Study of permanent deformations in asphalt concrete layers

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ABSTRACT: Rutting is a consequence of plastic deformation and consolidation of pavement layers and subgrade. The prediction of rutting evolution is a complex problem, requiring detailed knowledge of materials state, elastic and plastic deformability and viscosity of pavement materials. Several thickness design methods are generally based on limiting the vertical compressive elastic strain or stress in the top of the subgrade. Such procedures assume that surface plastic deformation is mainly due to the subgrade and do not consider deformations in the pavement upper layers. This article presents and compares rutting evolution of asphalt mixes in cored specimens using a laboratory LCPC traffic simulator and in a full-scale test section loaded by a linear traffic simulator. This study is part of a comprehensive research carried out in Brazil aiming at investigating the performance of asphalt concrete with both conventional and polymer modified binders.

1 INTRODUCTION

Rutting is a consequence of plastic deformation and consolidation of pavement layers and subgrade. In order to minimise the contribution of densification, appropriate compaction, which reduces void volume, and traffic post-compaction are required.

Several thickness design methods are generally based on one fundamental criterion: limiting the vertical compressive elastic strain or stress in the top of the subgrade. Such procedures assume that surface plastic deformation is mainly due to the subgrade and will be kept in acceptable values provided strains or stresses in the top of the subgrade do not exceed limit values. Thus, those procedures do not consider deformations in the pavement upper layers (sub-base, base and wearing courses).

Field and laboratory studies have shown that densification and plastic flow of flexible pavement layers may be characterised this way:

- Vertical plastic deformation in pavement layers and subgrade;
- Horizontal plastic flow in the asphalt layer.

The growth of permanent deformation in an asphalt layer, due to the repetition of traffic loads, is caused by the combination of volumetric reduction and shear strain. Several studies have indicated that plastic deformations in asphalt layers are mainly due to excessively high binder content and low voids volume. Deformations may be also caused by deficiencies in layers densification during construction, or by plastic movement of the asphalt mix subjected to high temperatures.

Plastic deformation may be partly minimised by an appropriate mix design and efficient construction control. In order to reduce asphalt mix susceptibility to plastic deformations, specifications of various mix parameters, such as binder type and content, aggregate type and gradation, compaction degree (air voids), are essential.

Asphalt influence on permanent deformations strongly depends on the conditions to which the mix is submitted. The binder inherent effects are important but their influence is small compared to the effects of aggregates and air voids, specially at higher temperatures (e.g. 40º C) or when the mix is submitted to a stress state that amplifies aggregate influence.

Aiming at achieving rut resistant asphalt mixes, field conditions have been simulated in laboratory by a variety of repeated loading tests. These tests are carried out following specified temperatures and stress magnitudes and variable loading times. Nevertheless, plastic deformations will occur due to densification and to pavement materials shear strains, caused by traffic loads.

2 PREDICTION OF RUTTING EVOLUTION

The prediction of rutting evolution is a complex problem, requiring detailed knowledge of materials state, elastic and plastic deformability and viscosity of pavement materials. Figure 1 illustrates the presence of rutting in a flexible pavement loaded by heavy, channelled and slow traffic.

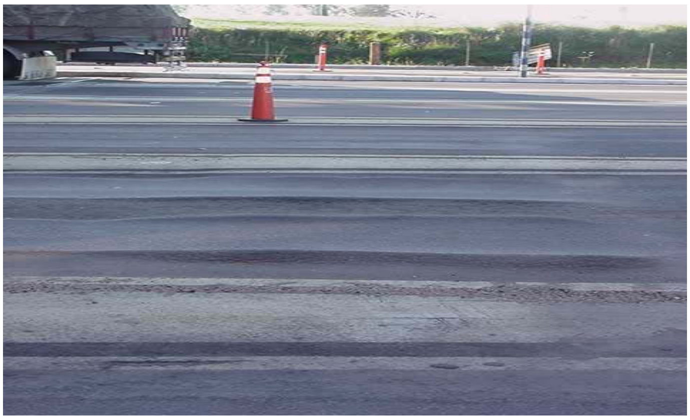

Figure 1. Rutting occurrence in a flexible pavement loaded by heavy traffic

Flexible pavements rutting has been modelled as:

$$N_d = f_1 \varepsilon_v^{-f_2} \quad (1)$$

where N_d = number of allowed load repetitions, ε_v = vertical compressive strain in the top of subgrade and f_1 f_2 = model parameters.

