roadways.

COS local roadways have thin pavement structures that greatly rely on the structural capacity of the subgrade. This is evident in the modified Shell CBR design methodology presently used in Saskatchewan. *In situ* subgrades in marginal or wet conditions do not provide the necessary structural capacity for traffic loads, especially in wet, seasonal conditions. Cement stabilization of the subgrade layer greatly reduces the shear strains and peak vertical compressive strain in a pavement structure's subgrade layer. By designing and constructing a subgrade layer with reduced vertical compressive strains at the top of the subgrade layer, structural failures due to subgrade failures are less likely.

The cement stabilized granular base layer examined in the study showed improved shear strain and horizontal strain behaviour when compared to the unstabilized granular base layer. This improvement confirms that cement stabilization of granular base materials has an enhanced primary response. It was expected that the unstabilized pavement structure would have the highest peak surface deflection under primary weight limits higher when compared to cement stabilized base and subgrade materials. The cement stabilized subgrade has a lower peak surface deflection than the cement stabilized granular base; this shows that perhaps cement stabilization of the subgrade layer better optimizes the structural capacity of a stabilized road structure when compared to the granular base layer.

This study demonstrated that COS pavement designs are highly dependent on subgrade type and condition state and that cement stabilization of subgrade materials can improve the structural primary response of the subgrade layer. Furthermore, reducing shear and vertical strains in the subgrade eliminates potential for subgrade failure, which is a common pavement structure failure mechanism. It is recommended that the City of Saskatoon 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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