



Asphalt layer rutting performance prediction tools

Denis Jelagin
Abubeker Ahmed
Xiaohu Lu
Safwat Said

VTI rapport 968A

Asphalt layer rutting performance prediction tools

Denis Jelagin

Abubeker Ahmed

Xiaohu Lu

Safwat Said

Reg. No., VTI: 2016/0501-92
Publication No.: VTI rapport 968A
Cover pictures: Hejdlösa Bilder AB
Published by VTI 2018

Abstract

Flexible pavement rutting due to permanent deformation accumulation in asphalt layers is one of the most common modes of road failures. In addition to creating high maintenance costs, rutting is a major concern for traffic safety, as the rut development increases the risk of hydroplaning and introduce difficulties in vehicle steering. In this context, accurate methodologies for pavement rutting performance prediction are crucial for decision support in pavement design and rehabilitation. In particular, better rutting performance models are needed to evaluate, new asphalt materials as well as to evaluate the impact of different vehicle types on roads' service life.

The main goal of this report is to present a summary of the existing asphalt rutting performance prediction tools. The present review is limited to available and/or frequently referred to tests and models with an established link to field rutting performance. Accordingly, models focusing solely on permanent deformation on the material level are beyond the framework of the present study.

Road structure and its materials, heavy vehicle parameters and climate affecting rutting accumulation in the field are identified. Their significance has been evaluated based on the experimental and numerical findings reported in the literature. Several rutting performance prediction models recently proposed in the literature are summarized along with the material characterization tests used in the models. The reviewed models' capability to quantify the influence of various structural, material and traffic parameters on the pavement's rutting performance is examined.

It is concluded that implementation of rutting performance models incorporating experimentally measured viscoelastic and permanent deformation properties of asphalt mixtures is a promising way to improve the accuracy of pavement performance predictions. In particular since they allow the effect of novel materials, e.g. polymer-modified, on the pavement's rutting performance to be quantified.

Title: Asphalt layer rutting performance prediction tools

Author: Denis Jelagin (KTH, <https://orcid.org/0000-0002-0596-228X>)
Abubeker Ahmed (VTI, <https://orcid.org/0000-0002-6327-4709>)
Xiaohu Lu (Nynas)
Safwat Said (VTI, <https://orcid.org/0000-0002-6308-7487>)

Publisher: Swedish National Road and Transport Research Institute (VTI)
www.vti.se

Publication No.: VTI rapport 968A

Published: 2018

Reg. No., VTI: 2016/0501-92

ISSN: 0347-6030

Project: Prediction of rut development in asphalt concrete layers

Commissioned by: Vinnova, Trafikverket, SBUF, Nynas AB, DRF, Volvo Technology

Keywords: Rutting, asphalt material, model, viscoelastic, elastic, shear test

Language: English

No. of pages: 52

Referat

Spårbildning i bitumenbundna beläggningar är en av de vanligaste vägskadorna. Utöver de höga underhållskostnaderna orsakar detta ett stort problem för trafiksäkerheten, eftersom risken för vattenplaning ökar och fordonsstyrningen försvåras. Noggranna och praktiska metoder för prediktering av spårutveckling är avgörande för beslutsstöd i dimensionering och rehabilitering av vägar. Bättre spårmodeller behövs också för att utvärdera nya massabeläggningar samt för att kunna utvärdera effekterna av olika fordonstyper på vägarnas livslängd.

Huvudsyftet med denna rapport är att presentera en sammanfattning av de tillgängliga och praktiska modellerna för prognostisering av spårtillväxt i asfaltlager. Den aktuella litteraturstudien är begränsad till tillgängliga och/eller ofta refererade modeller som validerats mot vägars prestanda. Följaktligen ligger modeller som enbart fokuserar på permanent deformation på materialnivå bortom ramen för föreliggande studie.

Vägkonstruktioner och dess material, trafikparametrar och klimatinverkan som påverkar spårbildning i fält har identifierats. Deras betydelse har utvärderats utifrån de experimentella och numeriska rön som rapporterats i litteraturen. Flera modeller som under senare år föreslagits i litteraturen har sammanfattats tillsammans med de materialkaraktäriseringstester som används i modellerna. De granskade modellernas förmåga att kvantifiera påverkan av olika konstruktions-, material- och trafikparametrar på spårtillväxt hos vägar utvärderas.

Det konstateras att implementering av spårmodeller som innehåller experimentellt uppmätta viskoelastiska och permanenta deformationsegenskaper för asfaltblandningar, är en lovande metodik att förbättra noggrannheten i prognostisering av vägars spårutveckling. I synnerhet eftersom de tillåter kvantifiering av effekten av nya material, t.ex. polymermodifierad, på vägens motstånd mot spårbildning.

Titel:	Asfaltbeläggningars spårtillväxt prognostiseringsverktyg
Författare:	Denis Jelagin (KTH, https://orcid.org/0000-0002-0596-228X) Abubeker Ahmed (VTI, https://orcid.org/0000-0002-6327-4709) Xiaohu Lu (Nynas) Safwat Said (VTI, https://orcid.org/0000-0002-6308-7487)
Utgivare:	VTI, Statens väg och transportforskningsinstitut www.vti.se
Serie och nr:	VTI rapport 968A
Utgivningsår:	2018
VTI:s diarienummer:	2016/0501-92
ISSN:	0347-6030
Projektnamn:	Prognostisering av spårtillväxt - asfaltbeläggningar
Uppdragsgivare:	Vinnova, Trafikverket, SBUF, Nynas AB, DRF, Volvo Technology
Nyckelord:	Spår, asfaltbeläggning, modellering, viskoelasticitet, elasticitet, skjuvning
Språk:	Engelska
Antal sidor:	52

Foreword

The work presented in this report has been carried out as a part of the project Prediction of rut development in asphalt concrete layers, funded by the Strategic Innovation Program (a joint venture by Vinnova, Formas and the Swedish Energy Agency), the Swedish Transport Administration, SBUF, Nynas, Volvo Technology and DRF (Däckspecialisternas Riksförbund). The project aims to implement and evaluate a new asphalt layer rutting model, PEDRO, developed at VTI. As a part of this work, the present study was conducted to examine the recently published research findings regarding the principal parameters controlling rutting accumulation in the field and to review some rational existing asphalt rutting performance models.

The project leader was Abubeker Ahmed (former project leader Safwat Said) and the following people were involved in the project:

Carl-Gösta Enocksson, Trafikverket

Mats Wendel, PEAB

Anders Gudmarsson, PEAB

Roger Nilsson, Skanska

Erik Oscarsson, Skanska

Jonas Ekblad, NCC

Lena Larsson, Volvo Technology

Heléne Jarlsson, Volvo Technology

Ulrik Jönsson, DRF

Denis Jelagin, KTH

Xiaohu Lu, Nynas

Safwat Said, VTI

Abubeker Ahmed, VTI

Linköping March 2018

Abubeker Ahmed
Project Leader

Quality review

An external peer review was performed on 5 September 2017 by the project group (see Foreword). The authors have made alterations to the final manuscript of the report. Research Director Björn Kalman examined and approved the report for publication on 8 March 2018. The conclusions and recommendations expressed are the author's/authors' and do not necessarily reflect VTI's opinion as an authority.

Kvalitetsgranskning

Intern peer review har genomförts 5 september 2017 av projektgruppen (se Förord). Författarna har genomfört justeringar av slutligt rapportmanus. Projektledarens närmaste chef Björn Kalman har därefter granskat och godkänt publikationen för publicering den 8 mars 2018. De slutsatser och rekommendationer som uttrycks är författarnas egna och speglar inte nödvändigtvis myndigheten VTI:s uppfattning.

Contents

Summary	9
Sammanfattning	11
1. Introduction	13
2. Parameters controlling rutting in asphalt layers.....	15
2.1. Asphalt mixture characteristics	15
2.1.1. Binder parameters	15
2.1.2. Aggregate phase parameters	19
2.1.3. Asphalt concrete materials	23
2.2. Traffic parameters	25
3. Experimental methods to characterize rutting resistance of asphalt mixtures	35
3.1. Repeated Load Uniaxial/Triaxial Tests	35
3.2. Shear Box Test	36
4. Rutting performance prediction models	39
4.1. AASHTO Model	40
4.2. CalME	40
4.3. VESYS	41
4.4. VEROAD	42
4.5. PEDRO	42
4.6. Summary and Discussion	43
5. Calibration of performance prediction models	45
6. Conclusions	46
References	47

Summary

Asphalt layer rutting performance prediction tools

by Denis Jelagin (KTH), Abubeker Ahmed (VTI), Xiaohu Lu (Nynas) and Safwat Said (VTI)

Surface rutting is a combination of deformations that correspond to wear of the surface layer, shear distortion of bituminous layers and deformation in the subgrade and unbound layers together with post-compaction due to traffic loading. In addition to the pavement materials' characteristics, local climate and traffic variables are essential factors in the estimation of deformation in the pavement layers. Depression of the road surface is a major concern for traffic safety. The risk of hydroplaning and difficulties in vehicle steering increase with depression or rut development. On one hand, the asphalt industry faces new challenges nowadays with demands for more sustainable and environmental friendly materials and technologies, which cannot be addressed fully without implementing new materials such as polymers and other additives. On the other hand, development and use of heavier and longer vehicles as well as an increasing proportion of wide-base single truck tyres are already a reality. With respect to both implementing new pavement materials and evaluating the impact of new vehicle types on roads' service life, new methodologies for pavement performance prediction are crucial for decision support in pavement design and rehabilitation of roads. A methodology should be technically correct and computationally inexpensive as well as user-friendly in the processing. This study examines available performance models for asphalt layer rutting resistance. The aim of this report is to present a summary of the principal parameters controlling rutting accumulation in the field and to review existing asphalt rutting performance models.

During the last decades, mechanistic analysis of the pavement structures and enhancement of construction materials, specifically using polymer-modified asphalt mixtures, have become crucial for the improvement of the road infrastructure. The linear elastic theory has frequently been used in pavement structure analysis, particularly with respect to its fatigue cracking performance, thus assuming time-independency of asphalt concrete properties. Time- and rate-dependent properties of the asphalt mixtures are, however, key parameters that control the stability of the asphalt concrete layers.

The permanent deformation response of asphalt mixes to loading must be characterized by a rate-dependent constitutive relationship, with a stress analysis being performed for the entire rutting zone (i.e. over the entire lane width) to effectively handle complex constitutive relationships and the transverse distribution of traffic. This relationship should take material behaviour in dilatation under shear and plastic properties into account and must reflect at least the effects of loading time, temperature and stress states. Loading history, e.g. loading time, axle load, wheel lateral position, etc. are therefore essential factors in the analysis of the long-term irrecoverable displacement in bituminous mixtures.

Investigators have outlined a linear viscoelastic analysis for the asphalt materials and estimation of long-term permanent deformation considering a moving rather than a stationary load and with the effect of a wheel lateral position taken into account. It was concluded that permanent displacement does not depend on the elastic properties and the simplest approach is to regard the asphalt materials as linear viscoelastic liquids rather than elastic solids. This approach resulted in several viscoelastic rutting performance models. The goal of the present literature study is two-fold. First, to determine the critical factors affecting the rutting performance of asphalt layers, the research findings concerning the influence of the pavement materials and structural characteristics as well as of traffic parameters on rutting accumulation rate are examined. A review of available experimental and modelling tools for pavements' rutting performance prediction is then performed. It should be emphasized that the present review is limited to available and/or frequently referred to tests and models with an established link to

field rutting performance. Models focusing solely on permanent deformation on the material level are thus beyond the framework of the present study.

In this report several relevant rutting performance models have been examined. As discussed, both elastic and viscoelastic methods are available for predicting asphalt concrete layer deformations. Compared to the elastic stress analysis, viscoelastic models are however both more theoretically correct and more flexible in terms of explicitly incorporating relevant mixture and/or traffic parameters. It may also be concluded that performance models incorporating experimentally measured asphalt mixture permanent deformation properties, e.g. the asphalt's viscosity, are a promising way to go forward, in particular when the effect of novel materials on the pavement's rutting performance is to be evaluated.

Sammanfattning

Asfaltbelägningars spårtillväxt, prognostiseringsverktyg

av Denis Jelagin (KTH), Abubeker Ahmed (VTI), Xiaohu Lu (Nynas) och Safwat Said (VTI)

Spårbildning i bitumenbundna beläggningar är en av de vanligaste vägskadorna. Spår på vägytan har sitt ursprung från bundna och obundna materiallager i vägkroppen samt från undergrunden och bildas som effekt av upprepad trafikbelastning. Förutom materialegenskaper är klimat och trafikparametrar viktiga faktorer för uppkomsten av deformationer i lager och spårbildning på vägytan. Utöver de höga underhållskostnaderna som spårbildning orsakar så är det ett stort problem för trafiksäkerheten, eftersom risken för vattenplaning ökar och fordonstyrningen försvåras. Noggranna och praktiska metoder för prediktering av spårutveckling är viktiga beslutsstöd i dimensionering och rehabilitering av vägar. I synnerhet behövs bättre spårmodeller för att utvärdera nya massabeläggningar samt för att kunna utvärdera effekterna av olika fordonstyper på vägarnas livslängd. Huvudsyftet med denna rapport är att presentera en sammanfattning av de tillgängliga och praktiska modellerna för prognostisering av spårtillväxt i bitumenbundna lager.

Under de senaste årtiondena har mekanistisk-empirisk analys av vägöverbyggnader och användning av nya material, särskild asfaltmassa med polymermodifierade bindemedel, ökat prestanda hos massabeläggningar. Linjärelastisk teori har ofta använts vid analys av vägkonstruktioner med avseende på utmattningsprickor och har förutsatt tidsberoende materialegenskaper. Tidsberoende egenskaper hos asfaltmaterial är dock avgörande vid bestämning av deformationsmotstånd hos massabeläggningar. Av den anledningen måste spårbildning hos asfaltlager analyseras med avseende på deformationshastigheten under belastning. Dessutom måste spänningsfördelning över hela spårzonen med beaktande av trafikfördelning i sidled och inte enbart i en punkt under belastning analyseras för att ta hänsyn till omlagringar i asfaltlagren under skjuvpåkänningar. Det konstateras att asfaltmaterial bör betraktas som en linjärt viskoelastisk vätska snarare än ett elastiskt fastmaterial vid analys av permanenta deformationer. Detta tankesätt har resulterat i flera viskoelastiska spårmodeller.

Målet med litteraturstudien är tvåfaldigt. För det första att bestämma vilka de kritiska faktorerna är som påverkar asfaltlagrens deformationsmotstånd. I detta syfte har forskningsresultat som visar på hur vägkonstruktioner och dess material, trafikparametrar och klimatinverkan påverkar spårbildning i fält identifieras. Dessa faktorerers betydelse har utvärderats utifrån de experimentella och numeriska rön som rapporterats i litteraturen. För det andra har flera modeller som under senare år föreslagits i litteraturen sammanfattats tillsammans med de tester som används för att identifiera modellparametrarna. De granskade modellernas förmåga att kvantifiera spårtillväxt hos vägar utifrån konstruktions-, material- och trafikparametrar har utvärderats. Det bör understrykas att den aktuella översynen är begränsad till tillgängliga och/eller ofta refererade tester och modeller där det finns ett etablerat samband med prestanda i fält. Modeller som endast fokuserar på permanent deformation på materialnivå ligger följaktligen bortom ramen för föreliggande studie.

I denna rapport har flera relevanta spårbildningsmodeller undersökts. Såsom diskuterats är både elastiska och viskoelastiska metoder tillgängliga för att förutsäga deformationer hos asfaltlager. I jämförelse med elasticitetsanalysen är viskoelastiska modeller emellertid både mer tekniskt korrekta och mer flexibla när det gäller att beskriva asfaltmassors egenskaper och trafikparametrar. Vi drar slutsatsen att spårmodeller som innefattar experimentellt uppmätta asfaltbelägningars permanenta deformationsegenskaper, t.ex. viskositet hos asfaltbeläggningar, är speciellt lovande. I synnerhet när effekten av nya material på vägars spårbildning ska utvärderas.

1. Introduction

Surface rutting is a combination of deformations that correspond to wear of the surface layer, shear distortion of bituminous layers and deformation in the subgrade and unbound layers together with post-compaction. In addition to the pavement materials' characteristics, local climate and traffic variables are essential factors influencing deformation in the pavement layers. Rutting is a major concern for traffic safety. The risk of hydroplaning and difficulties in vehicle steering increase with depression or rut development. On one hand, the asphalt industry faces new challenges nowadays with demands for more sustainable and environmental friendly materials and technologies, which cannot be addressed fully without implementing new materials. On the other hand, development and use of heavier and longer vehicles as well as an increasing proportion of wide-base single truck tyres are already a reality. With respect to both implementing new pavement materials and evaluating the impact of new vehicle types on roads' service life, new methodologies for pavement performance prediction are crucial for decision support in pavement design and rehabilitation of roads. The models should be technically correct and computationally inexpensive as well as user-friendly in the processing. This study examines available performance models for asphalt layer rutting resistance. The aim of this report is to present a summary of the principal parameters controlling rutting accumulation in the field and to review existing asphalt rutting performance models.

During the last decades, mechanistic analysis of the pavement structures and enhancement of construction materials, specifically using polymer-modified asphalt mixtures, have become crucial for improvement of the road infrastructure. Optimal rehabilitation, utilization of enhanced materials and reuse of available construction materials to take environmental and economic aspects into consideration require reliable and analytical pavement design models. The linear elastic theory has frequently been used in pavement structure analysis, particularly with respect to its fatigue cracking performance, thus assuming time-independency of asphalt concrete properties. Time- and rate-dependent properties of the asphalt mixtures are, however, key parameters that control the stability of the asphalt concrete layers.

