Mechanistic-Empirical Design of Unpaved Roads

Mickaël Le Vern, Master's degree student, *Université Laval*
mickael.le-vern.1@ulaval.ca

Guy Doré (ing., Ph.D.), Professor, holds the I3C CRSNG Chair, *Université Laval,*
Département de Génie Civil
guy.doré@gci.ulaval.ca

Jean-Pascal Bilodeau (ing., Ph.D.), Research Professional, i3C CRSNG Chair,
Université Laval, Département de Génie Civil
jean-pascal.bilodeau@gci.ulaval.ca

Paper prepared for presentation at the

**INNOVATIONS IN PAVEMENT MANAGEMENT, ENGINEERING AND
TECHNOLOGIES - DESIGN APPLICATIONS Session**

of the 2016 Conference of the

Transportation Association of Canada

Toronto, ON

ABSTRACT

Unpaved roads generally undergo heavy loads. In that context, a rigorous design method for that kind of roads is desirable, based on mechanistic-empirical principles and on subgrades mechanical behaviors. A mechanistic design approach, combined with empirical damage laws, allows to optimize unpaved roads structures and to reduce maintenance and construction costs.

Therefore, the goal of this project is to elaborate a mechanistic-empirical method for design of unpaved roads. First, a calculation model was developed in order to determine the stress and strain level in the pavement structure This model consists of an elastic multilayer road modeling, using Odemark's transformation and Boussinesq's equations. Then, empirical damage curves for unpaved roads were developed. Finally, this work has allowed to create design charts.

A two-step approach was adopted for the development of the transfer functions. The first one was, to establish rutting threshold values according to suitable functional and structural road conditions. Then, the development of allowable strain criteria that combines the calculated theoretical strains with the observed strains on real roads was performed.

Laboratory testing was performed on typical road samples using an accelerated load simulator. The instrumentation of the structures was designed to measure the resilient and permanent vertical deformation at the top of the subgrade. The rutting rate was also measured during the tests.

Keywords : unpaved roads, accelerated pavement testing, rutting, damage laws, design method

RÉSUMÉ

Dans le contexte où les routes non revêtues sont susceptibles de subir des charges importantes, une méthode rigoureuse pour la conception de ces chaussées basée sur des principes mécanistes-empiriques et sur le comportement mécanique des sols support est souhaitable. La conception mécaniste combinée à des lois d'endommagement permet l'optimisation des structures de chaussées non revêtues ainsi que la réduction des coûts de construction et d'entretien.

Le but de ce projet est donc la mise au point d'une méthode de conception mécaniste-empirique adaptée aux chaussées non revêtues. Il a été question tout d'abord de mettre au point un code de calcul pour la détermination des contraintes et des déformations dans la chaussée. Ensuite, des lois d'endommagement empiriques pour les chaussées non revêtues ont été développées. Enfin, les méthodes de calcul ont permis la création d'abaques de conception.

Le développement du code de calcul a consisté en une modélisation de la chaussée par un système élastique multi-couches. La modélisation a été faite en utilisant la transformation d'Odemark et les équations de Boussinesq pour le calcul des déformations sous la charge. L'élaboration des fonctions de transfert empiriques adaptées aux chaussées non revêtues a également été effectuée.

Le développement des fonctions de transfert s'est fait en deux étapes. Tout d'abord, l'établissement de valeurs seuil d'orniérage considérant des niveaux jugés raisonnables de conditions fonctionnelle et structurale de la chaussée. Ensuite, le développement de critères de déformation admissible en associant les déformations théoriques calculées à l'aide du code de calcul à l'endommagement observé sur plusieurs routes en service.

Les essais ont eu lieu sur des chaussées typiques reconstituées en laboratoire et soumises à un chargement répété par simulateur de charge. Les chaussées ont été instrumentées pour mesurer la déformation au sommet du sol d'infrastructure et les taux d'endommagements ont été mesurés au cours des essais.

Mots clés : chaussées non revêtues, chargements routiers accélérés, orniérage, lois d'endommagement, méthode de conception

INTRODUCTION

Roads are essential infrastructures for people and resources mobility and for the territories economic development. In a vast country, such as Canada, roads are also essential to connect small communities far apart from each other.

Low volume roads represent a significant part of the Canadian road network. These roads are mainly used by heavy vehicles, remote areas' residents, for leisure and outdoor activities. The management of these roads shall be subject to constraints: it is expensive and often unnecessary to pave these roads because they are generally far from activity centers and because to the low traffic level. In a general way, it is decided to put a thin asphalt layer or to keep the surface unpaved.

Unpaved roads design represents a technical and environmental issue: granular layers thicknesses have to be neither to high (wastage of material and energetics) nor too low (degradation, damage…).

The unpaved roads design is less documented than the paved roads design. The unpaved roads design is mostly based on the lessons of experience or on empirical design methods, because these roads are generally subject to low traffic (less than 400 vehicles per day) from heavy vehicles. The problem with the empirical methods is that they are most effective in the context and the conditions where they were developed. Out of this context, these methods can lead to an over-design, which is associated with a waste of materials. In the current circumstances of resources preservation and users security, it is necessary to optimize the unpaved roads design. In this project, the proposal is to going beyond the traditional empirical methods (AASHTO,…) by developing a mechanistic-empirical method in order to propose a more universal unpaved roads design.

As part of the development of a mechanistic-empirical approach, the objective of this project is to develop a design criterion for unpaved roads. This criterion should allow to choose optimal granular layers thicknesses, in relation to the subgrade soil and the number of load applications that the road will support during his lifetime. The specific objectives of the project are:

- To develop a rigorous calculation model for the determination of stress and strains in an unpaved road.
- To develop a « Deformation – Number of cycles to failure » curves for unpaved roads.
- To integrate computational methods in a practical design tool

BACKGROUND

Rutting, a design criterion

The main distress that is observed on unpaved roads is the permanent deformation accumulation in the different pavement layers. This deformation, due to the repetitive heavy vehicles movement, leads to rutting. Unpaved roads are not affected by the fatigue phenomenon because they are unsealed roads.

In the study « *Design of Low-Volume Roads Against Rutting* » [5], three rutting modes are defined (Figure 1):

_Mode 0: Post-compaction of the materials in the pavements (good compaction minimize it).

_Mode 1: Local shear close to the wheel. Rise due to dilative movement immediately adjacent to the wheel track (a consequence of inadequate granular material shear strength for the materials relatively close to the pavement surface).

_Mode 2: Whole pavement deformation (including subgrade soil). Important problem of structural rutting.

