Acta Scientiarum

http://www.uem.br/acta
ISSN printed: 1806-2563
ISSN on-line: 1807-8664
Doi: 10.4025/actascitechnol.v38i4.28497

Cost-benefit analysis of the construction of different flexible pavement structures considering the axle load and type of binder

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ABSTRACT. The status of Brazilian highways reflects a deficient pavement performance when they are subjected to loadings imposed by heavy traffic. Current legislation, as enacted by Contran (National Traffic Council), has increased the axle weight limit for cargo vehicles by up to 10%. Therefore, the aim of this study was to determine a cost-benefit ratio by using different types of structures, asphalt binders and load intensities. Typical pavements were determined and then analyzed by the software AEMC (SisPav) to obtain the horizontal tensile strain (εt) values at the bottom of the asphalt concrete layer and, later, the $N_{FATIGUE}$ value. It was found that the increase in weight, within values covered by legislation, might result in a reduction of approximately 50% in the $N_{FATIGUE}$ value for the pavement structures analyzed. As for economic impact, the same weight increase caused a mean increase of 120% in the cost of repeated loading on pavement structures (R\$ $N_{FATIGUE}^{-1}$). It was also observed that structures with more robust asphalt concrete layers can provide the best R\$ $N_{FATIGUE}^{-1}$ ratios. The best results for granular materials were found with thinner layers, associated with a thicker coating. The benefits of modified binders were shown by the analyses of the best structural options: both the polymer-modified binder and the rubber asphalt binder offer significant structural and economic improvements to the structure.

Keywords: fatigue, asphalt pavement, modified binders.

Análise custo/benefício de implantação de diferentes estruturas de pavimentos flexíveis considerando a carga por eixo e o tipo de ligante

RESUMO. A situação das rodovias brasileiras transparece a deficiência dos pavimentos em relação ao seu desempenho frente ao carregamento imposto pelo tráfego pesado. A legislação vigente, deferida pelo Contran, aumentou para até 10% o limite de tolerância de peso por eixo para os veículos de carga. Em vista disso, busca-se, neste trabalho, determinar uma relação custo/benefício, mediante a utilização de diferentes tipos de estruturas, ligantes asfálticos e intensidades de carregamento. Foram determinados pavimentos típicos, os quais foram analisados através do software AEMC (SisPav), para obtenção dos valores de deformação horizontal de tração (εt) no fundo do concreto asfáltico e posteriormente o valor de N_{FADIGA}. Verificou-se que o aumento de carga, dentro de valores contemplados pela legislação, pode ocasionar redução de aproximadamente 50% no valor de N_{FADIGA} para as estruturas estudadas. Em relação ao impacto econômico, o mesmo aumento de carga causou um acréscimo médio de 120% no custo por repetição de carga aplicada no pavimento (R\$ N_{FADIGA}^{-1}). Também foi possível verificar que estruturas com camadas de concreto asfáltico mais robustas proporcionam as melhores relações R\$ N_{FADIGA}^{-1}; já para os materiais granulares, obtêm-se melhores resultados com camadas mais delgadas, associadas ao revestimento mais espesso. Tratando-se dos benefícios dos ligantes modificados, constatou-se que, analisando as melhores opções estruturais, tanto o ligante modificado por polímeros quanto o ligante do tipo asfalto borracha proporcionam melhorias estruturais e econômicas significativas para a estrutura.

Palavras-chave: fadiga, pavimentos asfálticos, ligantes modificados.

Introduction

High investments in regular maintenance are required for a road network to offer adequate quality for users to drive along with comfort, safety and economy. Roads are exposed to aggressive environmental factors; furthermore, the high volume of traffic and excess loadings by different types of commercial vehicle axles may affect pavement performance.

The current legislation enacted by Conselho Nacional de Trânsito (Contran, 2014) increased the axle weight limit for vehicles by 10%. However, this rule is only valid for vehicles that do not exceed the 5% limit of total gross weight or of gross combined weight. The limit per axle remains 7.5 if the 5% total weight limit is exceeded.

In contrast with the new legislation, Brazilian highways do not show a positive response to high loadings. An alternative is to use modified asphalt binders, which can cope with the main rupture mechanisms (fatigue and permanent deformation).

Most of the literature presents performance models for the two main defects occurring in flexible pavements: fatigue cracking and permanent deformation. According to Franco (2007), performance models are limiting factors for determining structural layer thickness of pavement.

Fatigue damage to asphalt surface layer is the main cause of pavement failure in Brazil. According to Yoder and Witczak (1975), fatigue is the process of permanent structural change, progressive and located in a specific material point subject to variable amplitude stresses that produce cracks. Huang (1993) says that this cracks lead to total fracture, complete after sufficient repetitions of loading.