As was proposed by Monismith et al. (1994b), the permanent deformation response of asphalt mixes to loading should be characterized by a rate-dependent constitutive relationship, with a stress analysis being performed for the entire rutting zone (i.e. over the entire lane width), to effectively handle complex constitutive relationships and the transverse distribution of traffic. This relationship should take dilatation under shear and plastic properties into account and must reflect at least the effects of loading time, temperature and stress states. Loading history, e.g. loading time, axle load, wheel lateral position, etc. are essential factors in the analysis of long-term irrecoverable displacement in bituminous mixtures.

Investigators, among others Björklund (1984) and Thrower et al. (1986) have outlined a linear viscoelastic analysis for asphalt materials and estimation of long-term permanent deformation considering a moving rather than a stationary load and with the effect of a wheel lateral position taken into consideration. Thrower et al. (1986) concluded that permanent displacement does not depend on the elastic properties and the simplest approach is to regard the asphalt materials as linear viscoelastic liquids rather than elastic solids. This approach resulted in several viscoelastic rutting performance models, such as the PEDRO model, which is currently being implemented for field performance evaluation under Swedish conditions.

The present literature study is intended to provide a theoretical background for implementation of a viscoelastic asphalt rutting performance model. The goals of the present literature study are therefore two-fold. First, to determine the critical factors affecting the rutting performance of asphalt layers, the research findings concerning the influence of pavement materials and structural characteristics as well as traffic parameters on rutting accumulation rate are examined. Secondly, a review of available experimental and modelling tools for pavements' rutting performance prediction is then performed. It

has to be emphasized that the present review is limited to available and/or frequently used tests and models with an established link to field rutting performance. Models focusing solely on permanent deformation on the material level are thus beyond the framework of the present study.

2. Parameters controlling rutting in asphalt layers

Permanent deformation or flow rutting in asphalt concrete mixtures is defined as accumulated unrecoverable deformation that increases with loading time. Permanent deformation in an asphalt concrete layer is caused by two mechanisms: densification, which is a decrease in volume and increase in density of an asphalt concrete layer, and shear deformations, which are displacements of material at a constant volume. Vertical and lateral migration of material occurs under repeated loading. As stated earlier, the amount of the material displacement is highly dependent on the loading history, i.e. loading magnitude/rate/frequency and lateral distribution. It is also greatly affected by the material properties at elevated temperatures, when the mix characteristics are dominated by the viscous character of the material (Björklund 1984, Thrower et al. 1986, Sybilski 1996, Blab and Harvey 2002, Read and Whiteoak 2003, Bahia 2009, Al-Qadi and Wang 2009).

The key parameters determining the formation of rutting are permanent vertical shear strains induced by heavy vehicles, binder properties and aggregate phase characteristics, in particular aggregate size distribution, and their morphology and mechanical properties. In assessing permanent deformation, binder properties such as softening point, viscosity, complex modulus, G^* , phase angle, δ , and recovery properties are essential to limit rut development. In addition, climate conditions for example daily distribution of temperature are crucial in prediction of rutting.

2.1. Asphalt mixture characteristics

2.1.1. Binder parameters

In assessing permanent deformation (rutting performance), binder properties that are normally used include softening point, viscosity, complex modulus G^* (and phase angle δ), the SHRP rutting indicator ($G^*/\sin \delta$), and elastic recovery properties. These binder parameters are briefly discussed in this section. More comprehensive reviews can be found in BitVal (2006) and FunDBits (2016).

Softening point by the ring and ball test is a traditional parameter that has been used for bituminous binders for a very long time. It is an empirical parameter, defined as the temperature at which a bitumen sample can no longer support a specific steel ball. For conventional and unmodified bitumens, softening point is a good indicator of permanent deformation of asphalt mixtures (BitVal 2006). However, for modified binders, especially with polymers (PMBs), this parameter cannot give relevant information in terms of performance prediction (Lu and Isacsson 1997). One example from the literature is shown in Figure 1 (Roberts et al. 2012), and it was found that the relationship between the wheel tracking rut rate of asphalt mixtures and softening point of the unaged binders became poor ($R^2=0.68$) when PMBs were included for the examination. A similar observation was made for the binders after short-term ageing (RTFOT).

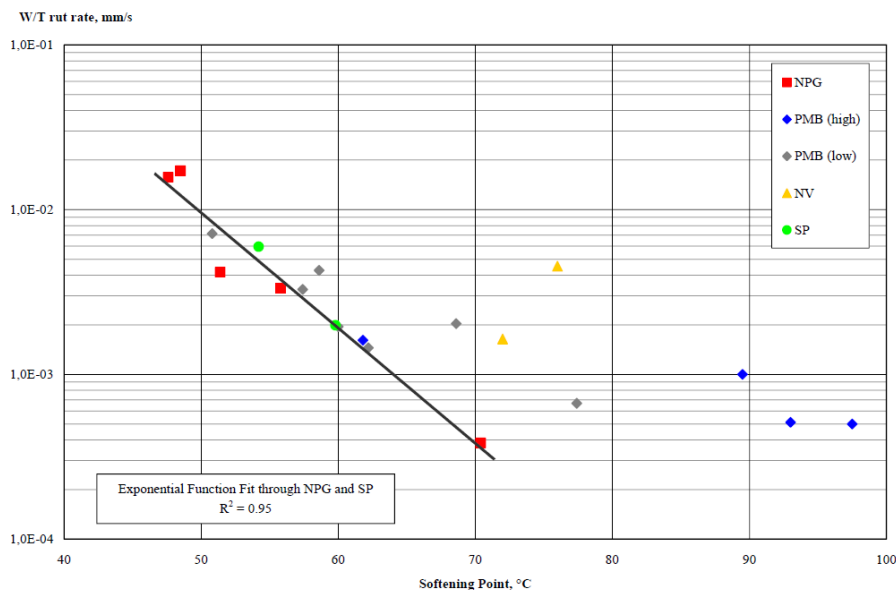


Figure 1. Wheel tracking rut rate at 60°C vs. softening point of unaged binders (NPG = Normal paving grades; PMB = Modified with elastomeric polymers; NV = FT wax modified; SP = Special bitumen) (Robertus et al. 2012).

Viscosity is a measure of a material's flow characteristic. For bituminous binders, different types of viscosity measurement may be applied, including kinematic or dynamic viscosity with a capillary viscometer, coaxial cylinder viscosity test, cone and plate viscosity tests, and zero or low shear viscosity by a dynamic shear rheometer (DSR). In general, there is a correlation between binder viscosity measured using a capillary viscometer and asphalt permanent deformation, but the correlation coefficient is not very high, and in some cases for PMBs, even no correlation can be established (BiTV al 2006; FunDBits 2016). The same statement is also valid for the coaxial cylinder viscosity test and the cone and plate viscosity test.

On the other hand, zero shear viscosity (ZSV) is a more suitable binder indicator of permanent deformation of asphalt concrete mixtures as shown in Figure 2. This property is measured (extrapolated) in a low shear creep test or in a DSR oscillation mode. For many unmodified bitumens, ZSV can be easily obtained. But for polymer-modified binders and waxy bitumen, it might be difficult to precisely define ZSV (Soenen et al. 2006). Viscosities measured at a low shear rate (so-called low shear viscosity, LSV) are also used. Normally, measurements of ZSV and LSV are conducted at elevated service temperatures, where binders are Newtonian. A typical example showing correlations between binder ZSV and asphalt rutting is illustrated in Figure 2. In this figure, different unmodified and polymer-modified binders were studied at 60°C with DSR in oscillation mode at low shear rates and ZSV extrapolated, while the SMA mixtures prepared with those binders were evaluated by means of the Hamburg wheel tracking test at three different temperatures.

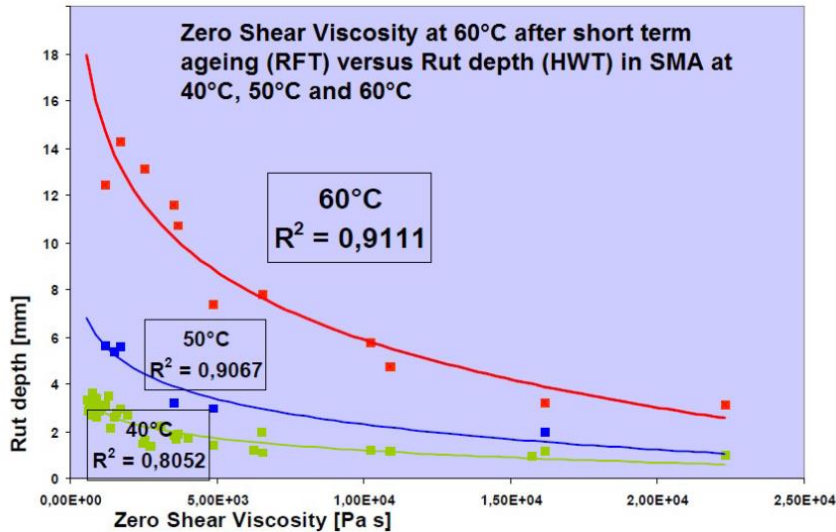


Figure 2. Asphalt rutting versus ZSV of unmodified and polymer modified binders (Guericke and Schlame 2008).

For resistance to permanent deformation, a binder with higher stiffness modulus and/or higher elasticity that results in lower irrecoverable deformation would be preferable. The binder stiffness and elasticity properties can be measured via complex shear modulus (G^*) and phase angle (δ), respectively, with a dynamic shear rheometer (DSR). In general, complex modulus is a measure of the overall resistance to deformation of a binder, while phase angle captures the relative contribution of viscous and elastic parts to the material's response. The importance of these fundamental parameters has been reflected in the American Superpave binder specification, in which $G^*/\sin\delta$ is specified for the rutting resistance. It should be noted that these parameters are determined in the linear viscoelastic region. For unmodified bitumen, correlations between $G^*/\sin\delta$ (or G^*) and asphalt mixture tests are in general good. However, for PMBs, these binder parameters can be problematic for predicting permanent deformation. An example of correlation between asphalt wheel tracking rate and $G^*/\sin\delta$ of the binders is shown in Figure 3. For the unmodified bitumen's alone, the correlation coefficient was found to be 0.99. When the examination was made together with PMBs, the correlation became rather poor ($R^2 = 0.5$).

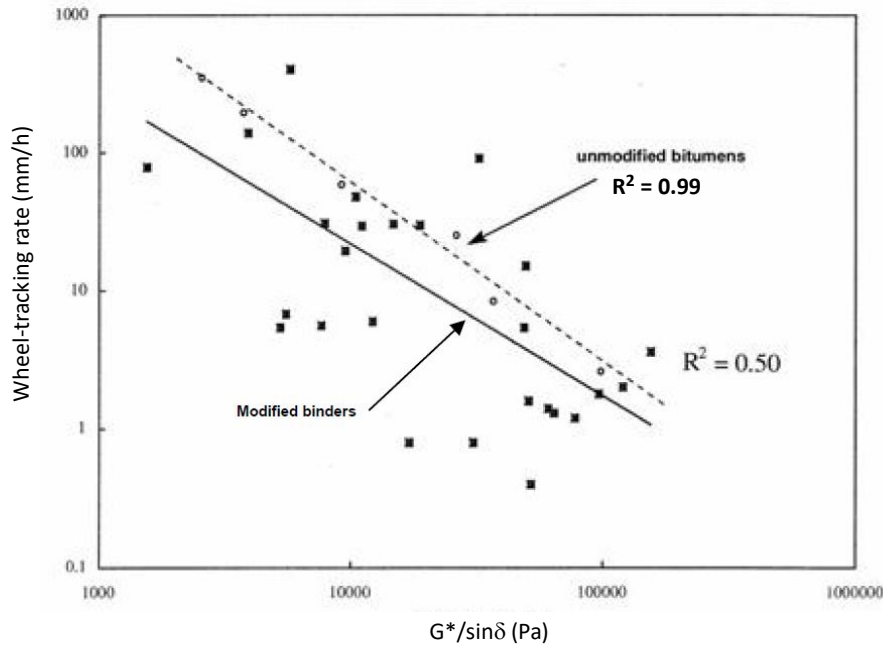


Figure 3. Asphalt wheel tracking rate versus binder $G^*/\sin\phi$ (BitVal 2006).

Recently, based on the creep studies conducted during the NCHRP 9-10 research programme (Bahia et al. 2000), the multiple stress creep and recovery (MSCR) test has been developed (D'Angelo et al. 2007; 2010). The MSCR test is conducted using DSR in creep mode at a specified temperature. The percentage recovery at multiple stress levels is intended to determine the presence of elastic response and stress dependence of bituminous binders. The non-recoverable creep compliance (J_{nr}) at multiple stress levels is intended to be an indicator of the sensitivity to permanent deformation and stress dependence of bituminous binders.

The MSCR test captures the non-linear response of bituminous binders, which has been shown to better relate to mixture rutting performance (Masad et al. 2009), especially for modified binders with different polymers and other additives (D'Angelo and Dongré, 2009; Robertus et al. 2012; Zoorob et al. 2012; Santagata et al. 2015; Lu et al. 2016). By using this test, differences between different binders can be clearly demonstrated, as exemplified in Figure 4. Figure 5 shows a large set of binders (20 in total), including PmBs and special binders, which were tested at both 45°C and 60°C. As shown in the figure, a good correlation was found between the wheel tracking rut rate (small size device) and J_{nr} from the MSCR test. The correlation was much better than with all other investigated binder properties (e.g. softening point, G^* , and ZSV). The correlation was also better with aged binders ($R^2=0,90$) than with fresh (unaged) binders ($R^2=0,79$).

The MSCR test is already standardized and implemented in the American standard specification for performance-graded bituminous binders (AASHTO M332, 2014). Very recently, it has also been standardized in Europe (EN 16659, 2015). However, more experience of this test method is needed, especially with respect to test conditions and the relation to asphalt concrete rutting in the field.

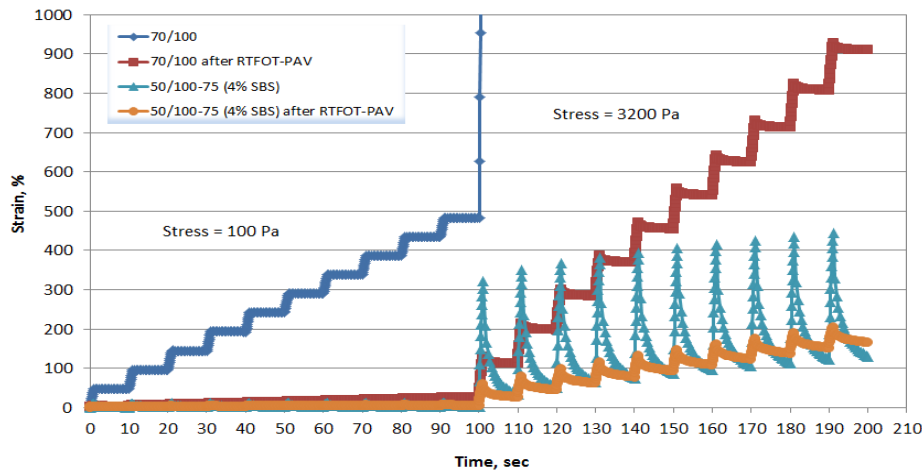


Figure 4. Strain response to repeated loading at 60°C for unmodified and SBS binders (Lu et al. 2014).

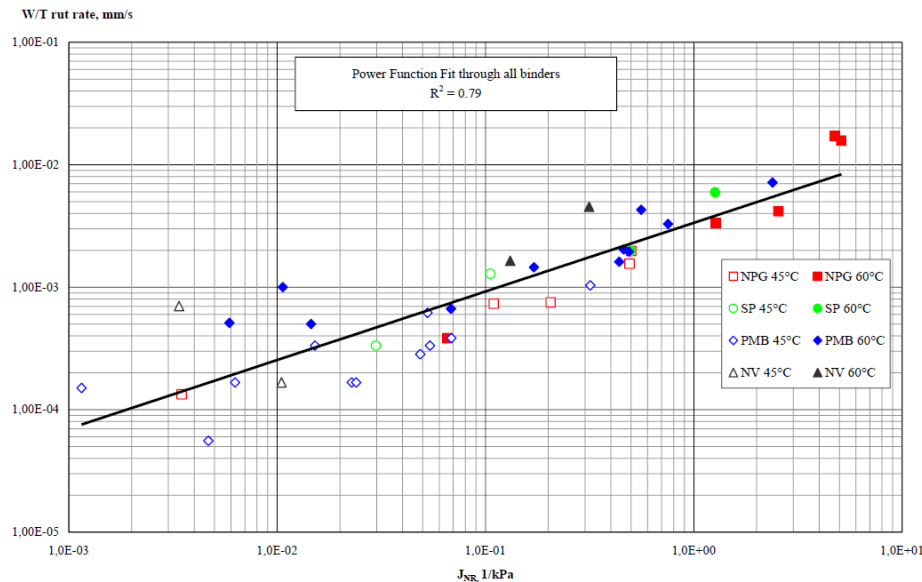


Figure 5. Wheel tracking rut rate vs. J_{nr} of aged binders at 45°C and 60°C (Robertus et al. 2012).