Table 1 presents values of model parameters in Equation (1), resulting from earlier research developed with the purpose of estimating plastic deformation in flexible pavement structures.

Table 1. Model parameters in Equation 1.

	Source	f_1	f_2
1	Transport & Road Researh Laboratory	1.130×10^{-6}	3.57
2	Belgian Road Research Center (BRRC)	3.050×10^{-9}	4.35
3	U. S. Army Corps of Engineers	1.807×10^{-15}	6.527
4	Instituto do Asfalto	1.365×10^{-9}	4.477
5	SHELL Research	6.150×10^{-7}	4
6	CHEVRON	1.337×10^{-9}	4.484

Thompson et al. (1998) presented a detailed review and a chronological synthesis of models based on laboratory studies carried out to characterise soils and aggregates resilient behaviour. Brown and Bell (1997) presented the following equation to estimate flexible pavements service life, considering 25 mm rut as failure criterion:

$$N = \left(\frac{8511}{\varepsilon_v}\right)^{7.14} \quad (2)$$

where N = number of repeated loads and ε_v = compressive strain in the top of the subgrade.

Later, Brown (1984) developed additional studies on the prediction of rut growth in British flexible pavements. Several pavement structures were considered and the following model was obtained:

$$\varepsilon_v = \frac{21{,}600}{\left(\frac{N}{f_{RD}}\right)^{0.28}} \quad (3)$$

where ε_v = vertical strain in the top of the subgrade, N = number of loads to achieve 20 mm rut depth (RD) and f = model parameter depending on base material type ($1 \leq f \leq 1.56$).

Kestler et al. (1997) used a kind of Asphalt Institute model to estimate rut depths of flexible pavements of low-volume roads.

$$N_s = 10^{\left[\frac{l}{m}(\log l - \log \varepsilon_v)\right]} \quad (4)$$

where N_s = number of repeated loads that cause failure due to excessive compressive vertical strain in the top of the subgrade, m = a constant value (0.25), l = a constant value (2.8×10^{-2}) and ε_v = vertical strain in the top of the subgrade.

Several model parameters for rutting prediction are presented in Table 2. Table 3 presents some results obtained by applying the aforementioned models.

Table 2. Model parameters for rutting prediction

Method	K	B	Origin
Austroads	0.00851	7.14	*CBR*
Shell	0.028	4.0	*AASHO Road Test*
University of Nottingham	0.0216	3.57	*U.K. Road Note 29*
British Airports Authority	0.00582	5.74	*U.S. Army Corps of Engineers*
Wardle/Rodway	0.004276	6.63	*U.S. Army Corps of Engineers*

Table 3. Comparative determination of rutting

	$N = \left[\frac{K}{\varepsilon}\right]^B$				
Subgrade strain	0.0005	0.0008	0.0010	0.0015	0.002
model					
Austroads	618×10^6	22×10^6	4.4×10^6	240	30.0
Shell	9.8×10^6	$1{,}5 \times 10^6$	620.0	120	38.0
Shell	1.7×10^6	260.0	105.0	21	6.5
Nottinghan	620×10^3	130.0	58.0	14	5
British Airports	1.3×10^6	90.0	25.0	2.4	460
Wardle/Rodway	1.5×10^6	68.0	15.0	1.0	160

Table 4 presents the contribution of each pavement layer and subgrade to rutting in AASHO test section.

Table 4. Layer contribution to rutting

Layer	Contribution to total permanent strain (%)
Asphalt layer	32
Base	14
Sub-base	45
Subgrade	9

Gronendijk et al. (1997) presented the results of a full-scale test carried out in the Netherlands. Two full depth pavements (asphalt mixes thicknesses of 0.15 m and 0.08 m) were built on a sandy subgrade and loaded by a linear traffic simulator, known as LINTRACK. During test periods, response variables, such as rutting, strains, temperature, cracking and FWD deflections, were measured in order to analyse pavements structural behaviour.