Preussler (1983) pioneered in Brazil to develop an experimental laboratory model to predict the asphalt mixtures fatigue performance. Pinto (1991) had introduced in Brazil scientific studies about models calibration from a laboratory/field factor, setting, in his research, curves to estimate the minimum and maximum values of the shift factor associated with specific initial tensile strain and differences in stresses on the surface layer of the analyzed sections.

Franco (2007) compiled the existing database at UFRJ (Federal University of Rio de Janeiro) and introduced three models that relate tensile strain of the asphalt layer and fatigue performance. Equations 1, 2 and 3 were determined by the author through the fatigue indirect tensile test, by diametrical compression (European standard EN 12697-24 - Comissão Europeia de Normalização [CEN], 2004). In his regressions, Franco (2007) also included test data developed by Pinto (1991), Benevides (2000), Ramos, Láo, and Farah (2000), Salini (2000), Soares, Motta, Paiva, and Branco (2000), Marques, Motta, and Leite (2001) and Dantas Neto, Farias, Leite, and Santos (2001).

Equation 1 is applicable to conventional mixtures, Equation 2 to SBS or EVA-modified binders, and Equation 3 to asphalt rubber binder.

$$N = sf * 1.904 * 10^{-6} * \left(\frac{1}{\varepsilon_t}\right)^{2.821} * \left(\frac{1}{RM}\right)^{0.74} \quad R^2 = 0.805 \quad (1)$$

$$N = sf * 4.455 * 10^{-7} * \left(\frac{1}{\varepsilon_t}\right)^{3.798} * \left(\frac{1}{RM}\right)^{1.493} \quad R^2 = 0.813 \quad (2)$$

$$N = sf * 7.26 * 10^{-3} * \left(\frac{1}{\varepsilon_t}\right)^{3.103} * \left(\frac{1}{RM}\right)^{1.918} \quad R^2 = 0.676 \quad (3)$$

where:
ε_t = horizontal tensile strain on the bottom of surface layer (m m^{-1});
RM = resilient modulus of AC (MPa);
sf = shift factor = 100000.

The Superpave™ (Superior Performing Asphalt Pavements) specification warns about the need to work with modified asphalt binders to achieve adequate performance for high traffic highways. Because of the rising cost of building materials, especially petroleum products, and the reduction in the availability of natural materials, researchers should seek new alternative materials with good performance and low cost. A large amount of research has highlighted the benefits of adding polymeric materials to asphalt binders, which include reduced thermal susceptibility and increased ductility, plus greater resistance to weathering and better binder-aggregate adhesion.

The National Infrastructure Department (Dnit) issued normative rulings for asphalt rubber in 2009 (Departamento Nacional de Infraestrutura de Transportes [Dnit], 2009a and b) and for modified polymer binders in 2011 (Departamento Nacional de Infraestrutura de Transportes [Dnit], 2011). However, the use of modified asphalt binders still encounters some resistance in Brazil, given the high cost of these products. Therefore, the present research is aimed at assessing, through a mechanistic analysis, the structural and economic performance of typical pavement structures in the State of Rio Grande do Sul, with different types of binders used in asphalt concrete layer (AC), while applying different loads (within the limits allowed by Resolution No. 489 of Contran – National Traffic Council) imposed by Twin-Wheel Single Axles.

Material and methods

In order to meet the research objectives, numerical simulations were performed by the AEMC tool of the SisPav software, while observing the effect of loading applied on the pavement and the effect of the type of binder that comprises the asphalt mixture on the $N_{FATIGUE}$ value. For each loading value, the layer thickness combinations generated 36 different structures, which were associated with 81 variations of resilient modulus, resulting in a total of 2916 data sets. The three load levels were analyzed for the data sets, totaling 8748 simulations.

The resilient modulus values were defined based on back-analysis of data collected by a falling weight deflectometer (FWD) offered by Dnit, from surveys conducted in five federal highways (BR 158, BR 285, BR 287, BR 290 and BR 392). Table 1 presents the structures and typical elastic parameters used in the composition of the data sets.

Table 1. Structures and typical elastic parameters.

Material	Height (cm)	Resilient Modulus Limits (MPa)	Poisson
Asphalt Concrete (AC)	5.0 - 7.5 - 10.0 - 12.5	3,283 – 4,280 – 5,278	0.25
Graded Gravel (GG)	12 - 15 - 18	117 - 163 - 208	0.35
Dry Macadam (DM)	16 - 21 - 32	100 - 200 - 300	0.35
Subgrade (SG)	Infinite	50 - 100 - 150	0.45

Each assessed set used loading applied by a Twin-Wheel Single Axle (TWSA) with loads of 80, 100 and 110kN, tire inflation pressure of 0.56 MPa and distance between wheels of 0.324 m. It is noteworthy that the loading values comply with the current legislation enacted by Contran.