2.1.2. Aggregate phase parameters

Aggregates are the major component of asphalt mixtures and accordingly aggregate phase properties (its gradation, aggregate morphological and mechanical characteristics) have a profound influence on materials' resistance to failure. With respect to rutting accumulation in asphalt layers, aggregate phase properties are of particular importance as the aggregate skeleton provides the main load-transferring mechanism in asphalt mixtures under compression and shear. This is especially so at higher temperatures when binder stiffness is reduced.

Aggregate gradation is one of the most important material parameters for asphalt concrete. A change in the size distribution of aggregates results in a different load distribution over the aggregate skeleton. Denser particle packing increases materials' stability through more inter-particle contacts for load distribution. However, there must be sufficient air void space to permit the bitumen to be incorporated and assure durability without filling all the space to avoid bleeding and/or rutting (Brown et al. 2009).

The first attempts to optimize asphalt concrete gradation were made more than a hundred years ago, and were focused on achieving the densest possible aggregate packing. For cement concrete, Fuller and Thompson (1907) examined the different combinations of stones and sand for concrete mixtures

that would give the densest material. As a guide to obtain the best concrete with constant cement quantity the authors concluded that the stones should be evenly graded, as an excessive amount of fine or medium sizes is very harmful to strength. Talbot and Richart (1923) and Weymouth (1938) evaluated the size distribution of spheres to obtain the densest packing. For asphalt concrete mixtures, Nijboer (1948) investigated the effect of particle size distribution taking shape into account. He found that the densest packing was produced by a size distribution following a straight line in a semi-log plot of the percentage passing a sieve size versus the sieve size. Empirically, it was found that for bituminous materials and aggregates as rough, shaped material, this line had a slope of 0.45.

In the 1980s Bailey developed a gradation analysis method that takes into account the packing characteristics of individual aggregates, providing a quantified criterion that can be used to control mix properties such as workability, segregation and compactibility (Vavrik, et al. 2001). In a mix design with a given compactive effort, three aggregate properties control the packing characteristics: gradation, surface texture and shape. The Bailey method determines coarse fraction as those particles that create voids and fine fraction as those particles that fit into the voids created by coarse aggregate.

Several studies have been conducted to relate the performance of HMA to its gradation. The Asphalt Institute (2001) has in the SuperPave mix design method established control points and restricted zones for gradation curves to control the air void content and provide better performance. Birgisson and Ruth (2001) conducted a study with the purpose of identifying aggregate gradations resulting in high rutting resistance under heavy traffic conditions. The following key characteristics for gradations to perform well have been identified: continuous and well-balanced gradation (from the 1.18, 2.36 or 4.75 mm sizes with a certain reduction or increase in fine aggregate for a filler content of less than 6%). It has to be pointed out, however, that conclusions regarding the influence of gradation on materials' performance are hard to generalize as the asphalt concrete performance will also be affected by other aggregate phase parameters, e.g. aggregate shape and mechanical properties.

However, densest packing is not the only parameter affecting the rutting performance of asphalt mixtures. In particulate materials, the load is transferred through chains of particles and other particles play the secondary role of preventing the load-transferring chains of particles from buckling. A theoretical approach to evaluate coarse aggregate structure based on gradation was proposed by Roque et al. (2006).

Roque et al. (2006) presented a method to identify the size range of the main load-carrying structure in asphalt concrete and relate the quality of this structure to performance. According to Roque et al. the primary load-carrying structure in asphalt concrete is formed by the range of interactive particle sizes, referred to as the dominant aggregate size range (DASR). DASR porosity should be below 48% for the particles to form a continuous contact network in the material. The DASR concept was evaluated using a wide range of mixtures from existing databases. Results indicated that the system could identify those mixtures with poor gradations that resulted in poor rutting performance. Using the DASR model, Guarin et al. (2013) examined how asphalt mixture performance (rutting and cracking) is affected by changes in the bitumen, aggregate smaller than the DASR and air void content. The authors defined so-called Interstitial Component, IC, consisting of bitumen, fines and stones smaller than the ones in DASR. Based on the particle packing theory and volumetric properties of aggregates, Guarin et al. (2013) defined the Disruption Factor (DF) as the ratio of the potentially disruptive IC particles to the volume of DASR voids. The DF was a parameter conceived to evaluate the potential of the IC aggregates to disrupt the DASR structure and accordingly to compromise its performance.

Lira et al. (2013) presented a further development of a gradation-based analysis framework for asphalt mixtures. Similar to the DASR principle, the framework presented by Lira et al. (2013) acknowledges the existence of a primary and a secondary aggregate structure and allows these structures in asphalt concrete mixtures to be detected and described. The identification procedure has however been generalized to allow arbitrary continuous size distributions in aggregate gradations to be taken into

account and to remove the limitation of a 2:1 size ratio between contiguous sieve sizes in DASR analysis.

The gradation-based analysis framework proposed by Lira et al. (2013) has been used to evaluate the performance of several field and laboratory asphalt mixtures and to correlate the observed performance with the quantitative parameters describing the quality of the aggregate skeleton, i.e. relative volume of material forming the primary interactive load-carrying network and the Disruption Factor. In Figure 6 (a) and (b), the laboratory and field rutting performance of several asphalt mixtures is shown as a function of DF. As can be seen from Figure 6, the materials with $DF > 1$ tend to have inferior rutting performance as compared to the ones with $0.5 < DF < 1$. As discussed in Lira et al. (2013), DF captures the relation between the interstitial component and the space available for it in the voids of the primary structure. Accordingly, $DF > 1$ represents a situation when there is an excessive amount of the interstitial component in the material. As a result it disrupts the contacts between the primary structure particles, compromising the materials' load-bearing capacity.

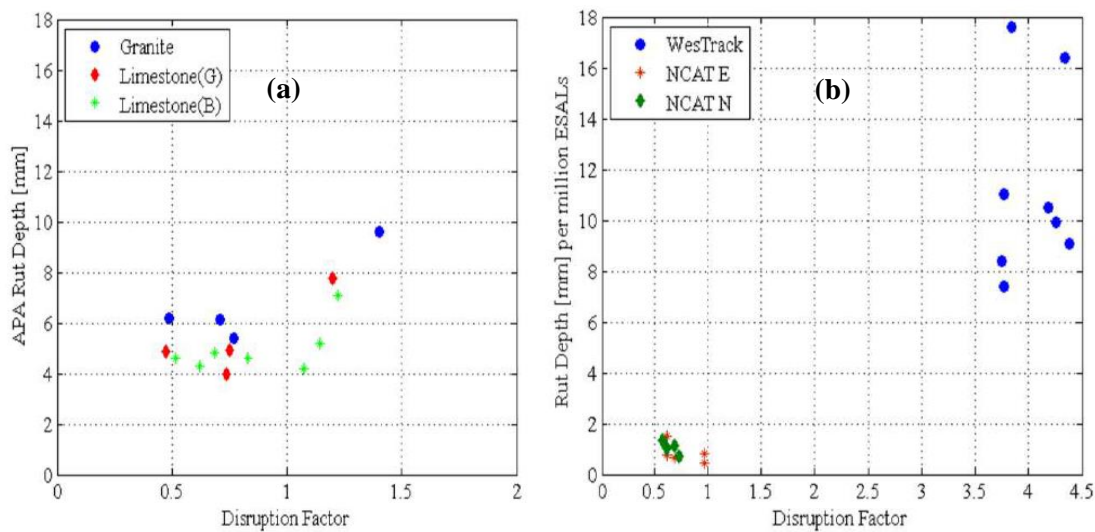


Figure 6. Asphalt concrete rutting performance (laboratory (a) and field (b)) as a function of Disruption Factor. (Lira et al. 2013).

The GB5^R concept of asphalt concrete from EIFFAGE Travaux, named High-Performance Asphalt HPA (Olard 2012) is based on optimization of compaction of the coarser aggregate material. The technique was originally developed to produce high-modulus cement concrete. The principle is to maximize the packing density of granular materials. The objective is to mix different aggregate fractions to minimize voids in mineral aggregate and use the minimum binder content to coat all aggregate particles. The minimum air void content principle is shown in Figure 7. Void index is a relationship between voids and the volume of aggregate material. The highest density is achieved with the least air voids. Through a good contact between the coarse aggregate particles, a high modulus is produced without the use of hard bitumen (10–30 penetration) as is the case in the manufacture of HMA (EME). GB5^R or HPA is an asphalt mix for road bases with a bitumen content of about 4–4.5%. It contains significantly lower bitumen content than the mix EME (5.7%) as a road base mix. Optimization of aggregate grading for asphalt mixes is performed by compaction of coarse and fine fractions in steps (dry without binder) using a gyratory compactor. In Figure 8, typical grading curves are presented for some HPA mixes compared to a standard mix GB2 0/14. Note the particle jumps in HPA grading curves.

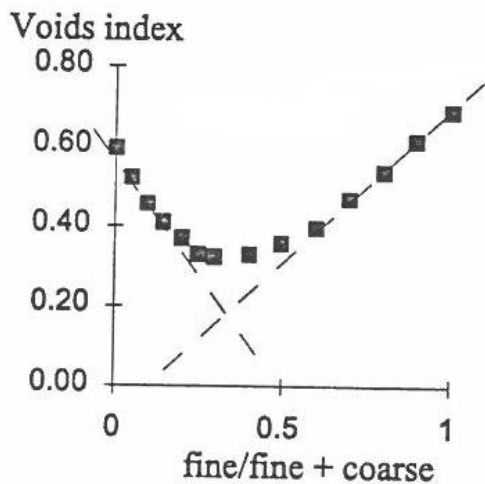


Figure 7. Voids index vs fine grade proportion (de Larrard 2002).

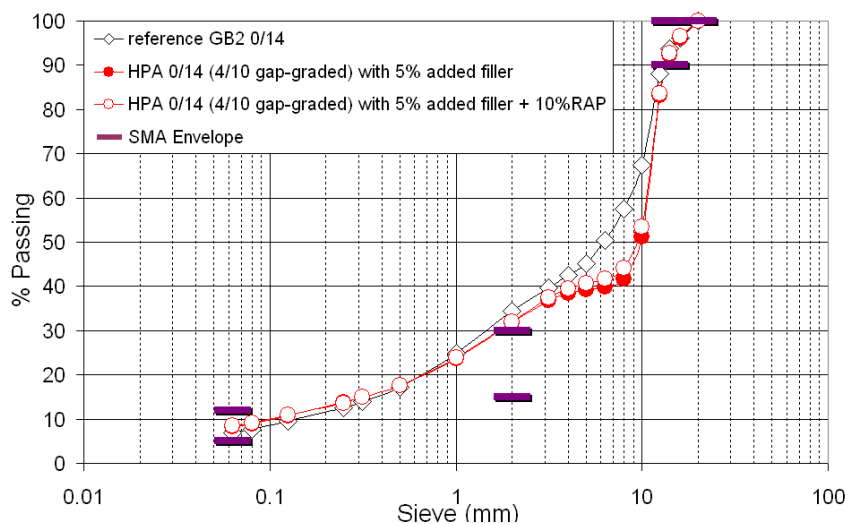


Figure 8. Grading curves for the optimal 10/14 - 0/4 - 0/2 filler vs typical grading curve of the reference mix GB2 (Olard 2002).

In addition to aggregate size distribution, the rutting resistance of asphalt concrete is also affected by the morphological characteristics of the aggregate phase, e.g. Barksdale et al. (1992), Pan et al. (2006), Sefidmazgi et al. (2012), Liu et al. (2017). As discussed in Sefidmazgi et al. (2012), in asphalt concrete the stone-to-stone contacts provide the main load-transferring mechanism, in particular under compressive and shear loading. Accordingly, the characteristics of contact conditions (with respect to contacts' number, orientation and geometry) arising in a given type of asphalt mixture will influence its performance profoundly. Sefidmazgi et al. (2012) proposed a 2D image analysis methodology to measure number and geometrical characteristics of stone-to-stone contact pairs. They have also proposed several indices reflecting the aggregate contact network characteristics. In particular, Sefidmazgi et al. (2012) found a strong correlation between number of contacts and their total length (which also indirectly captures contact curvature) and asphalt concrete performance in a flow number test. Sefidmazgi et al. (2012) also proposed a parameter, called internal structure index (ISI), that captures the combined influence of total contact length and their orientation with respect to the loading direction.

The influence of aggregate morphology on rutting performance has also been examined experimentally by Pan et al. (2006). As shown in their study, based on the results of the flow number test performed on 18 different Superpave asphalt specimens, both aggregate angularity and texture affected the materials' rutting resistance.

It may be pointed out that the results regarding the influence of aggregate morphology on the asphalt concrete rutting performance, summarized above, were obtained based on 2D morphology characterization methods. It may be argued, that potentially better insight into this issue may be obtained with 3D characterization techniques, e.g. X-Ray computer tomography (CT), cf. e.g. Onifade et al. (2016). Based on X-Ray CT measurements, Liu et al. (2017) examined numerically the influence of aggregate morphology on the rutting performance of asphalt mixtures. The primary focus in their study was the aggregate angularity's influence on the asphalt concrete response in uniaxial compressive tests. Liu et al. (2017) showed that aggregate angularity has a profound effect on asphalt's load-carrying capacity. They reported that increasing aggregate angularity below a certain threshold value results in higher effective stiffness of the material. Once the angularity exceeds a certain threshold, further increase results in decreasing the materials' effective stiffness. These observations have been attributed by Liu et al. (2017) to the combined action of two competing effects, both promoted by higher angularity; better aggregate interlock and higher damage accumulation in the asphalt mastics phase.

2.1.3. Asphalt concrete materials

From the results presented in sections 2.1.1 and 2.1.2, it may be concluded that there is strong research evidence regarding the influence of both binder and aggregate phase characteristics on asphalt concrete rutting performance. At the same time, establishing direct correlation between binder and/or aggregate phase characteristics and asphalt's rutting performance is not an easy task, in particular when modified binders are involved. Accordingly, the rheological characteristics of asphalt concrete are needed in the prediction of pavement performance. Shearing and viscosity properties of asphalt concrete are performance indicators of an asphalt mixture's resistance to deformation. Flow rutting is mainly caused by mix displacement at constant volume (Eisenmann and Hilmer 1987, Monismith et al. 2007, 2006), which indicates the importance of the shear resistance of bituminous mixtures. In addition to traffic history, pavement structure and climatic factors, rut depth prediction requires knowledge of the bituminous mix properties in relation to temperature with respect to loading time when the mix properties are dominated by the viscous character of the material. In the range of temperatures of interest in pavement applications, the asphalt materials behave like non-Newtonian materials and the viscosity is thus a function of temperature and loading time. It should, therefore, be of value to know the viscous characteristics of asphalt concrete materials under various conditions. Björklund (1984), Thrower (1986) and Hopman (1996a and b) reported the crucial role of the asphalt concrete's viscosity at the temperatures to which the pavement is subjected for application of viscoelastic models in predicting permanent deformation in asphalt concrete layers. The viscous response of bituminous mixtures can be determined by mechanical testing of, for example, the shear resistance of the mixes (Mezger 2011, van Wazer et al. 1963, van der Poel 1954, Airey 2001).

An example of the influence of mix variables on asphalt concrete properties is shown in Figure 9. The influence of binder type and aggregates characteristics on mix performance with respect to shear dynamic moduli and phase angle is clear.

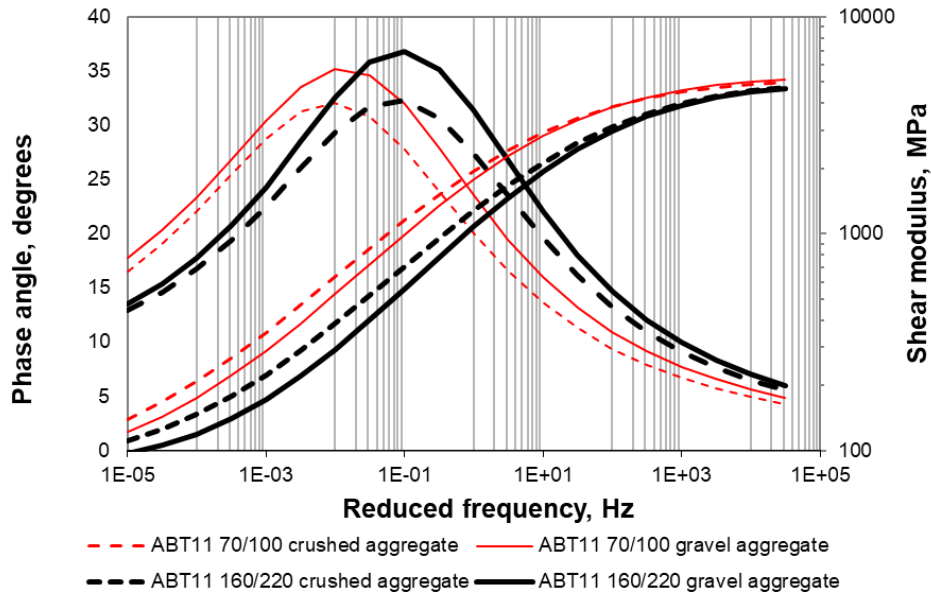


Figure 9. Master curves of the shear moduli and phase angles of asphalt mixes at 10°C (Said et al. 2013).

The viscosity of asphalt materials is determined from the master curves (Eq. 1) of shear modulus and phase angle. For practical use, the master curves may be fitted to mathematical functions presented by Said et al. (2013). Gudmarsson (2014) used analytical models, HN (Havriliak–Negami) and 2S2P1D (Olard and Di Benedetto, 2003) models, to describe the moduli and the phase angle of a viscoelastic material.

$$|\eta^*| = \frac{|G^*|}{\omega} \quad (1)$$

Where, η^* is complex viscosity (MPa s), G^* is complex shear modulus (MPa) and ω is angular frequency (rad/s).