It was shown that rutting was mainly due to the sandy subgrade. The authors also identified a good agreement between the observed rutting in the test sections trafficked by LINTRACK and rut depth predicted by Shell design method (that considers three models according to the reliability level adopted).

Table 5. Shell models for rutting prediction

Model	Reliability level (%)
$\varepsilon_v = 2{,}8 \times 10^{-2} N^{-0{,}25}$	50
$\varepsilon_v = 2{,}1 \times 10^{-2} N^{-0{,}25}$	85
$\varepsilon_v = 1{,}8 \times 10^{-2} N^{-0{,}25}$	95

A research project, developed in order to establish a mechanistic model for rutting estimation was reported by Owsu-Antwi et al. (1998). Experimental data resulting from Long Term Pavement Performance (LTPP) research were used. The model assumes that rutting in asphalt pavements is due to the accumulation of plastic deformations in each pavement layer because of traffic loading.

Therefore, assuming that rutting is caused by vertical compression, the plastic deformation rate in each element of a given layer is proportional to the resilient strain, that is:

$$\frac{\partial \varepsilon_a}{\partial N} = \mu N^{-\alpha} \varepsilon_r \quad (5)$$

where ε_a = permanent strain, N = number of load repetitions, ε_r = resilient strain, α and μ model parameters.

Typical values of α and μ range from 0.006 to 0.92 and from 0.006 to 8.82, respectively. Several attempts have been made in order to relate these parameters to test characteristics and materials properties; however, laboratory tests have shown that α and μ are not remarkably affected by either parameters of mix design (binder type and content and aggregate type) or test procedures (temperature and deviator stress).

The Asphalt Institute developed software called CAMAS with the purpose of helping in the performance based asphalt mixes design. The following model is included in order to minimise repeated shear strains in the top of the subgrade:

$$N_v = d_0 \times \varepsilon_v^{d_1} \quad (6)$$

where ε_v = vertical compressive strain in the top of the subgrade. According to the Asphalt Institute MS-1, $d_0 = 1{,}365 \times 10^{-9}$ and $d_1 = -4{,}477$, considering rut depths from 13 mm to 19 mm, exclusively due to subgrade deformation.

In order to predict permanent deformations in asphalt concrete CAMAS uses Equation (7) as default:

$$\begin{aligned} \log \varepsilon_p &= -14{,}97 + 0{,}408 \log N + 6{,}865 \log T \\ &+ 1{,}107 \log \sigma_d - 0{,}117 \log V_{is} \\ &+ 1{,}908 \log P_{eff} + 0{,}971 \log V_v \end{aligned} \quad (7)$$

where P_{eff} = effective asphalt volume percentage, V_v = air voids volume, σ_d = deviator stress (psi), V_{is} = viscosity at 21ºC (10^6 poises) and T = temperature (ºF).

Rodrigues (2000) points out that in order to elaborate a diagnosis on the structural condition of a given pavement in relation to rutting, it is necessary to investigate the existence of a relationship between vertical compressive strain in the top of the subgrade (e_v) and rutting. If such a relationship exists, then the subgrade contributes in a decisive manner to the accumulation of plastic deformations, and it is possible to calibrate a model like this:

$$N_v = F_c \times 1{,}6 \times 10^{-8} \times \varepsilon_v^{-4{,}26} \quad (8)$$

where F_c is the calibration factor.

It may be seen that if $F_c = 1$ the model in Equation 8 represents an average value of the principal models developed in Europe and in the USA.

If no relationship exists between rutting and compressive strain in top of the subgrade, then plastic deformations have accumulated mainly in pavement granular layers (base and sub-base) because of the weakening effect caused by water inflow through cracks. If an open graded asphalt mix exists, it is possible that rutting might be due to crushing of such a low resistant layer. Dynamic loads giving rise to excess pore pressure in saturated layers, may be also blamed for the gradual stripping of the binder film covering the mineral aggregates.