Rutting is a complex interaction between resilient and plastic response of the pavement layers. In most cases, Modes 1 and 2 appear simultaneously.

Ruts on roads cause a reduction of driving comfort and an increase in fuel consumption. They also increase the aquaplaning risk because of water retention. Moreover, water can more easily infiltrate the pavement structure. This causes a water concentration in the subgrade rut, which reduces the bearing capacity of both the granular layer and the subgrade soil, and which contributes to increase the degradation rate.

Mode 1 rutting is not necessarily an issue for unpaved roads, as it can be controlled by a regular maintenance with a grader. Mode 2 rutting poses problems because it occurs at significant depths, mostly at the top of the subgrade soil. Indeed, the soil is the weakest layer of a road structure and, when its deformation is too excessive, this imposes deep and costly repairs, particularly if it is necessary to excavate and rebuilt the road.

In the context of road design, a critical rut depth should be specified. The study « *Roadway Hydroplaning – Measuring Pavement Wheel Rut Depths to Determine Maximum Water Depths* » [7] sets up criteria to prevent aquaplaning. An equation was developed to calculate the water retention depth depending on rut depth and other geometric parameters (Figure 2).

Based on flexible pavement tests, this study estimates, when the vehicle speed exceeding 70km/h, that the critical water depth ("WD" in Figure 2) is 3mm to risk aquaplaning. For lower speed, the critical water depth is 5mm. Taking into account the assumption of a 1000mm rut width (L=500mm) and of a 3% cross slope, the critical rut depth will be 20mm if the vehicle speed is lower than 70km/h. This result holds for flexible pavements. Requirements are less stringent for unpaved roads, whose current design methods suggest deeper critical ruts (25mm, 50mm, 75mm, even 100mm or beyond). Considering a 1m width surface rut, it can be admitted, considering the stress dispersion in a road structure, that the rut at the top of the subgrade soil is likely to be about 1,5m wide. Unpaved roads have generally cross slopes between 3% and 4%. Therefore, a 25mm structural rut depth will cause a water retention between 0 and 2,5mm while a 50mm structural rut depth will cause a water retention between 20 and 27mm. Thus, taking into account the water retention issue, a 50mm allowable rut

depth seems to be a consistent unpaved roads design criterion. This criterion has also been retained by the AASHTO design method [1] and the Giroud and Han design method [6].

In a general way, the main approaches to reduce rutting are to increase the granular quality, to improve the compaction and to increase granular layers thicknesses. It is possible to put a thin asphalt layer on the surface to reduce stresses in inner layers and to promote the sealing of the surface.

Existing design methods

In the book "*AASHTO Guide for Design of Pavements Structures*" [1], the American Association of State Highway and Transportation Officials proposed an empirical method of pavement design based on design nomograms. The book includes a low-volume roads design chapter. This method is based on nomograms developed using roads that were monitored over; it is an empirical method. These roads were all built on the same subgrade soil, a low plasticity silt, and have suffered channeled road traffic. There are many other empirical design methods, but the AASHTO method is currently one of the most used in North America for unpaved roads design.

The article *« Mechanistic-empirical approach for design of low volume pavements »* published in the International Journal of Pavement Engineering [8] describes a mechanistic-empirical approach for design of low volume roads. The authors carried out in parallel a road instrumentation and a Finite Element analysis with ANSYS. The experimental approach has allowed to obtain the following damage criterion:

$$\epsilon_z = 0{,}0058 \cdot N^{-0{,}171} \qquad (1)$$

With: ϵ_z = vertical compressive strain over subgrade (mm/mm)

   N = number of standard axle load repetitions leading to failure (ESAL)

Thus, the design process is as follow: The number of cycles that the road will be subjected to is initially determined. The vertical compressive strain over subgrade is deduced from the equation (1). Then, the designer must choose the minimum granular layer thickness to reach this strain level (with the Finite Element model).

Mechanistic-empirical design approach

The mechanistic-empirical process combines analytical response models with experimentation. On one hand, this approach consists in trials on soils to assess their performance and to obtain a general design criterion in relationship with the experimental measurements. On the other hand, it consists in elaborating a calculation model in order to determine the road response under load. Experimentation allows to adjust the mechanistic model with real conditions, because the mechanical approach is usually based on simplifying assumptions.

This project is based on Boussinesq equations for determining stresses and strains in a road structure under loading. Boussinesq equations are:

$$\sigma_z = \sigma_0 (1 - \frac{z^3}{(a^2 + z^2)^{1,5}}) \qquad (2)$$

$$\sigma_r = \frac{\sigma_0}{2}[(1 + 2\mu) - \frac{2(1 + \mu)z}{(a^2 + z^2)^{0,5}} + \frac{z^3}{(a^2 + z^2)^{1,5}}] \qquad (3)$$

$$\epsilon_z = \frac{(1 + \mu)\sigma_0}{E}[(1 - 2\mu) + \frac{2\mu z}{(a^2 + z^2)^{0,5}} - \frac{z^3}{(a^2 + z^2)^{1,5}}] \qquad (4)$$

$$\epsilon_r = \frac{(1 + \mu)\sigma_0}{2E}[(1 - 2\mu) - \frac{2(1 - \mu)z}{(a^2 + z^2)^{0,5}} + \frac{z^3}{(a^2 + z^2)^{1,5}}] \qquad (5)$$

Where : σ_z = axial strain (kPa)

σ_r = radial strain (kPa)

ϵ_z = axial stress (mm/mm)

ϵ_r = radial stress (mm/mm)

σ_0 = Pressure applied to the surface (kPa)

z = Depth (mm)

a = Loading plate radius (mm)

E = Young Modulus (MPa)

μ = Poisson ratio

These equations apply to a homogenous and isotropic soil with a linear elastic behavior. These assumptions are simplifications and have limitations because a granular soil is heterogeneous and anisotropic. Within the context of a mechanistic-empirical analysis, these assumptions can be done if experimentations are conducted in parallel, in order to adjust the model with the reality. However, roads have typically several layers with different modulus, so Boussinesq equations are not directly applicable. It is necessary to use the Odemark model to transform a multi-layers system in a single layer system with the "equivalent heights" method.

METHODOLOGY

In this project, a calculation model was developed in order to calculate stresses and strains in an unpaved road structure subjected to heavy traffic effects. This calculation model is based on Boussinesq equations applied to elastic systems corresponding to road layers. Rutting performance criteria for unpaved roads were developed from trials on typical laboratory roads. Tests were carried out using a small-scale heavy vehicle simulator (Figure 3). Four road samples were built, using four different subgrade soils: a silty-clay, a silty-sand, a clay and a sand. Each road sample underwent a hundred thousand wheel load cycles using a multistage stress approach. The instrumentation of the

structures was designed to measure the resilient and permanent vertical deformation at the top of the subgrade.