In the linear viscoelastic constitutive formula for estimation of permanent strain (e.g. in PEDRO and VEROAD), it is stated that the steady state (zero) shear rate viscosity (ZSV) of the AC is used. Hopman and Nilsson (2000) and Nilsson (2001) suggested using the zero-shear rate viscosity presumed at an indicative temperature (50°C). Oscarsson (2011) predicted the zero-shear rate viscosity of bituminous materials using a frequency sweep test and the master curve of the mix. In the determination of the ZSV of an asphalt concrete material, the calculated apparent viscosity based on measured data must be extrapolated to the steady state shear rate viscosity, for example using Cross's extrapolation model. The reliability of the extrapolation depends on the lowest testing frequencies being as close to zero-shear rate as possible and this depends on the extrapolation model (Oscarsson 2011). This is could be practical for liquid material (ex. Bitumen) but complicated for solid material like asphalt concrete mixes. On the other hand, a linear viscoelastic model (e.g. PEDRO and VEROAD) assumes that the ZSV is used in the constitutive equation. The ZSV (Newtonian behavior – independent of loading time) is not a usual case under moving vehicles since the asphalt material under a moving load behaves as non-Newtonian material. However, the apparent viscosity, unlike the ZSV, is dependent on the strain rate, which is related to vehicle speed. Not using the ZSV may violate the assumption of the LVE. Nonetheless, using viscosity at peak phase angle (Said et al. 2013) is quite related to low-shear rate viscosity or zero-shear rate viscosity. It is a parallel shift to a somewhat lower level of viscosity, see Figure 10 with $R^2 = 0.997$. Note that the ZSV results in a very small amount of deformation and viscosity at peak results in a large amount of deformation. Both methods need an adjustment factor in prediction of rutting. In addition to the simplicity of the test of viscosity at peak

phase angle, it has higher reliability and no extrapolation is needed in comparison to the determination of the ZSV. The latest version of PEDRO, therefore, recommends using the viscosity at peak phase angle (Said et al. 2014, 2017) to make it more user-friendly. Figure 11 shows examples of some earlier measurements of viscosity at peak phase angle in laboratory-compacted specimens and cores from field at 20°C collected from various projects indicating reasonable values.

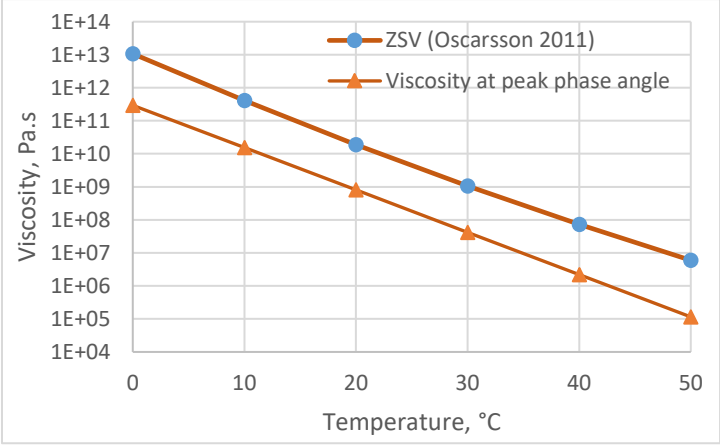


Figure 10. Zero-shear viscosity compared to viscosity at peak phase angle ($R^2 = 0.996$), mix ABT11 70/100, based on the same data.

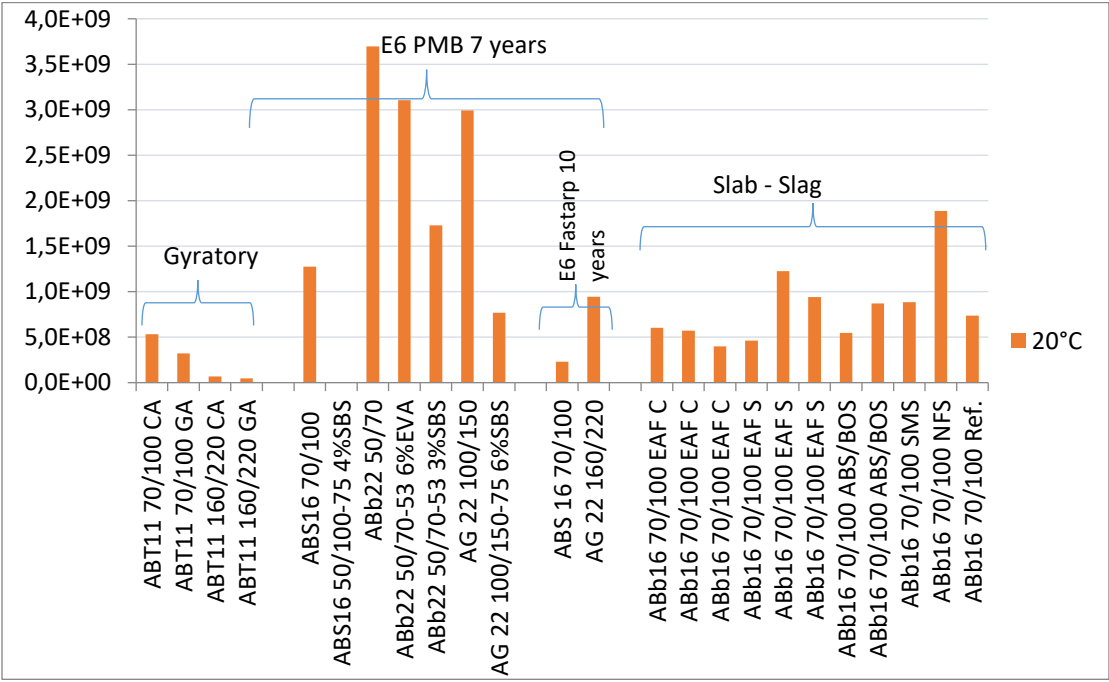


Figure 11. Examples of viscosity at peak phase angle at 20°C.

2.2. Traffic parameters

As discussed above, the rutting in flexible pavements is a result of permanent deformation accumulation in a road’s structural layers due to traffic loading. The traffic load parameters (magnitude, frequency and spatial distribution) therefore have a substantial impact on the rate of rutting in the field. In addition to traffic load parameters, the distribution (and orientation) of contact

tractions arising at pavement-tyre interface are highly affected by the tyre's design and inflation pressure.

At present, innovative vehicle and vehicle component designs are proposed by the industry, driven primarily by the need to reduce fuel consumption and limit environmental impact associated with freight transport. A trend to move towards longer and heavier trucks, i.e. High Capacity Transport (HCT), driving support systems allowing truck platooning, as well as new truck tyre designs with reduced rolling and improved wear resistance are major examples in this context, Vierth et al. (2008), Varin et al. (2014). Assessment of the effect of new vehicles and vehicle component designs on the pavement service life is therefore a crucial component for evaluation of the full socio-economic effect of the transport technology innovations outlined above.

A considerable amount of research has been done in recent decades to examine various aspects of dynamic vehicle-road interaction through experimental, numerical and field observations. A comprehensive literature review on the subject is beyond the scope of this section. Representative results from previous studies concerning the influence of traffic parameters are however summarized below, as pertinent to the following major aspects:

- Dynamic axle loads arising from truck-road interaction,
- Influence of tyre design on contact tractions at pavement surface,
- Influence of traffic speed, density and spatial distribution.

Traffic loads applied to the pavement are controlled by the dynamic interaction of vehicles with the pavement surface and may considerably exceed the static axle loads. Cebon (2000) argues that dynamic effects are responsible for roughly 20–30% of pavement damage increase. The magnitude of dynamic loads depends on vehicle design parameters (geometry, axle loads, tyres, suspension system), pavement surface profile and driving scenario. In Figure 12, the amplitude of the dynamic component of vehicle axle load is shown for vehicles' passage at a velocity of 30 m/s along two road profiles. Results are obtained based on the quarter car truck model, cf. Khavassefat et al. (2015). In Figure 12, profile 1 has an international roughness index (IRI) of 0.99 m/km and corresponds to a relatively smooth road. Profile 2 has IRI=2.3 m/km, thus representing a rough road surface. As may be seen from Figure 12, the rough pavement surface profile results in a maximum force amplitude approximately 40% higher than for the smooth surface.

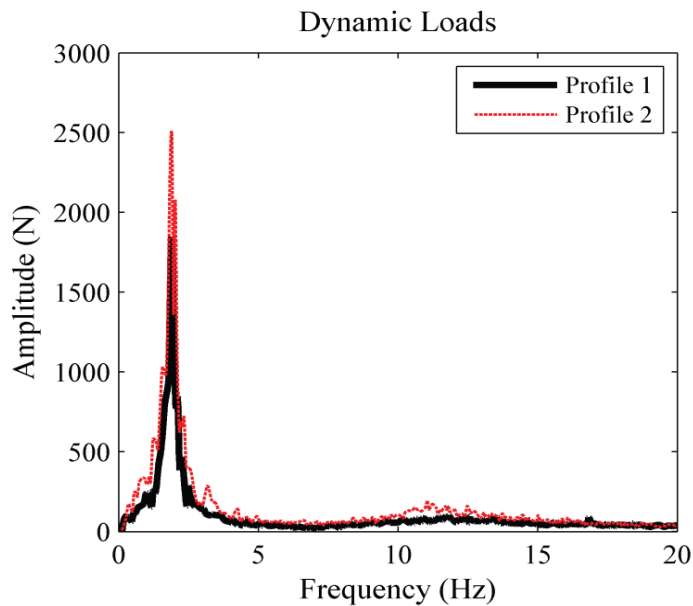


Figure 12. Dynamic load component of a quarter car model for smooth (profile 1) and rough (profile 2) pavement surface profiles (Khavassefat et al. 2015).

The dynamic loads presented in Figure 12 are limited to the dynamic component of normal load for the truck moving at constant speed. It might be argued that the quarter car model is too simplistic to capture all aspects of truck dynamics. This is in particular the case, when the dynamics of longer vehicles are of interest in driving scenarios different from free rolling, e.g. acceleration or braking, cornering or driving over a pothole. An illustration of these effects is shown in Figure 13 and Figure 14, where the evolutions of dynamic axle loads at the steering axle are shown for the cases of truck braking and driving over a pothole. In these figures, results are obtained with a full 3D dynamic model of a 5-axle truck; the braking scenario is represented with 6 m/s deceleration from 90 km/h and pothole has a parabolic profile in the longitudinal direction of 1 m in length and 5 cm maximum depth. As can be seen from the figures, 3D dynamic effects may result in a significant increase in both normal and longitudinal axle forces.

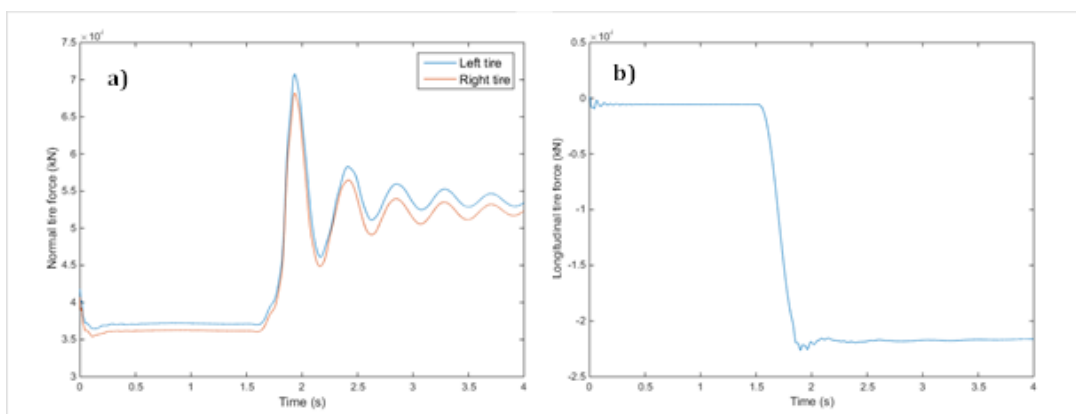


Figure 13. Forces on steering tyres when braking: (a) normal, (b) longitudinal.

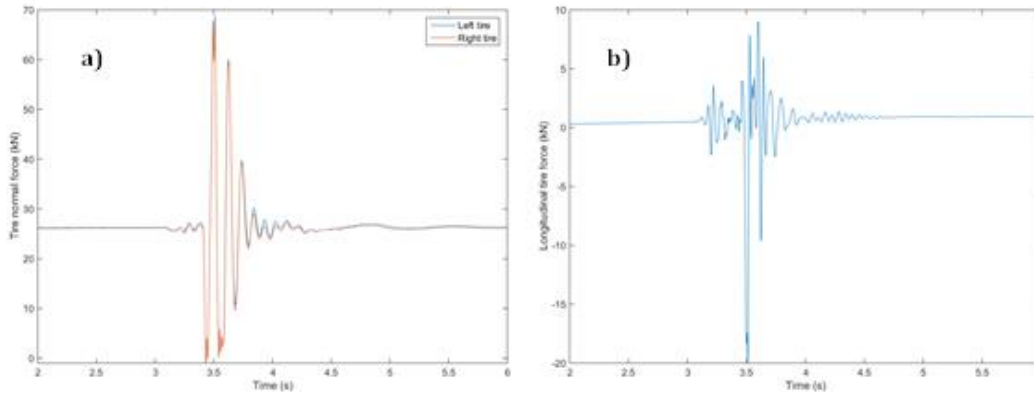


Figure 14. Forces on steering tyres when driving over a pothole: (a) normal, (b) longitudinal.

It is also well established through both experimental measurements (e.g. De Beer et al. (1997)) and numerical modelling (e.g. Wang (2011)) that contact stresses at the tyre-pavement interface are non-uniform and have both normal and tangential components. The latter are in turn composed of both longitudinal and transverse tractions. The stress concentrations arising at the tyre-pavement interface due to the presence of non-uniform tyre tread are quite high, in particular when tyre inflation pressure and/or axle load deviate significantly from the design values, cf. De Beer et al. (1997). The magnitude of this effect as measured experimentally is illustrated in Figure 15, as reported in the De Beer et al. (2005) study.

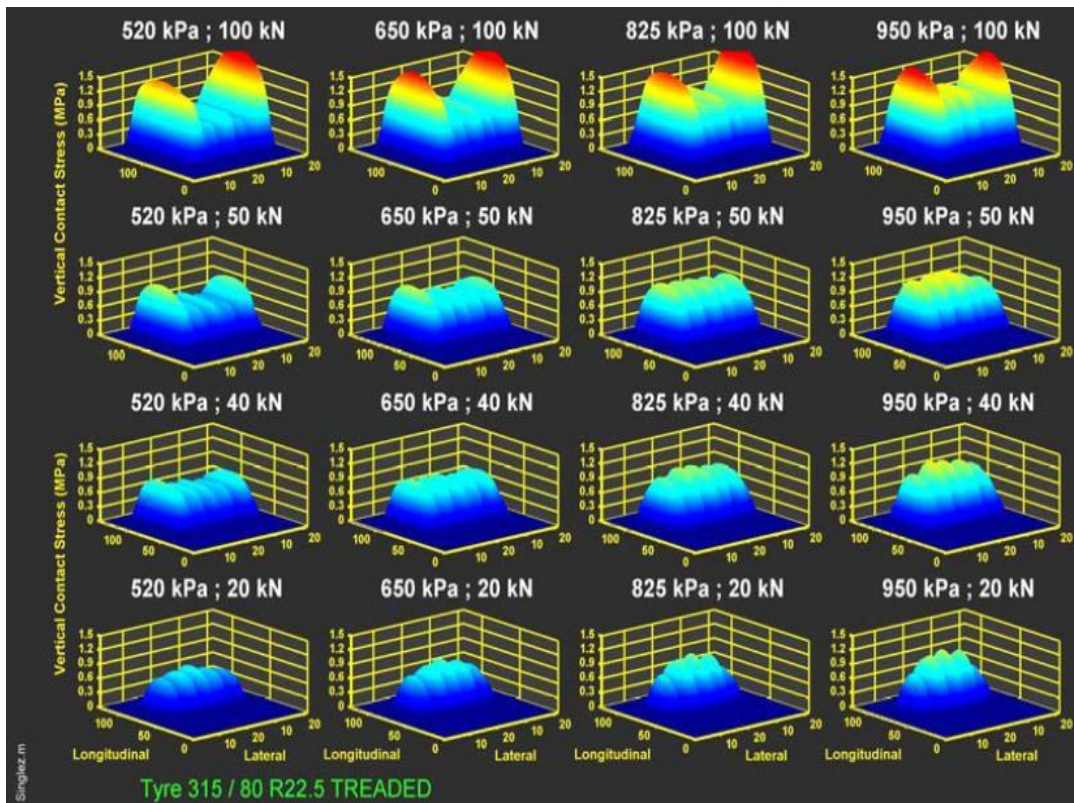


Figure 15. Contact pressure distribution at different axle loads and inflation pressures (De Beer et al. 2005).