3 ASPHALT MIXES RUTTING MEASUREMENTS

This paper analyses rutting evolution in conventional and polymer modified asphalt mixes. A field linear traffic simulator, working in an installation held by the Federal University of Rio Grande do Sul (UFRGS) and the State Roads Departments (DAER/RS), as well as LCPC (French Laboratory of Pavements and Bridges), laboratory simulator were used. The experimental design was presented elsewhere (Gonçalves et al. 2000).

3.1 Laboratory tests with LCPC traffic simulator

LCPC traffic simulator is shown in Figure 2. Both specimens cored from full-scale test sections (that would be latter loaded by UFRGS-DAER/RS traffic simulator) and laboratory compacted specimens were tested at the Pavement Laboratory of São Paulo State University (Brazil). Tests were stopped when rutting had accumulated 15 mm. Figure 3 shows some tested specimens.

Table 6 presents some characteristics of asphalt mixes. Figure 4 shows experimental results of tests carried out on six specimens (sizes 180 x 50 x 500 mm). Tests were always carried out on two specimens, one in each side of the device. Temperature and loading magnitude and frequency were controlled.

Table 6 Characteristics of asphalt mix specimens cored from test sections

Mix	Thickness (mm)	Binder content (%)	Resilient modulus (MPa)	Tension strength (MPa)
Conventional Asphalt concrete	40, 60 & 80	5,0	3 100	0,930
Polymer modified asphalt concrete	40, 60 & 80	5,0	3 000	1,030

Figure 2. LCPC traffic simulator

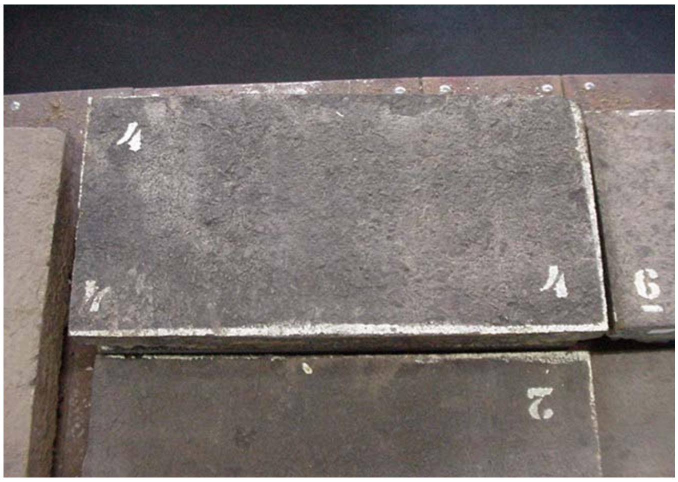

Figure 3. Specimens cored from full-scale test sections

Following LCPC recommendations, rutting evolution is accompanied plotting in a logarithm graph measured rut depths and number of loads repetitions. A model similar to that of equation 9 may be defined:

$$RD = A\left(\frac{N}{1000}\right)^{b} \qquad (9)$$

where RD = rut depth (mm), b = curve slope, A = model parameter and N = number of loading cycles.

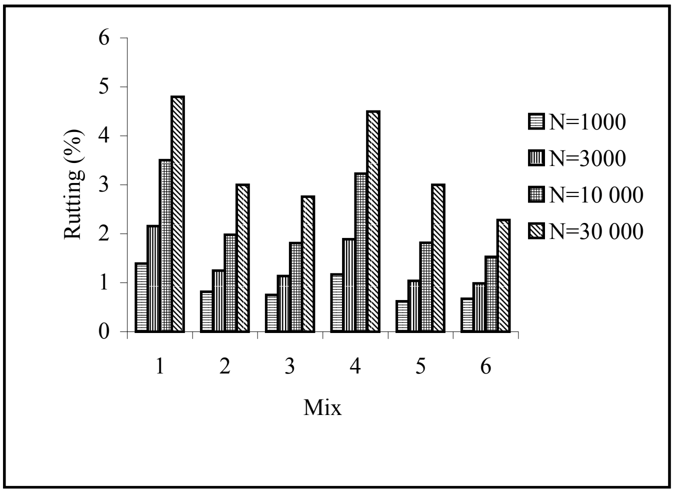

Figure 4. Laboratory tests results using LCPC simulator

3.2 Full-scale tests using UFRGS-DAER/RS traffic simulator

The UFRGS-DAER/RS traffic simulator shown in Figure 5(a) is a device used to quantify the performance of full-scale test pavements under accelerated loading (Núñez 1997, Ceratti et al. 2000).