RESULTS AND ANALYSIS

Strain response of pavement samples

A LVDT sensor allowed to monitor the resilient and permanent deformation at the top of the subgrade during loading of the pavement samples. Figure 4 shows the resilient deformation and the permanent deformation accumulation measured by the sensor for specific test conditions. The measurements presented in Figure 4 correspond to the results collected for the maximum load applied on the first saturated road sample (silty clay subgrade).

Figure 5 shows the permanent deformation evolution at the top of the subgrade during the four stress stages on the second sample road (silty sand subgrade). In this figure, "P" is the contact pressure between the wheel and the pavement.

Figure 6 presents the resilient deformation mean values per stress stage for each sample.

Figure 7 provides the surface rutting evolution for the second sample during the first stress stage. An extrapolation was made on the last eight points of the graph in order to obtain a mathematical model which best describes the rutting development and allows to predict its evolution beyond 50 000 cycles.

Establishment and validation of damage curves

One of the main goals of this project was to establish wöhler curves for unpaved roads. These curves allow to determine, after establishing a damage criterion, the lifetime of the road (number of loading cycles) with respect to the characteristic resilient deformation at the top of the subgrade induced by each cycle for a given stress level.

During the experiments, resilient deformations at the top of subgrades were compiled (Figure 6) and the rutting evolution was measured (Figure 7). Allowable rut depths criterion were selected in order to have acceptable water retention into the ruts, as previously explained. Two criteria were adopted: 25 or 50mm allowable rut depth at the top of the subgrade. Using rutting extrapolation equations, the number of cycle to reach the critical rut depth criterion may be determined. Based on this analysis, wöhler curves can be traced: Figure 8 corresponds to the silty clay and silty sand (blue dotted line) and the clay (green dotted line) wöhler curves, for a 25mm rut depth criterion. The curve corresponding to tests performed on sand subgrade soil is not plotted.

Table 1 shows the resulting wöhler curves equations. These curves were extrapolated from laboratory results (blue and green cross, Figure 8), in order to obtain the same slope in a logarithmic scale graphic. The use of this method enables to obtain a good correlation with the results. Moreover, the insertion of field data in Figure 8 shows that wöhler curves' extrapolations are consistent. Indeed, field data are between the two proposed curves. These field data were obtained from the study «Design *of Unsurfaced Road Using Geosynthetics*» [9]. These are rutting evolution and top of subgrade deformation measurements of unpaved roads sections build on a clayed soil in Scotland. Some sections were built without geosynthetics (red cross), but most of them were reinforced (violet cross).

8

Comparison with other methods

Boussinesq-Odemark calculation model, when is combined with the wöhler curves, leads to an unpaved road design method. Designer defines a pavement structure (layers thicknesses and modulus) and loading characteristics (pressure and tire width). Then, with the calculation model, it is possible to determine the resilient deformation at the top of the subgrade soil induced by the load. From this deformation, the wöhler curve corresponding to the soil allows to determine the lifetime of the road (number of loading cycles before reaching the defined damage criterion). Thus, the designer can adapt road layers thicknesses in order to reach the specified number of cycles.

It would be interesting to compare the method developed with existing unpaved roads design methods. Comparisons describe below were carried out with the same subgrade, the same base course and the same loading. For a same road service life, comparisons were carried out between recommended foundation thicknesses obtained with the developed mechanistic-empirical method and with the empirical AASHTO method (Figure 9). Wöhler curves developed in this project were compared with other wöhler curves developed for low-volume roads (Figure 10). One of the design charts developed in this project has also been compared with Gupta and al.'s chart (Figure 11).

Methods mentioned above do not take account the type of soil but only of the bearing capacity of the soil. However, wöhler curves developed in this project make a distinction between the behavior of silty clay-silty sand, clay or sand. Clay and sand curves would require more data to be validated, they were not included as part of the comparisons performed. Only the silty clay-silty sand wöhler curve (blue curve, Figure 8) is considered here, but this type of soil represents a typical subgrade soil in the Quebec's geological context.

For the comparison with the AASHTO method, 100 roads were modeled. Depending on rutting criterion selected (25 or 50mm rut depth), for a same number of load cycles, foundation thicknesses planned by the two methods were compared (Figure 9). Generally, the proposed mechanistic-empirical method provides longer service life. This is reflected in smaller foundations thicknesses. Foundations thicknesses stay in the same order of magnitude for the two methods. Nevertheless, the mechanistic-empirical method provides foundations thicknesses 25% lower than the AASHTO method on average. This observation is consistent in the sense that the mechanistic-empirical method takes into account the subgrade rutting while the AASHTO method takes into account the surface rutting (which occurs more rapidly). These observations suggest that the AASHTO method would lead to an over-design, on the basis of structural rutting occurring at the top of the subgrade.

In the past, low-volume roads have already been the subject of wöhler curves establishment. Generally, low-volume roads are unpaved roads or have just a thin pavement. Most of these wöhler curves have been cited by Gupta and al. (2014). Figure 10 shows the comparison between these curves (solid lines) and the wöhler curves developed in this project (dotted lines) for a 25mm rut depth criterion. The silty clay – silty sand wöhler curve developed in this project was found to be similar in trend to Shell (1978) and Sahoo (2009) curves. For a large number of cycles, this curve also matched closely the ones proposed by Gupta (2014) and TRRL (1987), but was away from the ones proposed by Austroads (2004) and Theyse (1996). The clay curve differs quite substantially from the other curves. Excluding the clay curve, all the wöhler curves stay in the same order of deformations magnitude, even if they have different slopes. The comparison interval, between 100 and 100 000 000 cycles, is very large and shows that the silty clay – silty sand wöhler curve developed in this projet provide realistic and consistent results when compared to the other curves developed in the past. This curve tends to be validated, but not the clay curve which is far from the other curves.

One of the charts developed in this project was compared with the chart developed by Gupta and al. for a same rutting criterion and a same foundation resilient modulus (Figure 11). The thicknesses

provide by the developed method are globally higher than Gupta and al. thicknesses. Thus, the method established in this project appears as a compromise between existing design methods: this method underlines that empirical methods tend to over-design the roads, while providing higher thicknesses than the Gupta and al. mechanistic-empirical design method.