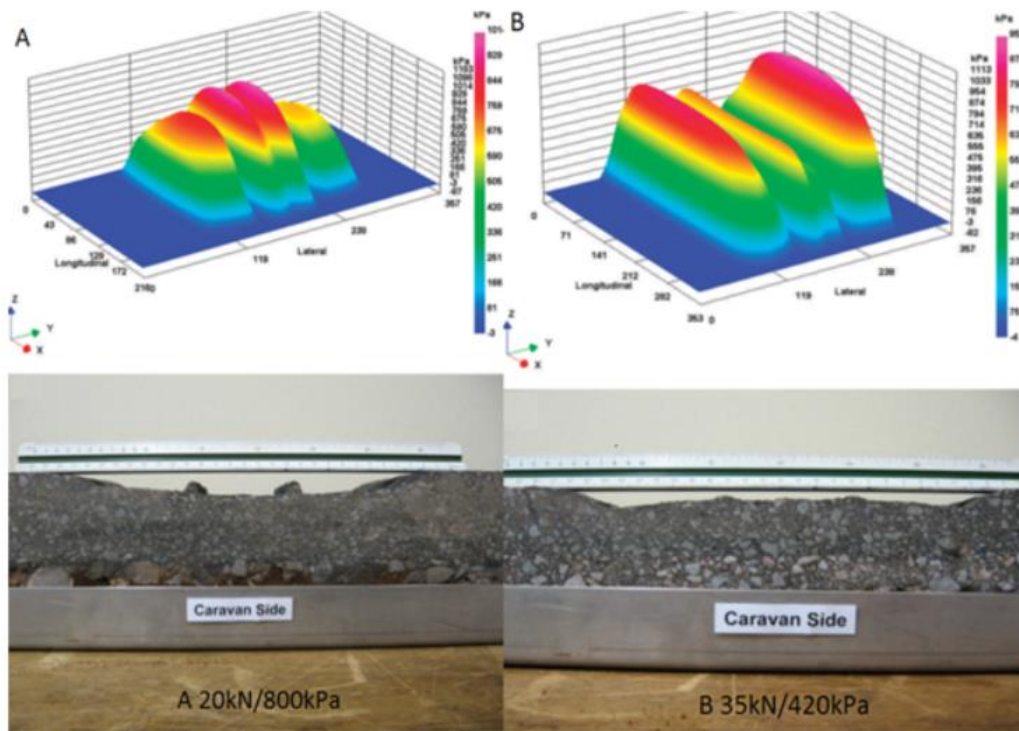


Figure 16. Rutting profile at different tyre pressure distributions (De Beer et al. 2005).

As shown in several studies, the characteristics of tyre contact pressure as well as of the size and shape of the contact patch substantially affect the pavement failure modes originating in the upper layers, i.e. fatigue cracking, rutting of asphalt layers, and, in case of thin asphalt overlays, rutting in unbound base layers, cf. e.g. Karlsson (2016). The influence of tyre parameters on permanent deformation accumulation in asphalt layers is illustrated in Figure 16. Based on the FE simulation of radial-ply tyre stress, Wang (2011) reports concentrations of approximately 150% as compared to the tyre inflation pressure. The tyre-pavement contact patch shape has also been found to be closer to a rectangle than to a circle due to the tyre's structural characteristics, cf. Al Qadi et al. (2008). Based on the measured contact stresses, Al Qadi et al. (2008) evaluated the relative fatigue and rutting damage induced in pavements by a passage of dual tyre respective wide-base tyre. The main focus in their study was secondary roads, i.e. roads with relatively thin asphalt layers, and it was shown that tyre type has a significant impact on the amount of pavement damage.

The effect of tyre choice on pavement damage was shown by Al Qadi and Wang (2009) to be dependent on pavement structure, temperature, layers' mechanical properties as well as on the damage model assumed. As reported in Al Qadi and Wang (2009), wide-base tyres cause approximately 1.5-2.5 times more damage with respect to fatigue cracking and rutting (due to combined permanent deformation in asphalt and unbound layers) than the dual ones. At the same time, Al Qadi and Wang (2012) show that the calculated maximum vertical shear strains induced in HMA layers were somewhat smaller in the case of wide-base tyres compared to dual tyres. It is therefore suggested in their study that new generations of wide-base tyres have the potential to reduce near-surface damage modes in asphalt layers (i.e. rutting due to permanent deformation of asphalt layer and top-down cracking).

Figure 1 shows the in-depth vertical shear strain distribution in the asphalt layer under dual and wide-base tyres. The results obtained based on 3D FE numerical analysis show that the new generation of wide-base tyres may induce somewhat smaller vertical shear strains at elevated temperatures than dual tyres (Al-Qadi and Wang 2012). Figure 18 shows the impact of the change in wheel load (8–14 kN

simulating extra-large wheel tracking test) and tyre inflation pressure (0.6– 1.2 kPa) on shear distribution in an asphalt concrete layer at 40°C (Said and Hakim 2016). It was found that the compressibility is mainly affected by the wheel load magnitude at constant tyre pressure (Figure 18a), whereas a change in tyre pressure (Figure 18b) has a certain effect on the deformation down to a few centimetres from the surface (with the influence of tyre pressure basically vanishing below 10 cm from the surface). It was also found that the shear flow in the upper layer region is affected by changes in both wheel load and tyre pressure. In lower regions, however, the shear rutting is only influenced by changes in the wheel load. Comparing Figure 18a with Figure 18b with respect to total deformation (integrated over the asphalt concrete thickness of 400 mm), it can be concluded that a change in tyre pressure would result in less variation in the total deformation compared to the tyre load over an expected range of variation of those parameters in the field. Ahmed et al. (2017) reported damage per ton for the new longer and heavier truck types. According to their study new truck types may produce less damage per ton of goods than a conventional truck fleet, cf. (Table 1).

Table 1. Damage per ton of three longer and heavier vehicle scenarios at 25°C derived from triaxial tests.

LHV type	Strain level ($\mu\epsilon$)	Damage per ton at 25°C
8-axles	4 000	1.00
9-axles	4 000	0.88
11-axles	4 000	0.57

However, Salama et al. (2007) reported from a mechanistic analysis of a flexible pavement that whether there is strain interaction between axles or not in asphalt concrete layers, Axle Factors (AF is a ratio of the damage of an axle group to the damage of a single axle) are proportional to the number of axles, i.e., the damage is proportional to the gross load carried by the axle group. The authors noted that these results should be confirmed further.

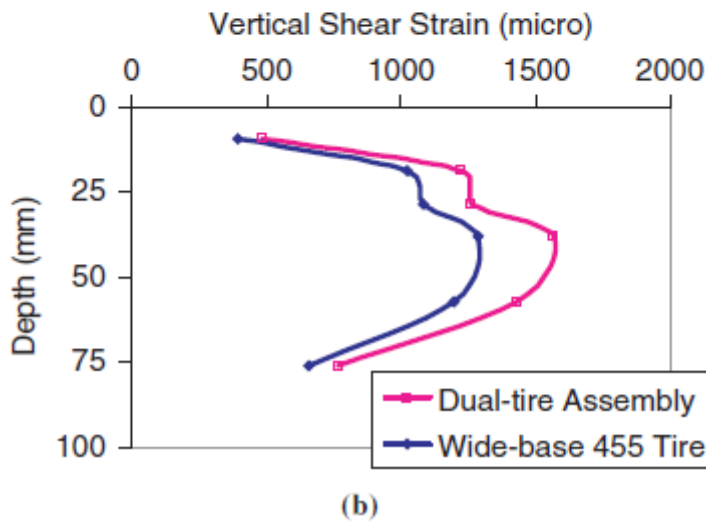
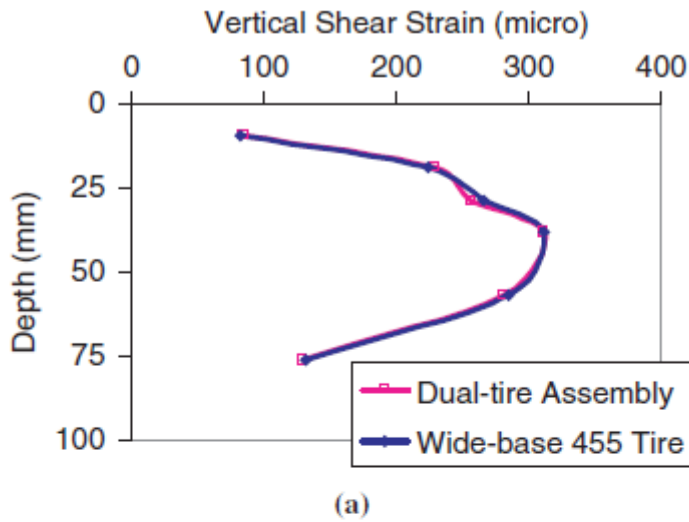


Figure 17. Effect of wide-base 455/55R22.5 compared to dual 11R22.5 tyre on in-depth shear strain distribution induced by 35.5 kN, 724 kPa and 8 km/h at (a) 25°C and (b) 47°C (Al-Qadi and Wang 2012).

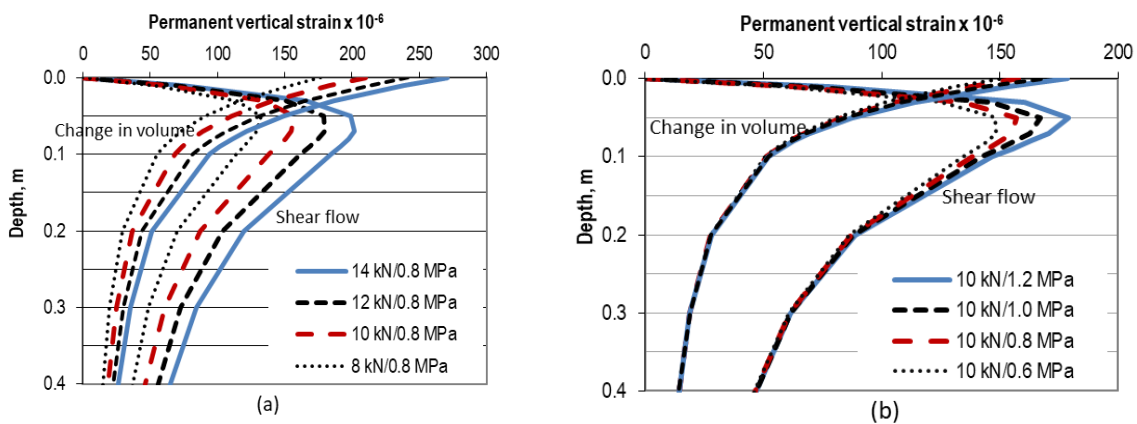
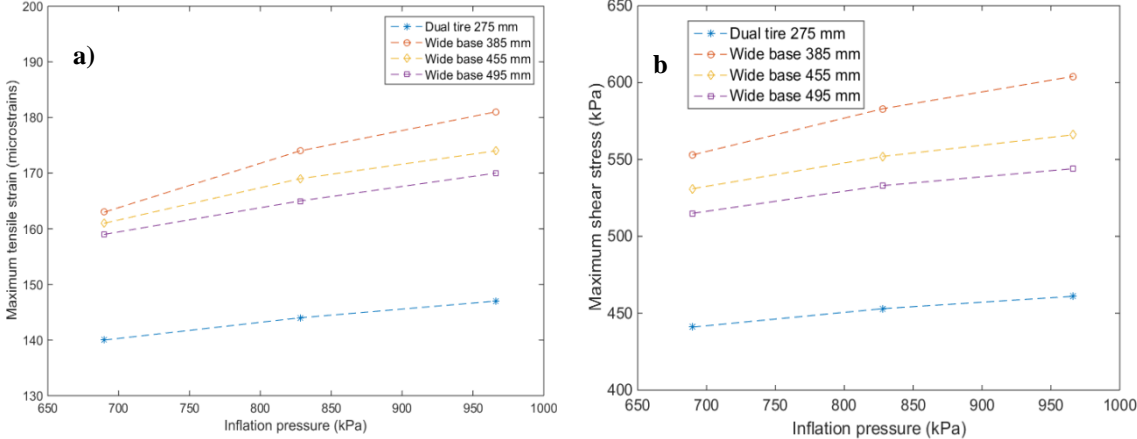


Figure 18. In-depth vertical strain distributions due to compressibility and shear flow (a) at different wheel load, (b) at different tyre pressure.

In addition to dynamic axle loads and tyre type, tyre inflation pressure may significantly affect both the magnitude and the distribution of contact stresses at the tyre-pavement interface. The influence of tyre inflation pressure on maximum tensile strains and maximum shear stresses induced in the asphalt layer is illustrated in Figure 18 as obtained with 3D FE simulations. In the simulations, contact tractions at the pavement surface were assumed to be equal to tyre inflation pressure and the contact area was assumed to be rectangular with a width equal to the tyres' structural width and length determined from equilibrium considerations.



Figur 19. First principal strain (a) and maximum shear stress (b) induced in the asphalt layer.

Asphalts' non-linear and rate-dependent mechanical behavior, i.e. materials' viscoelastic, plastic and viscoplastic properties, results in the pavement response being dependent on traffic speed and density. In particular, asphalts' viscoelasticity received considerable attention in the literature, cf. Nilsson (1999). As reported in Khavassefat et al. (2012), in the presence of viscoelastic effects in the asphalt layer, the stress state induced in the pavement structure becomes dependent not only on axle loads but also on traffic speed and density and results in tensile stress build-up on the pavement surface. In Figure 19 (a, b) maximum tensile stress evolution with truck passages is shown at the top and bottom of the pavement. Results are presented for two different truck types, 5- and 7-axle, as well as for the traffic passing at two different speeds, 10 km/h and 100 km/h, cf. Khavassefat et al. (2012). As may be seen from Figure 19, there is an accumulation of tensile stress at the pavement surface accompanied by a small reduction in tensile stress at the bottom of the asphalt layer. The magnitude of those effects is also very dependent on truck type and speed. The effect of asphalts' plasticity and viscoplasticity on pavement response to dynamic loads is a much less explored topic. This is primarily due to the lack of well-established asphalt material and failure models incorporating those effects.

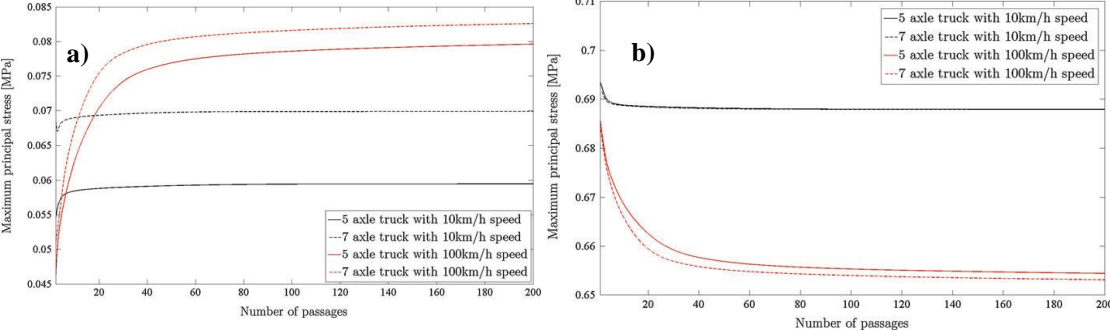


Figure 19. Maximum principal stress at the surface (a) and the bottom (b) of an asphalt layer. (Khavassefat et al. 2012).

The lateral wander of traffic is a crucial factor in predicting the deterioration of a road, as it influences the stresses' and strains' distributions in the pavement structure (Blab et al. 1995, Siddharthan et al. 2017) as well as surface rutting. Carlsson (2009) reported rut development on barrier-separated sections of a 2+1 lane road (alternating between single and double sections). It is concluded that a more than 40 percent change in surface rutting of more than 40 per cent might be related to the lateral wander of vehicles. A vehicle's position can vary depending on road type and lane width, as illustrated in Figure 20 and Figure 21 (McGarvey 2016).

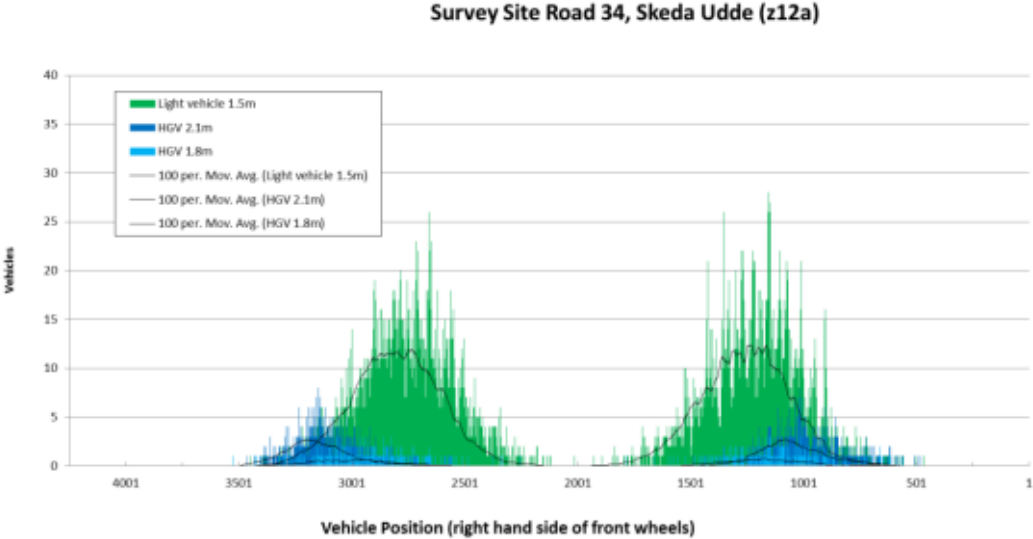


Figure 20. Distribution of wheel lateral position, Road 34 (2+1 road) (McGarvey 2016).