Figure 5(b) also shows a profilometer used to measure rutting evolution in test sections. Figures 6 and 7 present rutting evolution in a test section.

Six test sections were built, presenting in common the same subgrade soil (A-7-6) and 30-cm thick densely graded rock bases. Test sections differ in wearing course nature (conventional or polymer modified asphalt concrete) and thickness (40 mm, 60 mm and 80 mm). Test sections construction was finished by September 2000.

By the time of writing this paper 164,000 standard axle loads (82 kN) had been applied. Tire pressure was fixed at 800 kPa.

The results presented in this paper were obtained during trafficking the test section with 40-mm-thick polymer modified asphalt concrete wearing course. Figure 8 relates surface rutting to measured vertical compressive stress in the top of the subgrade and 20 cm below the top of the subgrade.

(a)

(b)

Figure 5. UFRGS-DAER/RS traffic simulator and profilometer

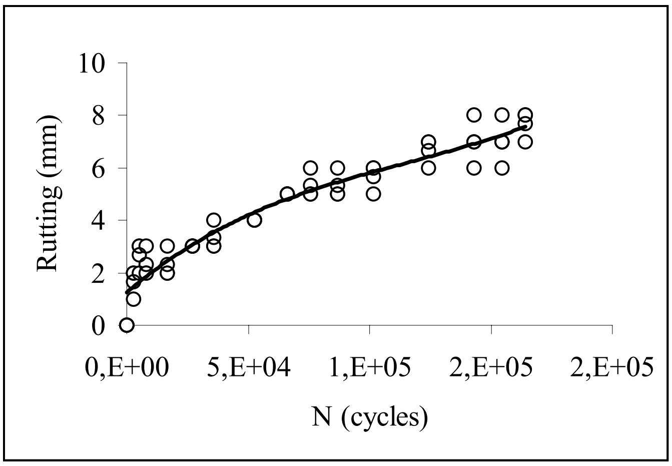

Figure 6. Rutting evolution in a test section loaded by UFRGS-DAER/RS traffic simulator