DISCUSSION

Work and results validity

Heavy vehicle simulator tests have led to consistent results. The increase of deformation at the top of the subgrade has been gradual for each road sample with the incremental increase of loads. The results achieved have allowed to establish wöhler curves and to distinguish the behavior of a soil saturated in comparison with an unsaturated soil. These results have been validated with substantial field data.

All in all, three wöhler curves were developed for each damage criterion (25 or 50mm rut depth): a curve for silty clay-silty sand soils, a curve for clays and a curve for sands. In the end, the sand curve was not analyzed because of the lack of literature data to be validate. Fine soils curves could be validated with field data. The silty clay-silty sand curve is well articulated with low-volume roads curves from Gupta and al. (2014), Shell (1978), Sahoo (1978), Austroads (2004), TRRL (1987) and Theyse and al. (1996). However, the clay curve is far from these curves and is not based on enough trials to be validated.

The design method was developed using the silty clay-silty sand curves and the Boussinesq-Odemark calculation model. Then, the results obtained with the method were compared with the results of current unpaved roads design methods. Differences between the mechanistic-empirical method developed and the AASHTO method, in terms of foundations granular layers, are 25% on average. The mechanistic-empirical method also provides lower foundations granular layers than the U.S. Corps of Engineers empirical method [3], the CBR method [2] and the Giroud and Han method [6]. These observations suggests that the use of the propose method may lead to a significant materials economy. These are important observations given that these methods are currently the most widely used methods in North America.

Implementation, enforcement of research results

Finally, the results of this study, have been used to develop a mechanistic-empirical design method for unpaved roads. Design charts have been established, using the proposed empirical damage curves developed and Boussinesq-Odemark calculation model. These charts are very similar to the Gupta and al. (2014) charts. The wöhler curves developed are specific to unpaved roads and can be added to I3C-ME, a mechanistic-empirical pavements design software [4]. This software takes into account the seasonal damage and the frost heave, so the design will be optimized as it would take into account seasonal variations of material properties, as well as frost protection design, if desired.

CONCLUSION

This study has enabled to develop a mechanistic-empirical design method for unpaved roads. On one hand, the implementation of a calculation model was done using the Boussinesq equations and Odemark transformation in order to determine the deformation at the top of the subgrade of a road under heavy traffic. This study focused on the subgrade deformation because structural rutting is considered as the most important unpaved roads degradation. On the other hand, tests were carried out using a small-scale heavy vehicle simulator on laboratory pavement samples. During these tests, rutting and deformations were measured, leading to the establishment of unpaved roads wöhler curves. To obtain these curves, two critical damage criteria were selected (25 and 50mm rut depth at the top of the subgrade soil). The wöhler curves and the calculation model made possible to develop design charts.

Wöhler curves developed in this study have been compared with other low-volume roads wöhler curves and with field data. The comparisons allow concluding that developed curves are relevant and that they provide realistic results. However, other tests should be conducted in order to fully validate the results on clays and sands.

The method was compared with the other design methods for unpaved roads. Empirical design methods generally over-design unpaved roads. Thus, the mechanistic-empirical design approach proposed in this study can lead to cost savings regarding materials.

The insertion of the wöhler curves developed in I3C-ME, a mechanistic-empirical pavement design software, will allow to rigorously design unpaved roads, taking into account also frost heave and seasonal damage.

ACKNOWLEDGEMENTS

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LIST OF TABLES AND FIGURES

TABLE 1 : Wöhler curves equations

Soil	Damage criterion	Wöhler curve equation
Silty-clay, Silty-sand	25mm rut depth	$\epsilon = 0,07.\,N^{-0,346}$ (6)
	50mm rut depth	$\epsilon = 0,1196.\,N^{-0,346}$ (7)
Clay	25mm rut depth	$\epsilon = 0,25.\,N^{-0,346}$ (8)
	50mm rut depth	$\epsilon = 0,34.\,N^{-0,346}$ (9)
ϵ : Resilient deformation at the top of the subgrade soil induced by each cycle (mm/mm) N : Number of loading cycles		
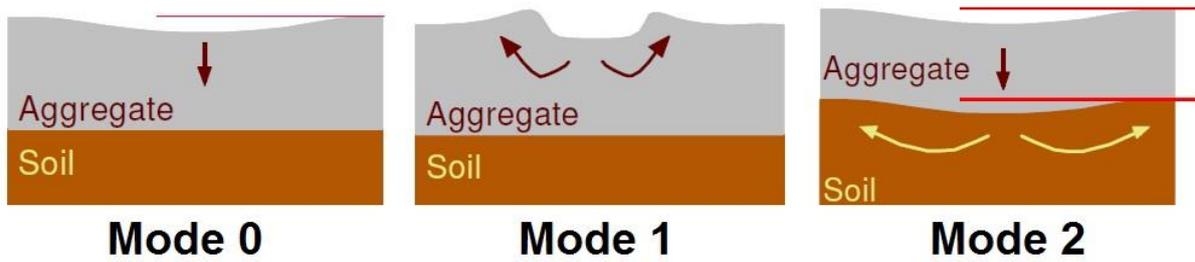
FIGURE 1 : Three rutting modes (Dawson, 1997)
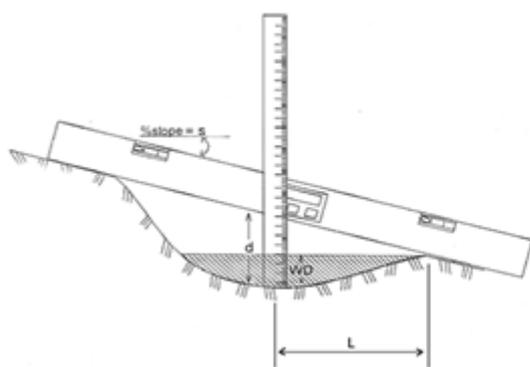
$$WD = d - L \times s$$

WD = water depth (mm)

d = rut depth (mm)

L = measurement from the lower side of the rut to the position of the maximum depth (mm)

s = cross slope (mm/mm)

FIGURE 2 : Water accumulation in ruts (Glennon, 2015)

1-Frame
2-Pavement sample
3-Lateral displacement rail
4-Longitudinal displacement rail
5-Axial loading system
(air-spring bellows)