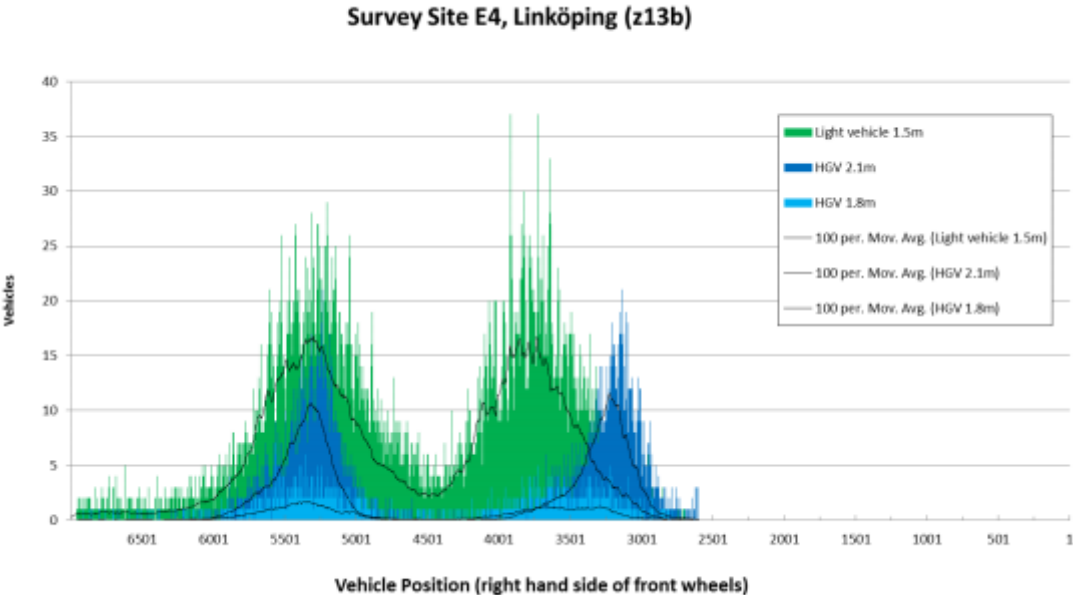


Figure 21. Distribution of wheel lateral position, motorway E4 (McGarvey 2016).

Siddharthan et al. (2017) reported that the procedures in the AASHTO M-E PDG and CalME methodologies to address the influence of wheel wander are relatively simple and suffer from the major limitation that vehicle position distribution is arbitrary and can, therefore, lead to biased results.

Erlingsson et al. (2012) reported the predicted differences using the M-E PDG procedure resulted in only a 4-5 per cent increase in rutting as the standard deviation of vehicle wander decreased from 0.285 to 0.235 m. However, using the PEDRO approach resulted in approximately 20 per cent for the same change in the standard deviation. The impact of wheel wander using PEDRO is in good agreement with Carlsson’s (2009) observations considering only the rutting in bituminous layers. In the PEDRO model, the influence of vehicles’ transverse position on rut profile is calculated at each 1 cm segment covering ± 1.25 m from the loading centre. The vertical strain distributions in a pavement structure in respect of wheel position are illustrated in Figure 22. The sum of deformation from all vehicle lateral positions, using a predefined standard deviation of a specific road section, results in a reasonable rutting transverse profile including upheavals.

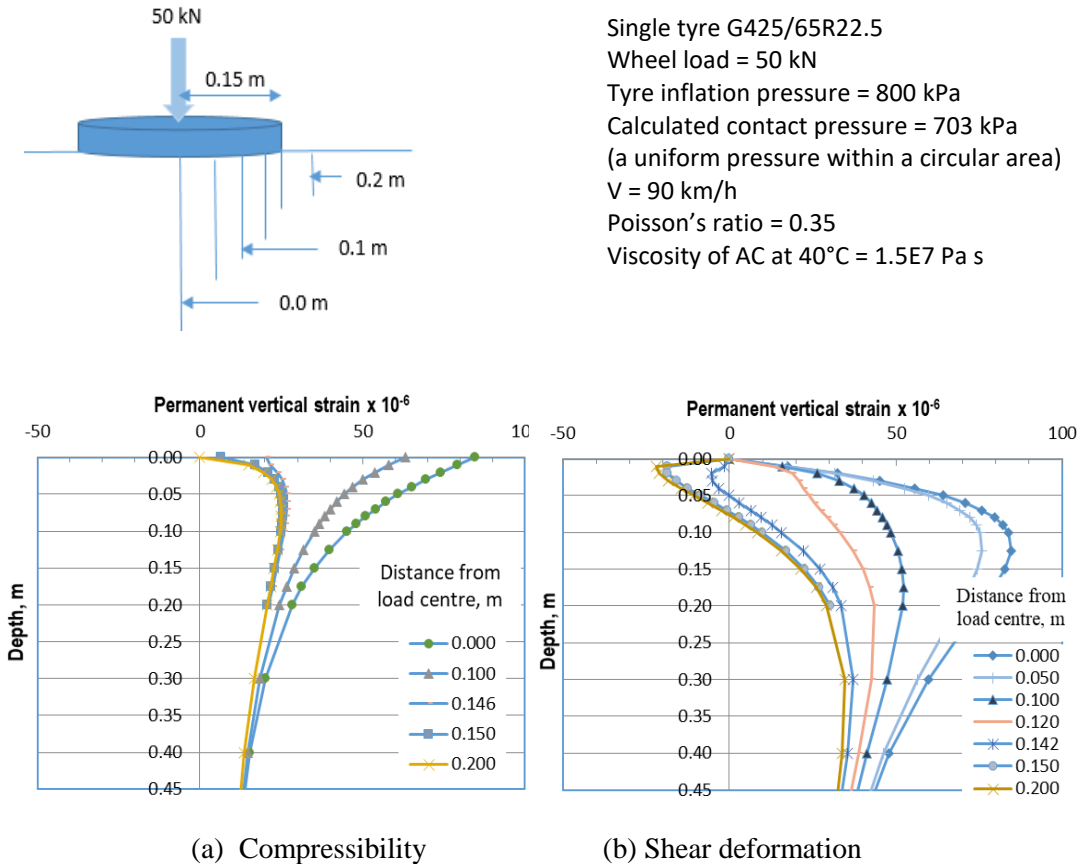


Figure 22. Vertical strain distributions as a function of depth and distance from loading centre in a pavement related to (a) compressibility (decrease in volume), (b) shear deformation at constant volume (Said and Ahmed 2017).

3. Experimental methods to characterize rutting resistance of asphalt mixtures

Several attempts have been made to propose asphalt concrete test methods correlating to the materials' field performance with respect to rutting. At the material level, all the proposed test methods focused on measurement of materials' viscoelastic and/or permanent deformation properties under either normal compression or shear. Furthermore, several testing procedures were proposed with an aim of representing idealized or down-scaled field conditions, e.g. wheel tracking tests. The present report, however, is focused on material-level tests, which can be used to determine the material parameters used in rutting performance models. The empirical performance tests are thus beyond the scope of this report.

3.1. Repeated Load Uniaxial/Triaxial Tests

In a uniaxial test, a cylindrical specimen is loaded repeatedly in axial compression and the resulting axial deformation is measured. With the addition of confinement pressure to an axial test, the test becomes triaxial. The triaxial test thus allows a more accurate representation of the real stress distribution in a pavement system as it simulates the level of confinement that may exist in the field. Both uniaxial and triaxial tests have been used to study the permanent deformation behaviour and/or to determine the linear viscoelastic properties of bituminous materials. The AASHTO Asphalt Mixture Performance Tester (AMPT) may be used to conduct uniaxial or triaxial tests, including the frequency sweep procedure for determination of master curves of dynamic modulus and phase angle.

The repeated loading with rest period is the preferred loading type to determine the resistance to permanent deformation of specimens having a diameter of 100 mm and a height of 150–200 mm. On the other hand, a repeated sinusoidal loading is applied to establish the linear viscoelastic properties such as the Complex or dynamic modulus and phase angle of bituminous mixtures. Frequency sweep dynamic modulus test at several temperatures was recommended as a simple performance test to complement the mixture design process under the US National Cooperative Highway Research Program (NCHRP, 2002). For linear viscoelastic materials such as bituminous mixtures, the stress–strain relationship under a continuous uniaxial sinusoidal loading is defined by a complex number called the complex modulus. Figure 23 presents an actual test set-up for the dynamic modulus test and typical loading types. Dynamic modulus tests are usually conducted on unconfined cylindrical specimens having a height to diameter ratio of 1.5. The dynamic modulus is the ratio of the peak stress (σ_o) to peak recoverable strain (ϵ_o). The phase angle, ϕ , is simply the angle at which ϵ_o lags σ_o , and is an indicator of the viscous (or elastic) properties of the material under consideration.

In general, for a purely elastic material, $\phi = 0^\circ$ and for a purely viscous material, $\phi = 90^\circ$. A value between 0 and 90° is observed for bituminous mixtures.

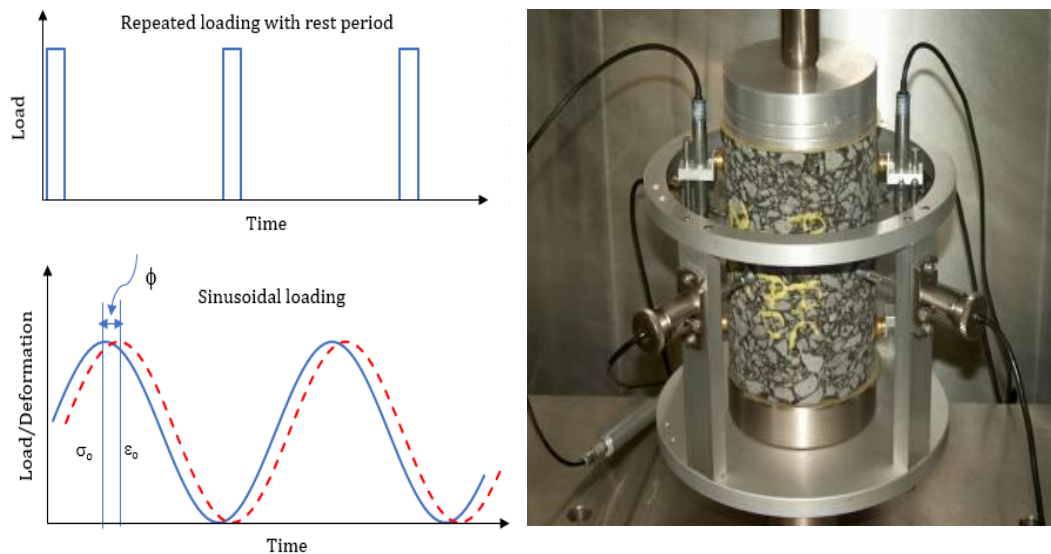


Figure 23. Triaxial test set-up.

3.2. Shear Box Test

Different types of shear test have been used to subject a specimen to shear forces. Junker (1987) induced shear stresses in a cylindrical specimen by means of a rod glued in a hole drilled in the specimen (Figure 24). In the SHRP study (Monismith et al. 1994, Sousa 1994), an advanced shear machine was developed (Figure 25). The test was conducted with a constant specimen height using two hydraulic actuators. In addition, the test is conducted with confinement pressure in order to conduct the test under constant volume and eliminate the effect of dilation of the specimen under testing. Lempe (1972) and Bonnot (1986) used two cylindrical and prismatic specimens, respectively, which are glued between three plates and the middle plate was loaded, inducing shear stresses in the two specimens.

The asphalt concrete shear box (ASB) in Figure 26 (Said et al. 2013) is similar to the Superpave simple shear tester with the exception that it applies a constant normal pressure. The shear box device is used to determine the linear viscoelastic properties, viz. the dynamic shear modulus and phase angle of bituminous mixtures. It consists of two guide plates, one rigidly fixed while the other moves freely in the shearing direction and connected to a hydraulic actuator. A cylindrical asphalt specimen having a diameter of 150 mm and a thickness of less than $\frac{1}{4}$ of the diameter is glued to two steel loading discs using epoxy. An adhesion rig, shown in Figure 26a, is used to centre the specimen and ensure that the loading discs are parallel. The glued specimen is mounted on the guide plates of the shear box, Figure 26c. The specimen is then subjected to a repeated or sinusoidal cyclic loading over a range of frequencies. The movement of the discs relative to each other (the shear deformation) is measured using two strain gauges.

The condition that thickness should be less than $\frac{1}{4}$ of the diameter is necessary to ensure that the specimen is under the state of pure shear. It is thus possible to test even thin drilled specimens from asphalt concrete pavement layers for forensic analysis. A constant normal compressive stress is applied to the specimen to ensure that no excessive dilation of the specimen occurs during testing.

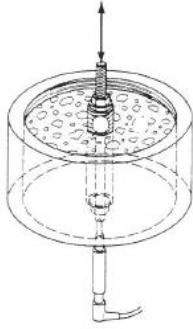


Figure 24. Shear test from EMPA (Junker 1987).

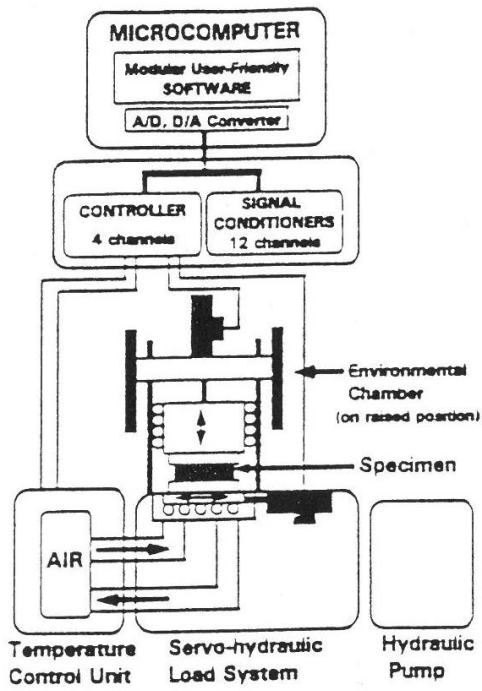


Figure 25. SHRP shear test.

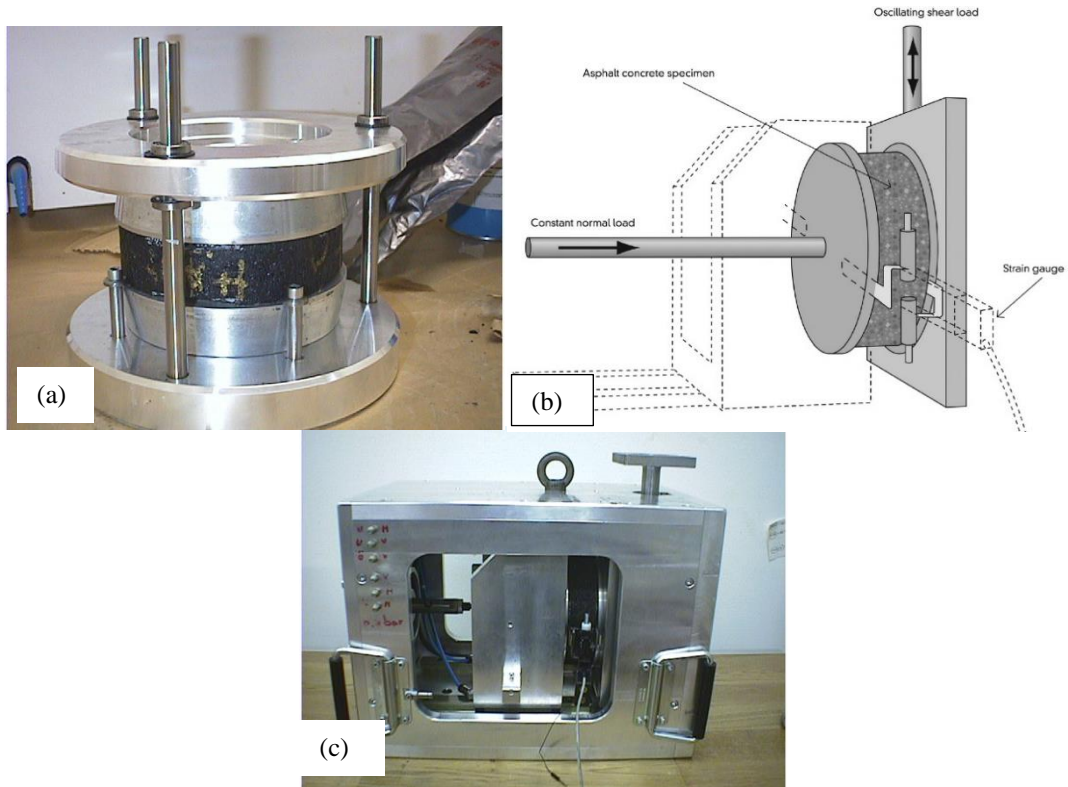


Figure 26. Adhesion ring (a), schematic diagram of the shear box set-up (b) and the shear box (c).

4. Rutting performance prediction models

There exist few rutting models that are employed to predict the permanent deformation in bituminous bound pavement layers. Until the eighties, permanent deformation in asphalt materials was assumed to be a question of mix design rather than pavement design. The Shell method (Claessen et al 1977) was probably the first attempt to incorporate rutting of bituminous layers in pavement design. Existing models can broadly be categorized into structural and functional performance model (Ullidtz 1987). The structural performance models determine the structural soundness or load-carrying capacity of the pavement. They are usually mechanistic-empirical, M-E, and are based on layered strain analysis with elastic or viscoelastic theories. The M-E models can be employed in the decision-making processes regarding pavement design, maintenance and rehabilitation strategies by identifying the structural condition with regard to bearing capacity.