Computer-aided mechanical pavements

To obtain the horizontal tensile strain values on the bottom of the surface layer (εt), the AEMC software, version 2.0.8.2, was used (application for elastic analysis of multilayered structures); it is part of the SisPav software developed by Franco (2007). The AEMC tool is a specific module for the calculation of stresses, strains and displacements, with routines for data entry and results. AEMC uses the multilayer elastic theory, developed by Burmister in 1945, in its routine calculation based on the program Julea and validated with the software Bisar.

For each dataset, i.e., the pavement structure with its respective resilient modulus for the constituent materials, the values of permissible fatigue solicitations ($N_{FATIGUE}$) were determined by the performance models of Franco (2007), mentioned above, for each of the three types of asphalt binders.

Costs

The survey about reference unit costs for services used in the defined structures was performed by means of the compositions of the system Sicro II (Departamento Nacional de Infraestrutura de Transportes [Dnit], 2014), with the month of March 2014 as a reference. The costs for paving a Class I Highway, located in Santa Maria (Rio Grande do Sul State), were taken in account. Figure 1 shows the section type and its constituent layers.

The unit cost of transportation for bituminous materials was determined through the methodology exemplified in the operating instruction Dnit-IS/DG n° 02 of January 18, 2011, (Departamento Nacional de Infraestrutura de Transportes [Dnit], 2011) which defines pricing equations for calculating the base cost of transportation for hot and cold bituminous materials, on different surfaces, using the ratio between the paving index of Fundação Getúlio Vargas (FGV) and the reference index of transportation equations. The value-added tax for the State of Rio Grande do Sul (ICMS) of (17%) was added. The determination of the unit cost per tonne for transportation of bituminous materials is exemplified in Table 2.

The costs of asphalt materials were calculated using data for the month of March 2014, provided by the Office for Defense of Competition (CDC) of the National Agency of Petroleum, Natural Gas and Biofuels (ANP), according to the decree no. 349 of March 6, 2010.

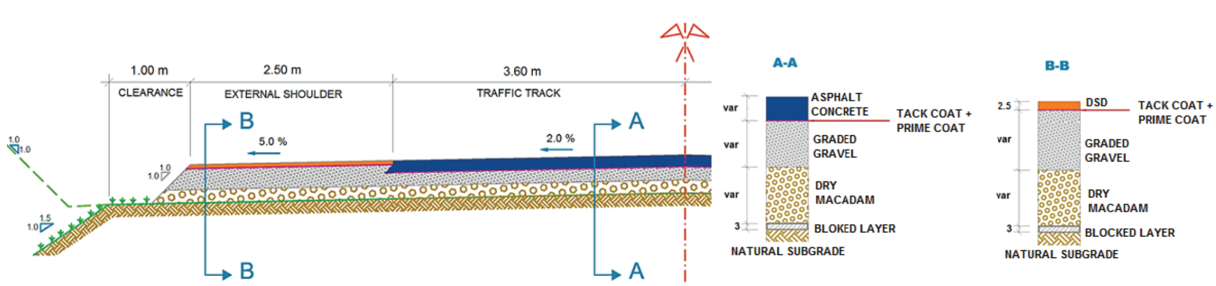

Figure 1. Section type for a class I highway for cost analysis and transversal section A-A and B-B presenting the composition of layers.

Table 2. Determination of transportation cost for bituminous materials.

Based on IS/ DG number 02 of January, 18th, 2011							
Base cost (R$ t^{-1})		Paving index FGV		Corrected cost (R$ t^{-1})		Final cost with ICMS 17% increase	
Hot: Cb = 22.715 + 0.247 x D	Cold: Cb = 22.244 + 0.223 x D	January, 2009	March, 2014				
		224.886	267.583	Hot	Cold	Hot	Cold
96.82	89.14	Correction factor:	1.1899	115.20	106.07	138.79	127.79

The final unit prices for asphalt concrete, binder paint, primer, graded gravel, dry macadam, blocking layer and double surface treatment, were found by adding profits and overheads (PO) of 28.98% to the base cost for materials, equipment and manpower. Asphalt binder content of 5.5% was observed for the conventional binder (CAP 50/70) and the polymer-modified binder (SBS 60/85); for the asphalt rubber binder, (AB 08) 6.5% content was considered. As for acquisition and transportation, 15% PO was added.

Table 3 presents a summary of the final unit price for each of the different services. For asphalt binders, the final cost with added state VAT resulted in R$ 1,081.46 tonne^{-1} for CAP 50/70; R$ 1,586.14 tonne^{-1} for AB/08; R$ 2,004.05 tonne^{-1} for SBS 60/85.