Juneau and Pierre 2008
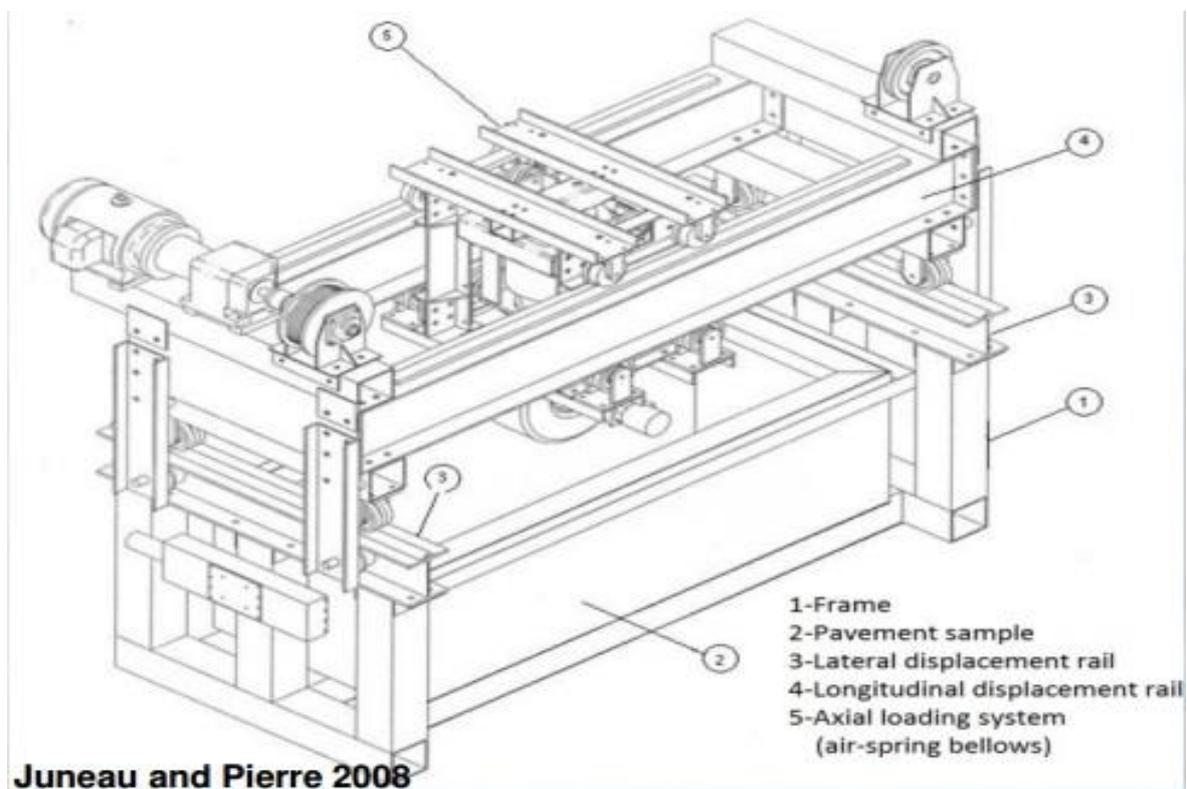
FIGURE 3 : Heavy vehicle simulator, Laval University (Juneau and Pierre, 2008)
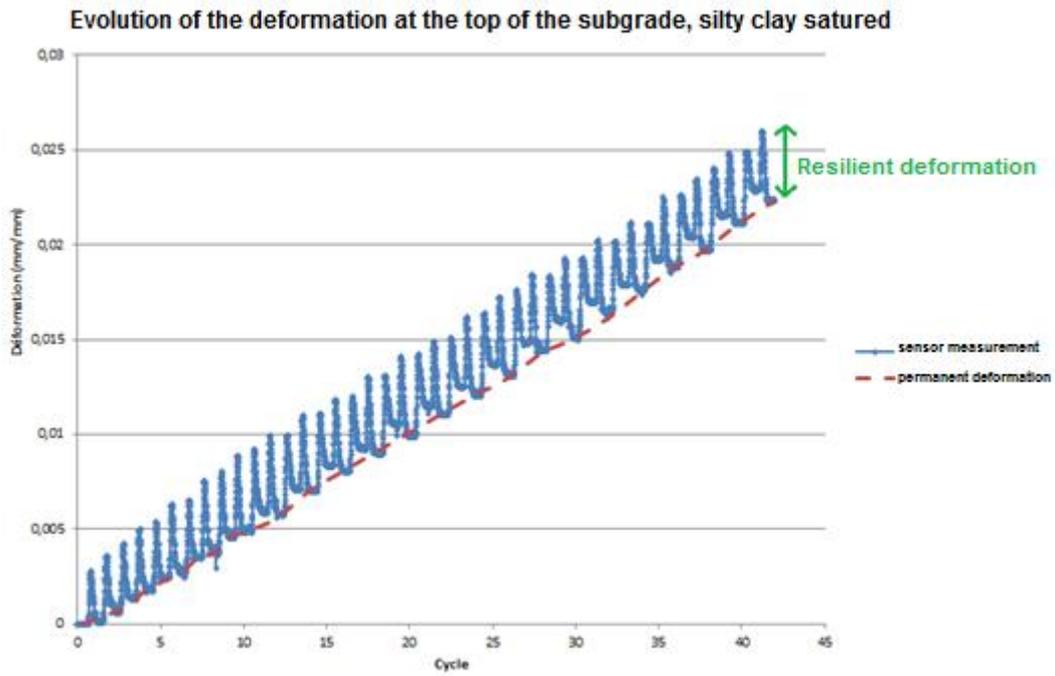
FIGURE 4 : Evolution of the deformation at the top of the subgrade, silty clay satured
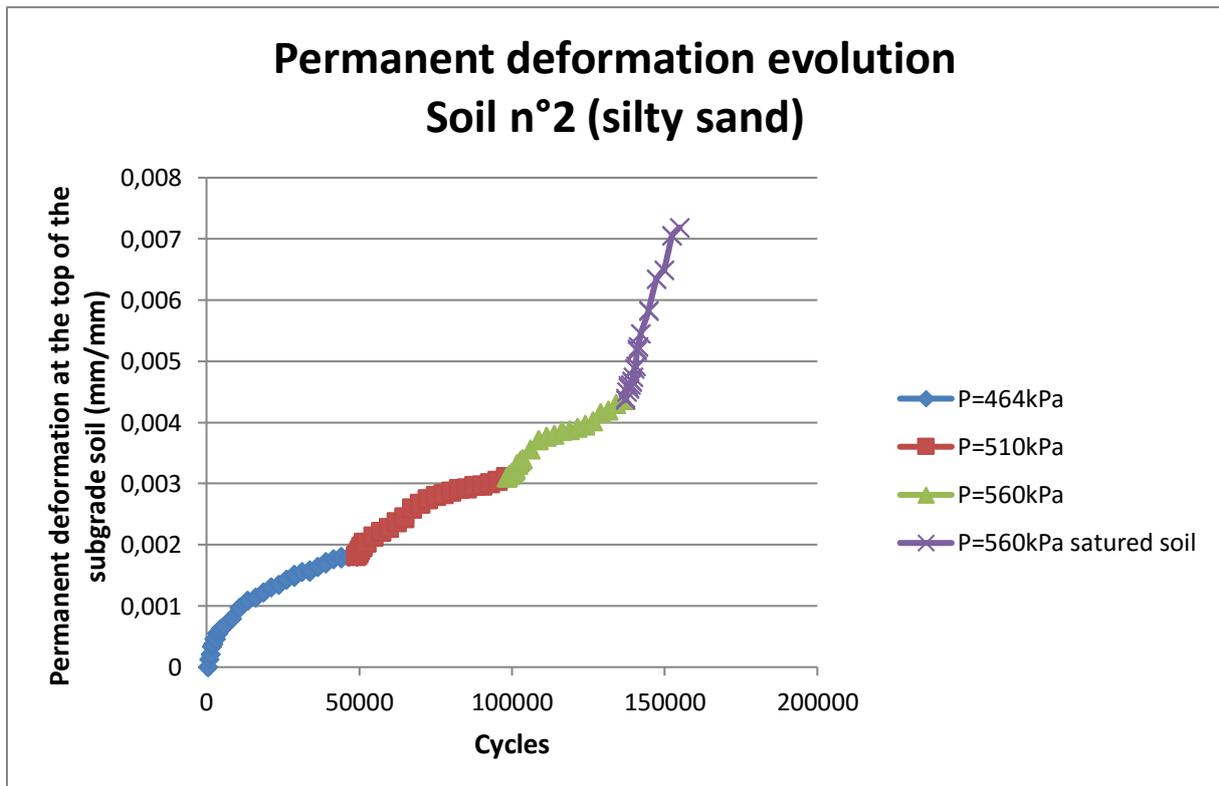
FIGURE 5 : Permanent deformation evolution. Soil n°2 (silty sand)
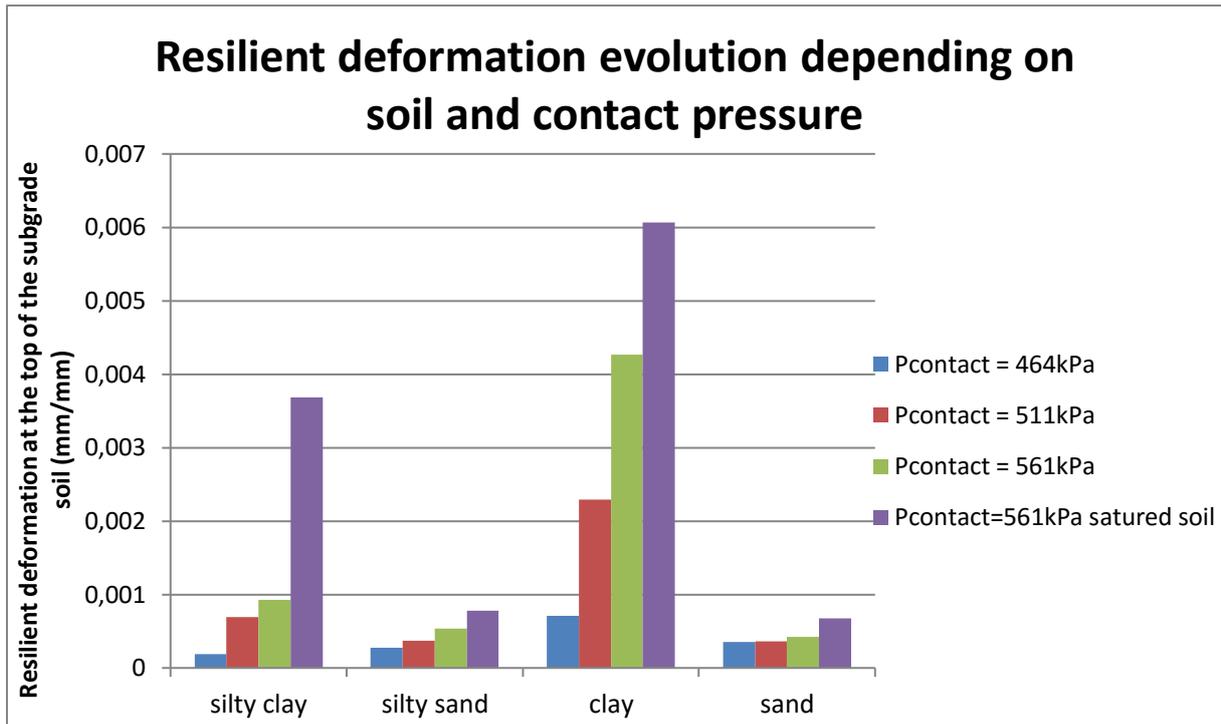
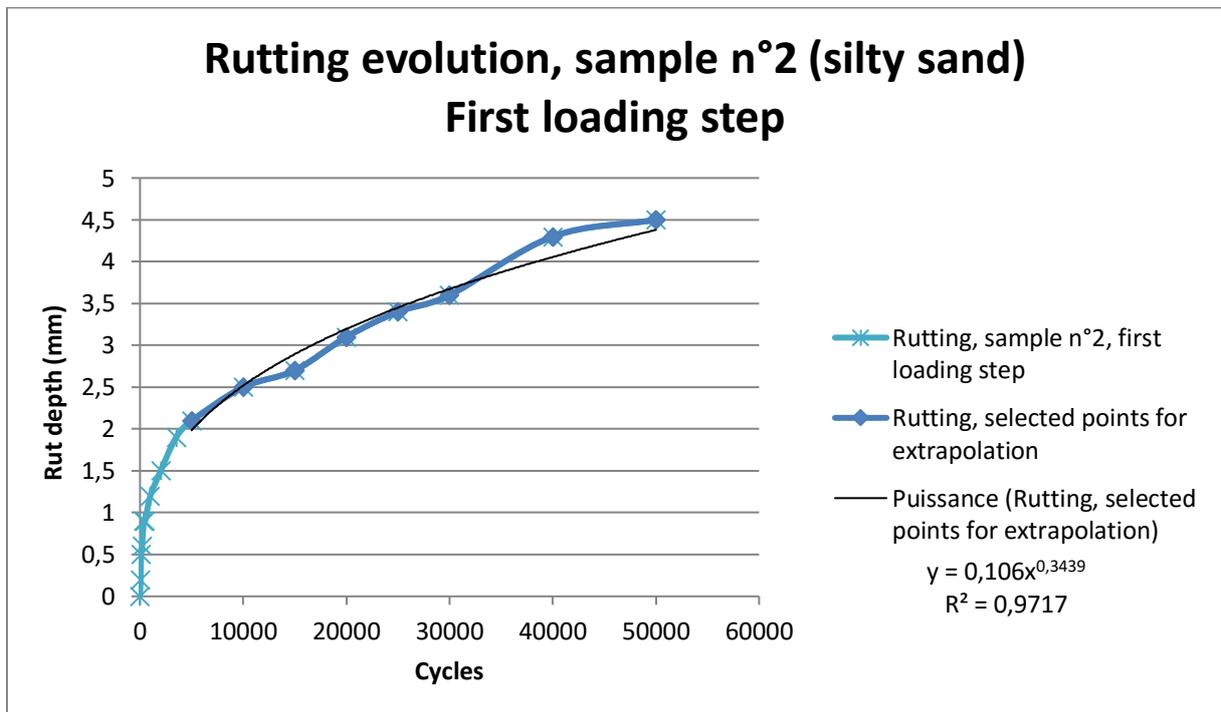**FIGURE 6 : Resilient deformation evolution depending on soil and contact pressure**