The functional performance models determine the ability of the pavement to provide a comfortable, safe, economical riding surface to the road users. Functional models determine the rate of deterioration in terms of functional parameters (e.g. evenness (International Roughness Index) and rut depth) with the age of the pavement and are applied on existing pavement as part of the pavement management system. This review is limited to the structural performance models.

Before proceeding to the short descriptions of selected structural rutting models for bituminous layers, it is important to look at a typical strain response of bituminous materials subjected to a given load pulse. Studies have indicated that this strain response consists of both recoverable and irrecoverable components. The recoverable part may be elastic or viscoelastic in nature, while the permanent part may be plastic or viscous. In general, any material behavior may be described by a combination of these four mechanical models and the total strain response may be represented as:

$$\varepsilon_{tot} = (\varepsilon_{el} + \varepsilon_{ve})_{Rec} + (\varepsilon_{pl} + \varepsilon_v)_{Per} \quad (1)$$

where

ε_{tot}	total strain response
ε_{el}	time-independent elastic or resilient strain
ε_{ve}	time-dependent viscoelastic strain
ε_{pl}	time-independent plastic strain
ε_v	time-dependent permanent viscous strain

The main assumption behind M-E models based on elastic theory is that the plastic strain is proportional to the elastic responses. The stresses or strains are obtained using linear or nonlinear elastic analysis. The permanent strain, which can be determined for example by compressive or shear tests, is presented as a function of elastic strain. The M-E elastic models thus express the permanent strain or deformation as a function of the material properties, stresses and/or strains in the pavement structure, temperature and number of load cycles.

The prominent examples of M-E elastic models are the AASHTO (American Association of Highway and Transportation Officials) model developed under the National Cooperative Highway Research Program (NCHRP) (APA, 2004), the CalME model developed at the University of California Pavement Research Center (Ullidtz et al. 2008) and the VESYS model developed at the Texas A&M University (Kenis and Wang 1997). It should be noted that although the M-E elastic models are based

on elastic theory, they account for time-dependent material characteristics using a type of repeated loading test.

Few M-E models (referred here as M-E viscoelastic models), on the other hand, attempt to capture the viscous nature of bituminous mixtures using linear or nonlinear viscoelastic/viscoelastoplastic constitutive equations. However, being computationally expensive (time-consuming) the nonlinear viscoelastic and viscoelastoplastic models have gained little usage (Collop et al. 1995). A typical example of an M-E viscoelastic model is the VEROAD linear viscoelastic multilayer computer program (Hopman, 1996, Nilsson, 2001). The PEDRO model is a linear viscoelastic uni-layer permanent strain model (Said et al. 2011, 2017). The main advantage of the viscoelastic models is the analytical approach to modelling shear distortion in bituminous layers including depression and upheaval in the wheel path. The upheaval could be a notable part of the rut depth (up to 15% of the rut depth). The subsequent sections present short descriptions of selected models.

4.1. AASHTO Model

The AASHTO model shown in Equation (2) is included in the Mechanistic – Empirical Pavement Design Guide (MEPGD) to predict the permanent strain in bituminous layers (ARA, 2004).

$$\frac{\varepsilon_p}{\varepsilon_r} = k_1 \times 10^{k_2} \times T^{k_3} \times N^{k_4} \quad (2)$$

where

- ε_p permanent strain
- ε_r resilient strain
- T temperature (°F)
- N number of load repetitions
- k_1 depth adjustment coefficient as a function of layer thickness and depth to the ground water table.
- $k_2, k_3,$ and k_4 material constants

The AASHTO model predicts the maximum permanent deformation in each layer as a function of time. The regression parameters are obtained from laboratory tests and field calibrated. The resilient strain ε_r is obtained by analysing the pavement structure using a response model such as multilayer elastic theory. The air voids within an asphalt layer are an important parameter. It is used in the estimation of the rutting related to post-compaction that may significantly increase the amount of rut depth. A time hardening approach related to repeated traffic loading is used to combine the permanent deformation contribution from different axle loads. The model is able to dissect the surface rutting between pavement layers, which is valuable in pavement design. Ahmed (2014) attempted to implement and calibrate the MEPDG model for thin Swedish pavement structures with the help of an extra-large wheel tracking (ELWT) device and full-scale accelerated pavement testing (HVS) and found about 20% difference in shift factor between the ELWT and HVS.

4.2. CalME

The CalME model is a shear-based approach. The inelastic (permanent) shear strain is determined from the Repeated Simple Shear Test at Constant Height (RSST-CH) as a function of shear stress and

elastic shear strain in relation to the number of load applications (Ullidtz et al. 2008). The rut depth is estimated for a 100-mm thick asphalt concrete layer based on shear stresses at 50 mm depth beneath the edge of the tyre.

The model is calibrated based on data from the Wes-Track test sections and Heavy Vehicle Simulator (HVS) (Oscarsson et al. 2011). The time hardening procedure is assumed to be caused by densification due to post-compaction and/or by ageing of the binder. The effect of post-compaction corresponds to 36 per cent of the original air void content that takes place over the initial 60 days with traffic loading. The latest version of the model is given in Equation (3). The model parameters are determined from the Repeated Simple Shear test at Constant Height. The elastic shear stress and strains are obtained from the layered theory.

$$\gamma_p = \exp\left(A + \alpha \times \left[1 - \exp\left(\frac{-\ln(N)}{\gamma}\right) \times \left(1 + \frac{\ln(N)}{\gamma}\right)\right]\right) \times \exp\left(\frac{\beta \times \gamma}{\tau_{ref}}\right) \times \gamma_e^\delta \quad (3)$$

$$RD = K \times h_i \times \gamma_p \quad (4)$$

where

γ_p	permanent shear strain
γ_e	resilient shear strain
τ	shear stress
τ_{ref}	= 0.1MPa reference shear stress
K	a constant relating the permanent shear strain to rut depth
h_i	thickness of layer i
RD	rut depth
N	number of load applications
A, α , β , γ , δ	constant determined from RSST-CH

Oscarsson (2011) applied the CalME model v0.82 on two pavement test sections on the E6 at Fastarp. The rut prediction correlated well with field rutting in the flexible pavement section, but to a lesser degree to rutting in the semi-rigid pavement section.

4.3. VESYS

Similar to the AASHTO and CalME models, the VESYS model (Kenis and Wang 1997) assumes that the permanent strain in a bituminous layer is proportional to the resilient elastic strain. The permanent strain model parameters of the layers are estimated by conducting repeated load (incremental static-dynamic) laboratory tests on cylindrical asphalt specimen having a diameter of 100 mm and a thickness of 200 mm as defined in Section 3.1. The VESYS model is given by

$$\frac{\Delta \varepsilon_p}{\varepsilon} = \mu N^{-\alpha} \quad (5)$$

where

$\Delta\epsilon_p$	the permanent strain due to a single (or Nth) load application
ϵ	elastic or resilient strain at the 200th repetition
μ	a parameter representing the constant of proportionality between the permanent and elastic strains
α	a parameter defining the rate of decrease in permanent deformation

The μ and α determined from the laboratory tests are transferred to layered system parameters μ_{sys} and α_{sys} with the help of the measured creep compliance and multilayer elastic theory.

4.4. VEROAD

The VEROAD (Visco - Elastic ROad Analysis Delft) is a three-dimensional linear viscoelastic multilayer program developed at the Delft University of Technology (Hopman, 1996a). The viscoelastic nature of bituminous materials is considered through the Burger's model (or Maxwell-Kelvin-Voigt model) and the layered system can be analysed under stationary or moving wheel loads using the layered elastic theory and the elastic-viscoelastic correspondence principle (Hopman, 1996a). Preference was given to an analytical approach over a finite element method to make a program that could be used in everyday engineering problems. Nilsson (2001) applied the VEROAD approach to evaluate the fatigue and rutting performance of a typical heavy-duty pavement. In particular, with respect to rutting performance viscous (ϵ_v) and plastic (ϵ_{pl}) components, described in Equation (1), have been taken into account. The viscous component has been calculated based on measured ZSV and the plastic component was estimated using the Mohr-Coulomb plasticity theory. The permanent deformation parameters for the plastic component calculation were determined from a triaxial creep test conducted on a specimen having a height of 200 mm and a diameter of 100 mm. The VEROAD model also considers lateral traffic wander.

4.5. PEDRO

PEDRO (the PERmanent Deformation of asphalt concrete layers for ROads) is a linear viscoelastic uni-layer permanent strain model (Said et al. 2011). Unlike the other models discussed in this review, the PEDRO model has two separate components, i.e. the volume and shape (shear) parts, to distinctly predict the effect of the post-compaction or volume change and shear flow in the bituminous mixture. The input material properties for the PEDRO model include the viscosity at the peak phase angle of the bituminous layers determined using a dynamic shear modulus test.

The PEDRO model is a shear-based approach that makes use of the constitutive relationship presented by Björklund (1984), presented in Equation (6). It is a complex function (the first term is the volume change and the second term shear flow) and calculates the permanent strain at a desired lateral and vertical location. It allows transverse profile and rutting contribution from each of the bituminous layers to be presented. This is valuable in the enhancement of pavement design and optimization of asphalt concrete materials.

$$\epsilon_p = \frac{\sigma_0 (1-2\nu)}{v^* \eta_p} \operatorname{Re} \left[\sqrt{(z+ix)^2 + a^2} - (z+ix) \right] + \frac{\sigma_0 z}{v^* \eta_p} \operatorname{Re} \left[1 - \frac{z+ix}{\sqrt{(z+ix)^2 + a^2}} \right] \quad (6)$$

where

ϵ_p	permanent strain;
σ_0	contact pressure (MPa)
ν	Poisson's ratio

x, z	x and z coordinates of the calculation point
η_p	viscosity at peak phase angle of the bituminous layer
V	speed (km/h)
i	the imaginary number ($\sqrt{-1}$)

4.6. Summary and Discussion

In general, all the models require a laboratory test to determine the model-specific parameters. The triaxial or a uniaxial test is the preferred procedure to determine the model's parameters: triaxial for the VESYS and VEROAD models and uniaxial for the AASHTO model. The triaxial test is a rather complex test and requires a 200 mm thick specimen, which is very difficult to obtain from field-cored samples in case of verification. On the other hand, the dynamic shear test, using the constant-height simple shear tester or shear box tester, is conducted to determine model parameters for the PEDRO and CalME models. The shear test can be conducted on thinner or thicker specimens that can be either laboratory-produced or field-cored.

Apart from model-specific parameters, all the models can take the effect of the geometry of the pavement system, traffic loading characteristics, lateral traffic wander distribution, and climate into account. In addition, permanent deformation in bituminous mixtures is a function of loading frequency and the PEDRO model takes the vehicle speed into account directly. Other models may consider the effect of loading frequency indirectly through the dynamic modulus master curves.

Further, unlike the other models, the PEDRO model consists of two distinct parts representing the volume change which estimates the permanent deformation due to initial stage compaction and the shape component representing the shear flow that occurs due to the movement of the mixture.

It is also worth mentioning that, with the exception of the PEDRO model, all the models are/use some function of stress or strain in the pavement system and their implementation therefore requires analysis of the pavement structure using multilayered elastic theory or Finite Element Method. This can be a computationally expensive process when the pavement analysis is performed considering the combination of actual traffic load and climate spectra. The PEDRO model in its current form is a function of the contact pressure and thus avoids the need for analysis of the pavement system. Table 2 shows a summary of the structure of the models, highlighting some essential differences between the models.

Table 2. Structure of the models.

	M-E model	Test method	Model Input parameters	Rut estimation	Output
AASHTO	Elasticity, multilayer	Uniaxial test	Resilient strain – calculated using LET	At loading centre	Rut depth
CalME	Elastic, multilayer	Repeated load Shear test	Resilient shear strain – calculated using LET**	Based on stresses at 50 mm depth beneath the edge of the tyre	Rut depth
VEYSYS	Elastic, multilayer	Triaxial	Resilient strain – calculated using LET	At loading centre	Rut depth
VEROAD	Viscoelastic, multilayer	Triaxial	ZSV, shear modulus	At loading centre	Rut depth*
PEDRO	Viscoelastic, Uni-layer	Frequency sweep shear test	Viscosity at maximum phase angle	Rutting zone ± 1.25 m (each cm)	Rut profile

* Rut profile may be calculated. ** Layer elastic theory

5. Calibration of performance prediction models

Mechanistic-empirical performance models are generalizations of field conditions. In reality, the pavements have uncertainty in material compositions and characteristics with respect to loading conditions, climate and ageing. The loading conditions induced by repeated vehicle loading are related to vehicle parameters such as axle load, tyre inflation pressure, speed, lateral wander and dynamic loading occurring under various climate conditions with respect to temperature and moisture conditions. Calibration of the prediction is therefore essential in the application of pavement deterioration models. To establish calibration factor/s for MEPDG and CAI Me, investigators (Ullidtz et al. 2008, El-Basyouny et al. 2005) attempt to create several calibration factors in line with the range of variation of values of the different key parameters and sub-models. The poor agreement with the observed rutting in the field is more the norm than the exception (Salama et al. 2007). Local calibration is therefore crucial when implementing the analytical models. As part of the calibration effort in the PEDRO model, Eriksson (2015) quantified the importance of some individual key variables of permanent deformation in a sensitivity analysis as the first step in the calibration of the PEDRO model.

6. Conclusions

Based on the references examined above, it may be concluded, that both aggregate and binder phase properties may significantly influence asphalt mixtures' resistance to permanent deformation under cyclic loading (and accordingly their rutting performance in the field). In particular, with respect to binder properties it is shown that empirical parameters and viscosity are not sufficient to characterize bituminous binders in terms of their contribution to asphalt mixtures' permanent deformation performance, especially when polymer-modified binders are to be examined. Binders' viscoelastic properties in terms of elastic and recovery properties (such as MSCR test) need to be considered when predicting asphalts' rutting performance.

The influence of the aggregate phase properties (i.e. aggregate size distribution and their morphology) on the mixture's performance also received considerable attention in the literature. Several parameters describing the load-carrying aggregate structure in an asphalt mixture, with respect to its density, composition as well as contact zone orientation and geometry have been proposed in the literature. The results presented indicate that these parameters may explain at least qualitatively experimental and field observations concerning materials' permanent deformation performance. At the same time, the reported results are difficult to generalize for new mixtures and/or aggregate types due to the combined action of many parameters affecting the materials' performance.

The asphalt mixtures' resistance to permanent deformation therefore needs to be evaluated with tests performed on the mixture level, with the individual phase parameters used as qualitative indicators of the materials' expected performance. Asphalt mixtures are anisotropic, viscoelastoplastic materials with damage accumulation substantially affecting their properties. As a reasonable practical compromise, however, an asphalt's temperature and rate-dependency may, at least approximately, be captured with viscoelastic description of material properties. In experimental evaluation, permanent deformation characteristics of materials should be obtained under conditions representative of rut-inducing stresses in the pavement.

Traffic load parameters (magnitude, frequency and spatial distribution) significantly impact the rate of rutting in the field. Furthermore, the shape of the tyre-pavement contact area as well as non-uniform distributions on normal and tangential contact stresses may significantly influence the shear stresses in the asphalt layer and accordingly its rutting performance. Asphalt layer rutting performance may thus not be fully inferred from the material properties alone. Rather, a structural performance model is required to take the combined influence of material, structural and traffic parameters into account. The lateral distribution of wheel load significantly influences the maximum rut depth and the rutting profile may not be captured fully by evaluating the asphalt layer's response at a single point, e.g. at the centre of the loaded area. Permanent deformation should instead be evaluated throughout the asphalt layer (with respect to both its thickness and its width) in order to obtain a full picture of the rutting profile.

In this report several relevant rutting performance models have been examined. As discussed, both elastic and viscoelastic methods are available for predicting asphalt concrete layer deformations. Compared to the elastic stress analysis, viscoelastic models are however both more theoretically correct and more flexible in terms of explicitly incorporating relevant mixture and/or traffic parameters. Based on the outcomes of section 2, it may also be concluded that performance models incorporating experimentally measured asphalt mixtures' permanent deformation properties, e.g. asphalts' viscosity, are a promising way to go forward, in particular when the effect of novel materials on a pavement's rutting performance is to be evaluated.