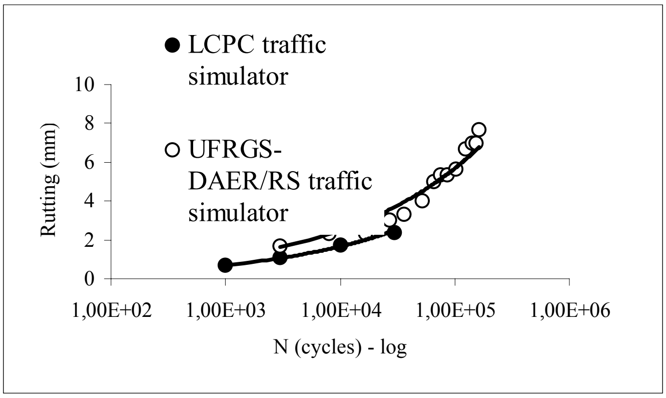

Figure 7. Comparison of rutting evolution using both traffic simulators

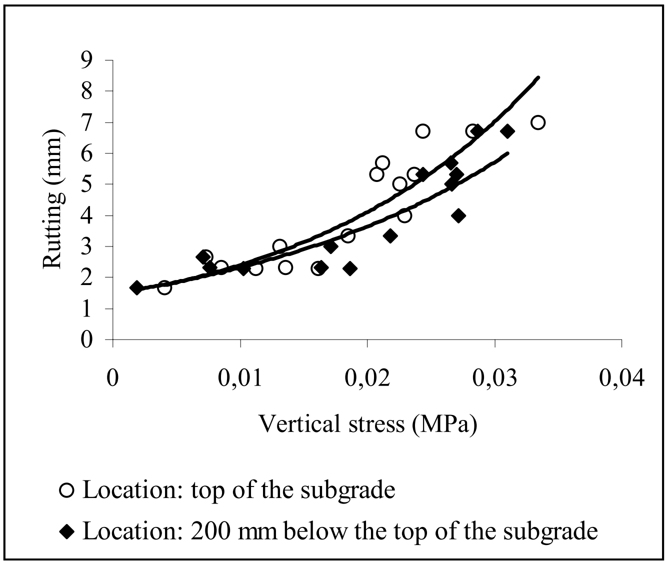

Figure 8. Rutting as a function of measured compressive stress

4 CONCLUSIONS

This article presented results of accelerated tests carried out in specimens of conventional and polymer modified asphalt mixes. A field linear traffic simulator and laboratory LCPC simulator were used.

The first results of vertical stress and rut depths measurements in a flexible pavement tested by the UFRGS-DAER/RS traffic simulator provided the experimental basis for the analysis. Vertical stresses measured using total stress cells installed in the subgrade compared well with values predicted using theoretical models.

Traffic on the first test section went on from May to October 2001. Considering the wearing course nature (polymer modified asphalt concrete) and thickness (40 mm), 13 mm rut or 60% of area cracked was established as failure criterion.

It is expected that the research results will allow by 2003 to set conclusions on the performance of asphalt mixes and on the practical application and limitations of traffic simulators used to analyse rutting of asphalt layers.

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REFERENCES

Brown, S.F. and Brunton, J. M. (1984) Improvements to pavement subgrade strain criterion. Journal of Transportation Engineering - ASCE, Vol. 110, N 6 November 1984 - pp. 551-567.

Brown, S.F. and Bell, C.A. (1977) The validity of design procedures for the permanent deformation of asphalt pavement. Proceedings of the Fourth International Conference on the Structural Design of Asphalt Pavements Proceedings, University of Michigan, Ann Arbor, pp. 467-482.

Gonçalves, F.P.; Ceratti, J.P. e Neto, L.S. (2000) Investigation on the performance of conventional and polymer modified asphalt mixes: Proposal of a study involving a linear traffic simulator. In: Proceedings of International Symposium on Pavements Maintenance and Technological Control. Institute Mackenzie, São Paulo, Brazil. In CD-Rom (In Portuguese).

Groenendjk, J.; Vogelzang, C.H.; Molenaar, A.A. and Dohmen, L.M. (1997) Rutting development in linear tracking test pavements to evaluate Shell subgrade strain criterion. Transportation Research Record, pp. 23-29.

Groenendjk, J.; Vogelzang, C.H; Miradi, A.; Molenaar, A. and Dohmen, L.M. (1997) Linear tracking performance tests on full-depth asphalt pavement. Transportation Research Record, pp. 39-47.

Ceratti, J.A., Nuñez, W.P., Gehling, W.Y., Oliveira, J.A. (2000) A full-scale study of rutting of thin pavements. Transportation Research Board, 79th Annual Meeting, Washington, D.C.

Núñez, W.P. (1997) Experimental analysis of slender pavements built with weathered basalts. Ph.D. Thesis, UFRGS/CPGEC, Porto Alegre, 294p. (In Portuguese).

Owusu-Antwi, E.B., Titus-Glover, L., and Khazanovich, L. (1998) A rutting model for implementation in mechanistic-based design procedures. Transportation Research Board, 77th Annual Meeting, Washington, D.C.

Kestler, M.A., Berg, R.L. and Moore, T.L. (1997) Reducing damage to low-volume roads by using trucks with reduced tire pressures. Transportation Research Record n.^{0} 1589, pp. 09–18.

Rodrigues, R.M. Performance prediction models for highway and airport pavements in Brazil (2000). *Final Report* FAPESP, São Paulo.

Rodway, B. and Wardle, L. (1998) Layered elastic design of heavy duty and industrial pavements - Proc. AAPA Pavements Industry Conf., Surfers Paradise, Australia, http://www.mincad.com.au/AAPA98/AAPA98f.htm

Tompson, M.R., Tutumluer, E.E. and Bejarano, M. (1998) Granular material and soil moduli, review of the literature. Final Report, COE Report n^0 1, Department of Civil Engineering, University of Illinois at Urbana Champaign, Urbana, Illinois.