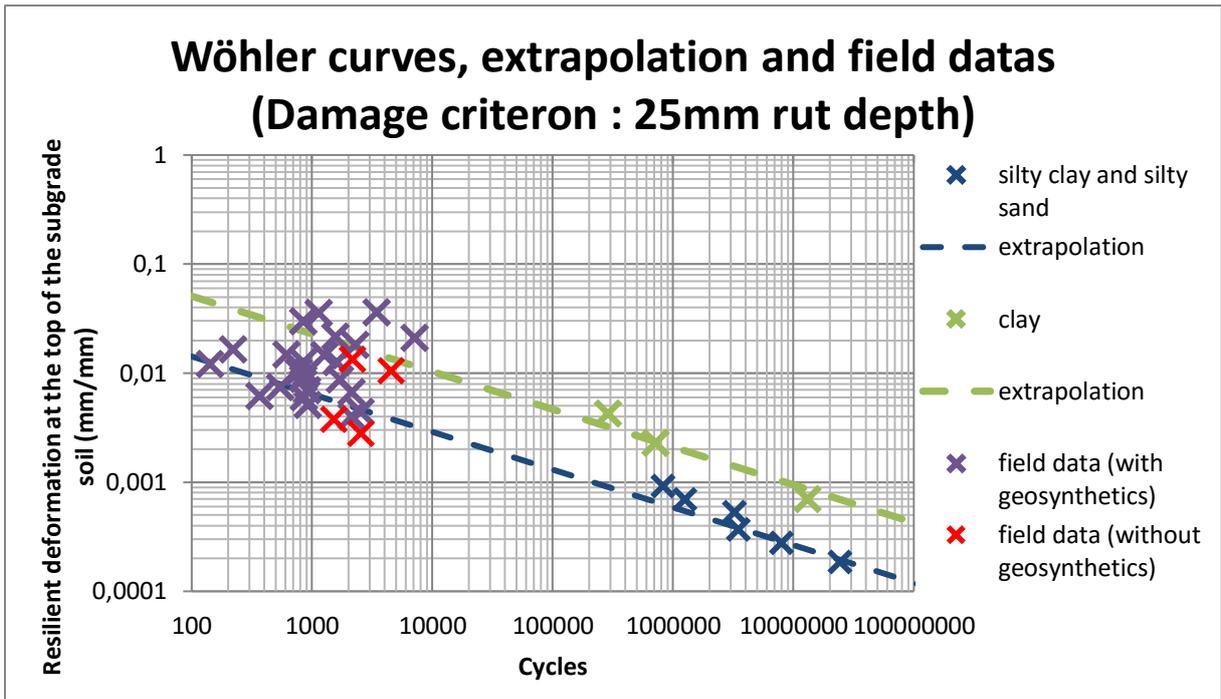**FIGURE 7 : Rutting evolution, sample n°2 (silty sand). First loading stage**