References

- AASHTO M332, Standard Specification for Performance Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test, 2014.
- Ahmed, A.W., M.S. Shafiqur and S. Erlingsson, 2017, Impact of longer and heavier vehicles on the performance of asphalt pavements: a laboratory study. BCRRA 2017, Greece.
- Airey, G.D., "Viscosity-Temperature Effects of Polymer Modification as Depicted by Heukelom's Bitumen Test Data Chart", International Journal of Pavement Engineering, Vol. 2:4, 2001, pp. 223-242.
- Al-Qadi and H. Wang, 2009, Evaluation of pavement damage due to new tire designs, Research Report ICT-09-048, Illinois Center for Transportation, Univ. of Illinois at Urbana-Champaign.
- Al-Qadi, I.L. and H. Wang, 2012, Impact of wide-base tires on pavement, TRR 2304, TRB.
- ARA., 2004. Guide for the Mechanistic Empirical Design of New and Rehabilitated Pavement Structure. (Report 1-37A), Washington, D. C: Transportation Research Board of the National Academies.
- Asphalt Institute (2001). Superpave Mix Design. Lexington, KY.
- Bahia H. U., Hanson D. I., Zeng M., Zhai H., Khatri M. A. and Anderson M. R. (2000). Superpave Protocols for Modified Asphalt Binders, The National Cooperative Highway Research Program NCHRP 9-10.
- Bahia, H.U., 2009. Modeling of asphalt binder rheology and its application to modified binders. In: Y.R. Kim, ed. Modeling of asphalt concrete. USA: ASCE Press, McGraw-Hill, 11-61.
- Barksdale, R., Pollard, C., Siegel, T., Moeller, S., 1992, Evaluation of the effects of aggregate on rutting and fatigue of asphalt, Research Rep., Georgia DOT Project 8812 and Georgia Tech Project E20-835, Georgia Institute of Technology, Atlanta.
- Birgisson, B., Ruth, B., 2001, Development of Tentative Guidelines for the Selection of Aggregate Gradations for hot Mix Asphalt. Aggregate Contribution to Hot Mix Asphalt (HMA) Performance, ASTM STP 1412, American Society for Testing and Materials, West Conshohocken, PA.
- BitVal - Analysis of Available Data for Validation of Bitumen Tests, FEHRL, 2006.
- Björklund A., 1984. Creep induced behaviour of resurfaced pavements. VTI Rapport Nr 271A, Swedish Road and Transport Research Institute, Linköping, Sweden.
- Blab R. and J. Litzka, 1995, Measurement of the lateral distribution of heavy vehicles and its effect on the design of road pavements. Proceeding of the 4th Int. symposium on heavy vehicle weights and dimensions, Ann Arbor.
- Blab, R. and Harvey, J.T., 2002. Viscoelastic rutting model with improved loading assumptions. Proceedings of International Society for Asphalt Pavements, 9th Int. Conf. on Asphalt Pavements. Copenhagen, Denmark, 1:6-2.
- Bonnot, J., (1986) Asphalt Aggregate Mixtures. Transportation Research Record 1096, 1986.

- Cebon, D., 2000, Handbook of Vehicle Road Interaction, Taylor & Francis.
- Collop, A. C., Cebon, D., and Hardy, M. S. A., 1995. Viscoelastic approach to rutting in flexible pavements. *Journal of Transportation Engineering*, ASCE, 121 (1). pp. 82-93.
- D'Angelo J. (2010). New High-Temperature Binder Specification Using Multiple Stress Creep and Recovery, *Transportation Research Circular E-C147*, December 2010.
- D'Angelo J. and Dongré R. (2009). Practical Use of Multiple Stress Creep and Recovery Test: Characterization of Styrene-Butadiene-Styrene Dispersion and Other Additives in Polymer-Modified Asphalt Binders, *Transportation Research Record* 2126, pp. 73-82.
- D'Angelo J., Kluttz R., Dongré R., Stephens K. and Zanzotto L. (2007). Revision of the Superpave High Temperature Binder Specification: The Multiple Stress Creep Recovery Test, *Journal of the Association of Asphalt Paving Technologists*, Vol. 76, pp. 123-162.
- De Beer, M., Fischer, C., Jooste, F. J., 2002, Evaluation of Non-Uniform Tire Contact Stresses on Thin Asphalt Pavements, *Procs of ICAP 2002*, Copenhagen, Denmark.
- De Beer, M., Sadzik, E. M., Fisher, C., Coetzee, C. H., 2005, Tyre-pavement contact stress patterns from the test tyres of the Gautrans heavy vehicle simulator (HVS) MK IV+, *Proc. of the SATC 2005*.
- de Larrard, F. (2002); Packing of particles – the compressible packing model. In Shah, S.P., V.K. Bui and M. Geiker, eds. *Rheology of cement-based materials self-compacting concrete*. DTU Lyngby. Edition, Shell UK Oil Products Limited, Thomas Telford Publishing. London, UK, Chap. 5.
- Eisenmann, J. and A. Hilmer, “Influence of Wheel load and Inflation Pressure on the Rutting Effect of Asphalt Pavements - Experiments and Theoretical Investigations”, 6th Int. Conf. on the Structural Design of Asphalt Pavements, The University of Michigan, Ann Arbor, USA, 1987.
- EN 16659, Bitumen and Bituminous Binders – Multiple Stress Creep and Recovery Test (MSCRT), 2015.
- Erlingsson, s., S.F. Said and T. McGarvey, 2012, Influence of heavy traffic lateral wander on pavement deterioration, EPAM, Malmö, Sweden
- Fuller, W., Thompson, S., 1907, The Laws of Proportioning Concrete. *Transactions, American Society of Civil Engineers*, Vol. 59, p. 67.
- FunDBitS – Functional Durability-related Bitumen Specification, CEDR, 2016.
- Guarin A., R. Roque, S. Kim, and O Sirin (2013) Disruption Factor of Asphalt Mixtures. *International Journal of Pavement Engineering*, DOI:10.1080/10298436.2012.727992.
- Gudmarsson, A., 2014, Resonance testing of asphalt concrete, Doctoral thesis, KTH, Stockholm.
- Guericke R. and Schlame K. (2008). A new “softening point” based on asphalt pavement performance figures. *E&E* 2008.
- Hopman, P. C., 1996a. VEROAD: A viscoelastic multilayer computer program. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1539, Transportation Research Board of the National Academies, Washington, D. C., pp. 72–80.

- Hopman, P.C., 1996b, The visco-elastic multilayer program, VEROAD, Heron Vol41(1), Netherlands School for Advanced Studies in construction, Delft, The Netherlands,
- Junker, J.P., 1987, Entwicklungen zur Bestimmung Mechanischer Materialkennwerte an bituminösen Baustoffen, insbesondere an Asphalt, EMPA.
- Karlsson, R., 2016, Konsekvenser av olika däckkonfigurationer på svenska vägnätet, TRV2016/22392.
- Kenis, W. and W. Wang, 1997, Calibrating mechanistic flexible pavement rutting models from full scale accelerated tests. 8th Int. conference on asphalt pavements, Seattle.
- Khavassefat, P., Jelagin D., Birgisson, B., 2012, A Computational Framework for Viscoelastic Analysis of Flexible Pavements under Moving Loads, Materials & Structures, 45.
- Khavassefat, P., Jelagin D., Birgisson, B., 2015, Dynamic Response of Flexible Pavements at Vehicle Road interaction, RMPD.
- Lempe, U., Determination of the Dynamic Modulus of Shear and the Fatigue Life of Bitumen – Bound Materials. 3rd Int. Conf. on the Structural Design of Asphalt Pavements, 1972.
- Lira, B., Jelagin, D., Birgisson, B., 2013, Gradation Based Framework for Asphalt Mixtures, Materials & Structures, DOI: 10.1617/s11527-012-9982-3.
- Liu, P., Hu, J., Wang, D., Oeser, M., Alber, S., Ressel, W., Falla, GC, 2017, Modelling and evaluation of aggregate morphology on asphalt compression behavior, Construction and Building Materials, 133, 196-208.
- Lu X. and Isacsson U. (1997). Characterization of styrene-butadiene-styrene polymer modified modified bitumens – Comparison of conventional methods and dynamic mechanical analyses. Journal of Testing and Evaluation, Vol. 25, pp.23-32.
- Lu X., Said S., Carlsson H., Soenen H., Heyrman S. and Redelius P. (2014). Evaluation of Test Sections with Polymer Modified Bitumens. ISAP 2014, Raleigh, USA.
- Lu X., Said S., Soenen H. and Heyrman S. (2016). Multiple Stress Creep and Recovery Tests of Bituminous Binders and Correlation to Asphalt Concrete Rutting Performance. ISAP 2016.
- Masad E., Huang C.-W., D'Angelo J. and Little D. (2009). Characterization of Asphalt Binder Resistance to Permanent Deformation Based on Nonlinear Viscoelastic Analysis of Multiple Stress Creep Recovery (MSCR) Test, AAPT, Vol. 78, pp. 535-562.
- McGarvey, T., 2016, Vehicle lateral position depending on road type and lane width. VTI rapport 892A.
- Mezger, T.G., "The rheology handbook. 3rd revised edition, Vincentz Network, Hanover, Germany, 2011.
- Monismith, C. L., R. G. Hicks, F. N. Finn, J. Sousa, J. Harvey, S. Weissman, J. Deacon, J. Coplantz, and G. Paulsen, 1994b, Permanent Deformation Response of Asphalt Aggregate Mix. SHRP-A-415 Report. TRB, National Research Council, Washington, D.C., 1994.

- Monismith, C. L., R. G. Hicks, F. N. Finn, J. Sousa, J. Harvey, S. Weissman, J. Deacon, J. Coplantz, and G. Paulsen. Permanent Deformation Response of Asphalt Aggregate Mix. SHRP-A-415 Report. TRB, National Research Council, Washington, D.C., 1994.
- Monismith, C.A. and L. Popescu, 2007, "Permanent deformation prediction in asphalt mixes and pavement: a current approach and a look ahead" NVF34 och NordFou, Reykiavik, Iceland
- Monismith, C.L., J.A. Deacon, and J.B. Sousa, 1994a "SHRP Deformation Test – The Key Component", SHRP and Traffic Safety on Two Continents, Hague, 1994.
- Monismith, C.L., L. Popescu and J. Harvey, 2006, Rut depth estimation for mechanistic-empirical pavement design using simple shear test results, AAPT
- NCHRP Report 465 (2002). Simple Performance Test for Superpave Mix Design. Transportation Research Board, National Research Council, Washington, D.C.
- Nijboer, L., 1948, Plasticity as a Factor in the Design of Dense Bituminous Road Carpets. Elsevier Science, New York.
- Nilsson, R., M., 2001. Viscoelastic Pavement Analysis Using VEROAD, Division of Highway and Engineering, The Royal Institute of Technology, KTH, Stockholm.
- Olard, F., 2012. GB5 Mix Design: High-Performance and Cost-Effective Asphalt Concretes by Use of Gap-Graded Curves and SBS Modified Bitumens, AAPT vol 81.
- Olard, F., Di Benedetto, H., 2003. General "2S2P1D" model and relation between the linear viscoelastic behaviours of bituminous binders and mixes. Road Material and Pavement Design, 4(2), 185–224.
- Onifade, I., Jelagin, D., Birgisson, B., Kringos, N, 2016, Towards asphalt mixture morphology evaluation with the virtual specimen approach, RMPD, 17(3), 579-599.
- Oscarsson, E., 2011, mechanistic empirical modeling of permanent deformation in asphalt concrete layers, Doctoral thesis, Lund University.
- Oscarsson, E., 2011. Evaluation of the mechanistic-empirical pavement design guide model for permanent deformation in asphalt concrete. International Journal of Pavement Engineering, 12(1), pp. 1-12.
- Pan, T., Tutumluer, E., Carpenter, S.H., 2006, Effect of Coarse Aggregate Morphology on Permanent Deformation Behaviour of Hot Mix Asphalt, Journal of Transportation Engineering, 132 (7), 580-589.
- Read, J. and Whiteoak, D., 2003. The Shell bitumen handbook, 5th Edition.
- Roberts C., van Rooijen R. and Thimm L. (2012). A comparison of binder tests that relate to asphalt mixture deformation, E&E 2012.
- Roque, R., B. Birgisson, S. Kim, A. Guarín, 2006, Development of Mix Design Guidelines for Improved Performance of Asphalt Mixtures. Florida Department of Transportation, Final Report, UF Project no. 49104554032-12.
- Said, S. F. & H. Hakim (2016) Asphalt concrete rutting predicted using the PEDRO model, Int. J. of Pavement Engineering, Vol 17:3, 245-252, <http://dx.doi.org/10.1080/10298436.2014.993184>

- Said, S. F., Hakim, H., Osscanson, E., and Hjort, M., 2011. Prediction of flow rutting in asphalt concrete layers. *International Journal of Pavement Engineering*, 12(6), pp. 519-532.
- Said, S.F. and H. Hakim (2014): Asphalt concrete rutting predicted using the PEDRO model, *International Journal of Pavement Engineering*, <http://dx.doi.org/10.1080/10298436.2014.993184>
- Said, S.F., A.W. Ahmed, (2017) Prediction of heavy vehicle impact on rut development using PEDRO model, 10th Int. Conference on the Bearing Capacity of Roads, Railways and Airfields, Athena, Greece June 2017
- Said, S.F., H. Hakim and O. Eriksson, 2013, “Rheological characterization of asphalt concrete using a shear box”, *ASTM Jour. of Testing and Evaluation*, Vol 41, No. 4.
- Salama, H.K., S.W. Haide and K. Chatti, 2007, Evaluation of new mechanistic-empirical pavement design guide rutting models for multiple-axle loads, TRR 2005, TRB.
- Salama, H.K., S.W. Haider and K. Chatti, 2007, Evaluation of new mechanistic-empirical pavement design guide rutting models for multiple-axle loads. TRR 2005. TRB.
- Santagata E., Baglieri O., Alam M. and Dalmazzo D. (2015). A Novel Procedure for the Evaluation of Anti-Rutting Potential of Asphalt Binders, *International Journal of Pavement Engineering*, Vol. 16, pp. 287-296.
- Sefidmazgi, N.R.; Tashman, L.; Bahia, H., 2012, Internal Structure Characterization of Asphalt Mixtures for Rutting Performance Using Imaging Analysis, *RMPD*, Volume 13, Suppl1, 21-37.
- Siddharthan, R.V., M. Nasimifar, X. Tan and E.Y. Hajj, 2017, Investigation of impact of wheel wander on pavement performance, *Jour. Road Materials and pavement design*. Vol. 18, No. 2.
- Soenen H., De Visscher J., Tanghe T., Vanelstraete A. and Redelius P. (2006). Selection of binder performance indicators for asphalt rutting based on triaxial and wheel tracking tests. *AAPT*, 2006.
- Sousa, J.B., *Asphalt-Aggregate Mix Design Using the Repetitive Simple Shear Test (constant Height)*. The Association of Asphalt Paving Technologists, 1994
- Sybilski, D., 1996. Zero-Shear Viscosity of Bituminous Binder and Its Relation to Bituminous Mixture's Rutting Resistance. *Journal of Transportation Research Board*, Transportation Research Record No 1535, Washington D.C. USA, 15-21.
- Talbot, A., Richart, F., 1923, The Strength of Concrete and its Relation to the Cement, Aggregate and Water. *Bulletin. Univeristy of Illinois Engineering Experiment Station*, Vol. 137, p. 1-118.
- Thrower, E.N., S. Mortazavi and J.W. Dougill, 1986, Methods for predicting permanent deformation in flexible pavements, *Contractor Report 38*, Transport and Road Research Laboratory, Crowthorne, Great Britain.
- Ullidtz, P., 1987, *Pavement analysis*, Elsevier Publication
- Ullidtz, P., J.T. Harvey, B-W. Tsai and C.L. Monismith, 2008, Calibration of mechanistic-empirical models for flexible pavements using the WesTrack experiment.
- Van Der Poel, C., “A general system describing the visco-elastic properties of bitumen and its relation to routine test data” *Journal of Applied Chemistry* Vol 4, 1954.

Van Wazer, J. R., J. W. Lyons, K. Y. Kim and R.E. Colwell, "Viscosity and flow measurements, a laboratory handbook of rheology", New York, USA: John Wiley & Sons, Inc, 1963.

Varin, P., Saarenketo, T., 2014, Effect of axle and tyre configuration on pavement durability – a prestudy, ROADDEX Report.

Vavrik, W., Pine, G. Huber, S.H. Carpenter, Bailey R., 2001, The Bailey Method of Gradation Evaluation: The Influence of Aggregate Gradation and Packing Characteristics on Voids in the Mineral Aggregate. Journal of the AAPT, Vol. 70, p. 132-175.

Vierth, I. et al. 2008. The effect of long and heavy trucks on the transport system. VTI report Wang, H., 2011, Analysis of Tire-Pavement Interaction and Pavement Responses Using a Decoupled Modeling Approach, PhD Thesis, Urbana, Illinois, USA.05A.

Weymouth, C., 1938, A Study of Fine Aggregate in Freshly Mixed Mortars and Concretes. Proceedings of the American Society for Testing and Materials.

Zoorob S. E., Castro-Gomes J. P., Pereira Oliveira L. A. and O'Connell J. (2012). Investigating the Multiple Stress Creep Recovery Bitumen Characterisation Test, Construction and Building Materials, Vol. 30, pp. 734-745.

VTI, Statens väg- och transportforskningsinstitut, är ett oberoende och internationellt framstående forskningsinstitut inom transportsektorn. Huvuduppgiften är att bedriva forskning och utveckling kring infrastruktur, trafik och transporter. Kvalitetssystemet och miljöledningssystemet är ISO-certifierat enligt ISO 9001 respektive 14001. Vissa provningsmetoder är dessutom ackrediterade av Swedac. VTI har omkring 200 medarbetare och finns i Linköping (huvudkontor), Stockholm, Göteborg, Borlänge och Lund.

The Swedish National Road and Transport Research Institute (VTI), is an independent and internationally prominent research institute in the transport sector. Its principal task is to conduct research and development related to infrastructure, traffic and transport. The institute holds the quality management systems certificate ISO 9001 and the environmental management systems certificate ISO 14001. Some of its test methods are also certified by Swedac. VTI has about 200 employees and is located in Linköping (head office), Stockholm, Gothenburg, Borlänge and Lund.

HEAD OFFICE
LINKÖPING
SE-581 95 LINKÖPING
PHONE +46 (0)13-20 40 00

STOCKHOLM
Box 55685
SE-102 15 STOCKHOLM
PHONE +46 (0)8-555 770 20

GOTHENBURG
Box 8072
SE-402 78 GOTHENBURG
PHONE +46 (0)31-750 26 00

BORLÄNGE
Box 920
SE-781 29 BORLÄNGE
PHONE +46 (0)243-44 68 60

LUND
Medicon Village AB
SE-223 81 LUND
PHONE +46 (0)46-540 75 00