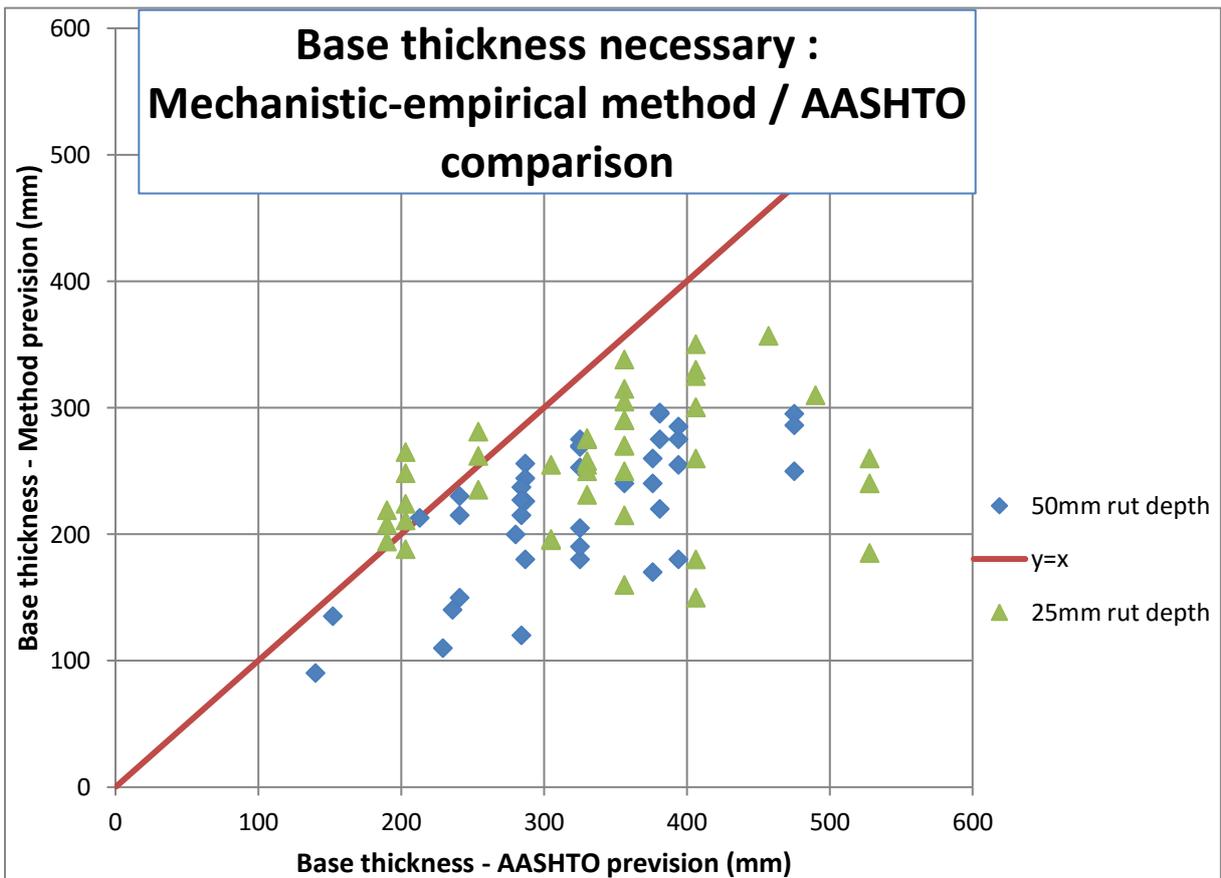**FIGURE 8 : Wöhler curves, extrapolation and field data (Damage criterion: 25mm rut depth)**

FIGURE9 : Base thickness necessary : Mechanistic-empirical method / AASHTO comparison
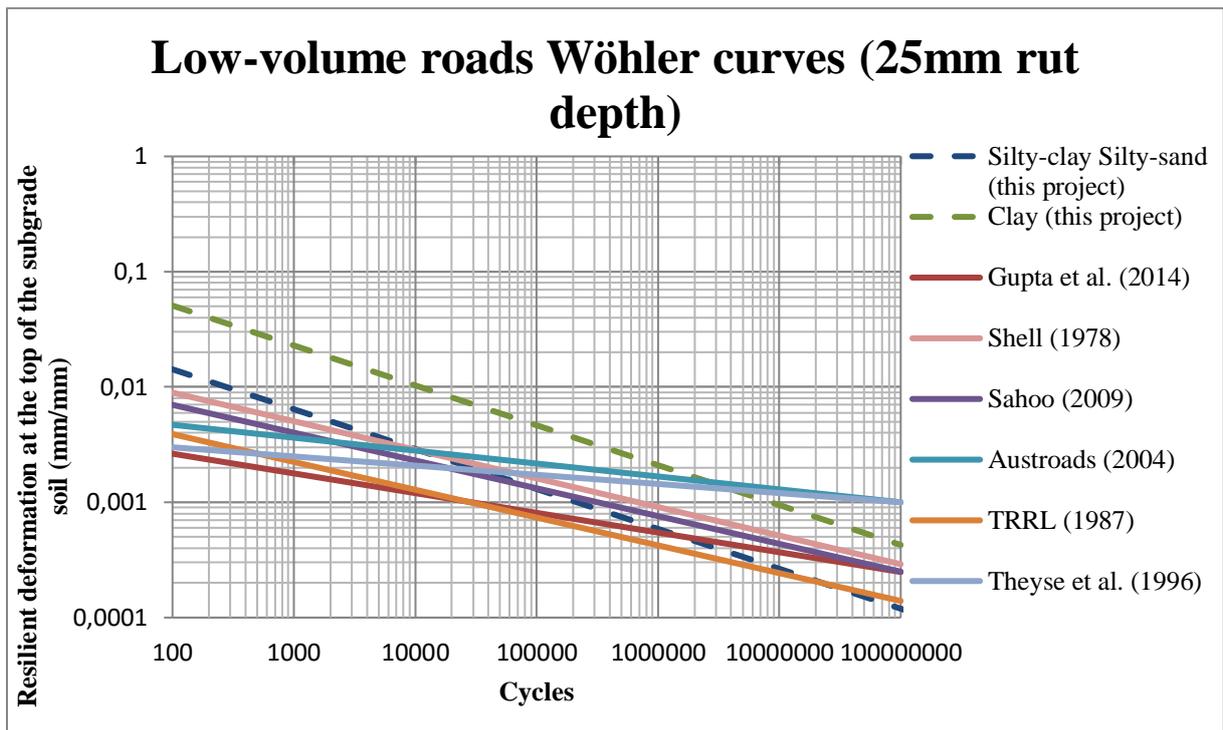
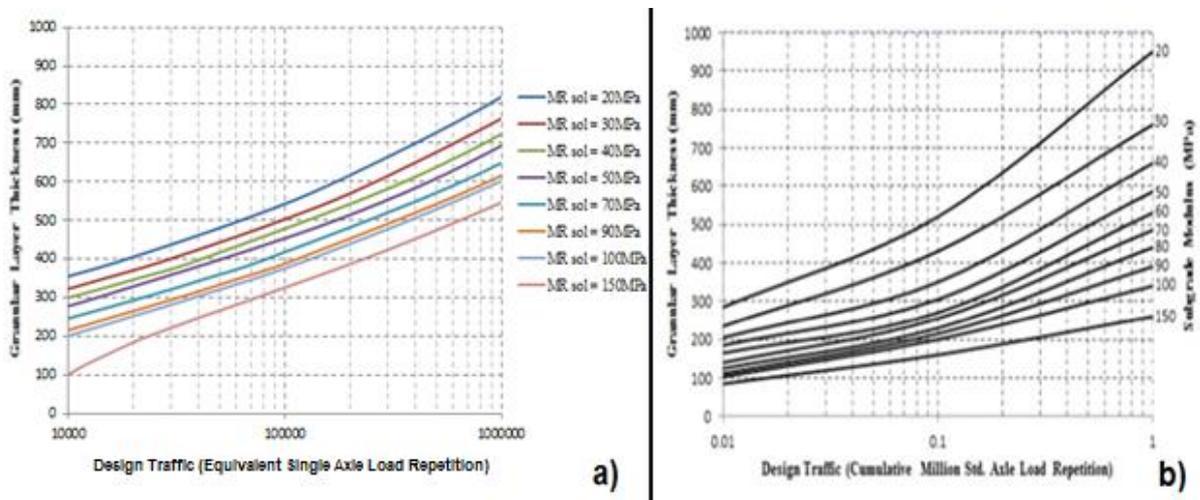FIGURE 10 : Low volume roads Wöhler curves (25mm rut depth)

FIGURE 9 : Comparison, for a 25mm rut depth criterion and a 150MPa base resilient modulus, between a) the chart developed in this project and b) the chart developed by Gupta and al. (2014)