Results and discussion

Based on the $N_{FATIGUE}$ values calculated for each structure, data were crossed, seeking the sets that provide the highest performance with the lowest pavement cost, namely, the most economical sets with the best performance.

Figure 2 shows, for loading applied by the TWSA, the value of 80kN and the pavement cost-$N_{FATIGUE}$ ratio, considering the three types of binders in the composition of the asphalt mixture.

The dispersion of the points in Figure 2 and also the low coefficients of determination (R^2) show that even if the $N_{FATIGUE}$ value tends to increase as costs increase, there is no single standard in the distribution of sets in the cost km^{-1} ratio for the fatigue model, i.e. sets at the same cost may have very different performance in the field. The same situation occurs for loadings of 100 and 110 kN.

Therefore, to interpret the results, a decision was made to use a ratio that represents the cost per repeated loading on the pavement (R$ $N_{FATIGUE}^{-1}$) for each different situation of loading and use of asphalt binder. Thus, the influence of load and type of binder on $N_{FATIGUE}$ and the R$ $N_{FATIGUE}^{-1}$ ratio was evaluated; moreover, the best structural options were identified in terms of cost-benefit ratio for the different types of binders.

Effect of axle weight on $N_{FATIGUE}$ and cost-benefit ratio

The three different loading values applied by the TWSA in the present study (80, 100 and 110 kN) comply with the current legislation. According to the recent resolution enacted by Contran, the 110 kN value is the maximum load value tolerated for this axle.

Figure 3 respectively shows, for the use of structures with conventional asphalt binder, SBS polymer- modified binder and rubber asphalt binder, data crossing between cost (R$ $N_{FATIGUE}^{-1}$) and $N_{FATIGUE}$ for the 2916 sets in each one of the applied loadings.

Table 3. Final unit price of different services.

Asphalt Concrete – Traditional asphalt binder (m^3)	Asphalt Concrete – SBS polymer – modified asphalt (m^3)	Asphalt Concrete – Asphalt rubber binder (m^3)	Tack coat (m^2)	Prime coat (m^2)	Graded Gravel (m^3)	Macadam (m^3)	Blocked Layer (m^3)	Double Surface Dressing (m^2)
R$ 530.17	R$ 671.68	R$ 651.68	R$ 0.78	R$ 2.83	R$ 233.55	R$ 214.82	R$ 192.09	R$ 9.01

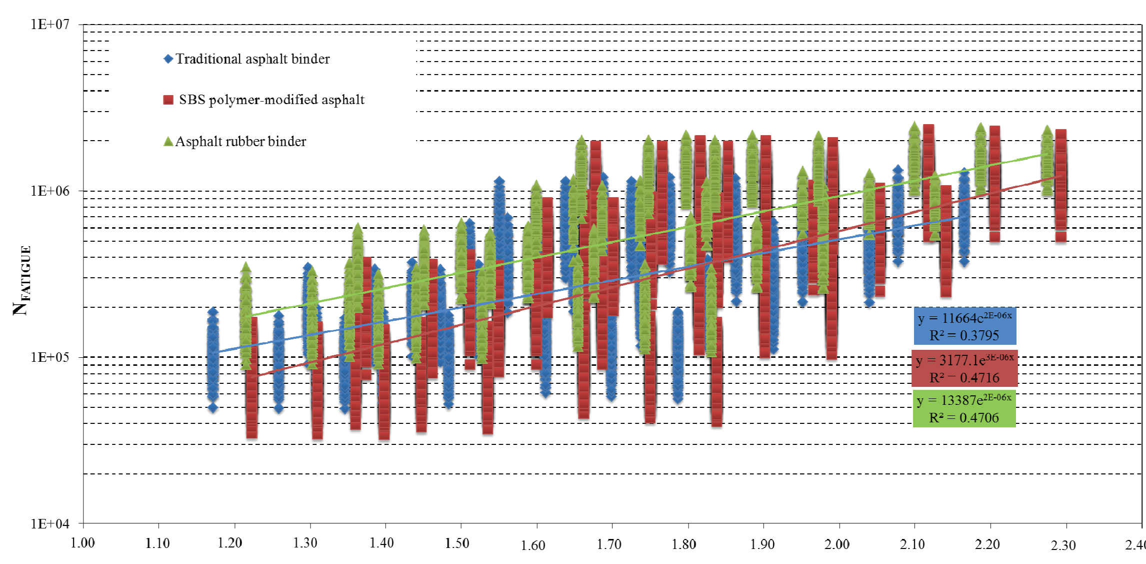

Figure 2. Ratio between $N_{FATIGUE}$ and cost km^{-1} for fatigue models with axle load of 80 kN.

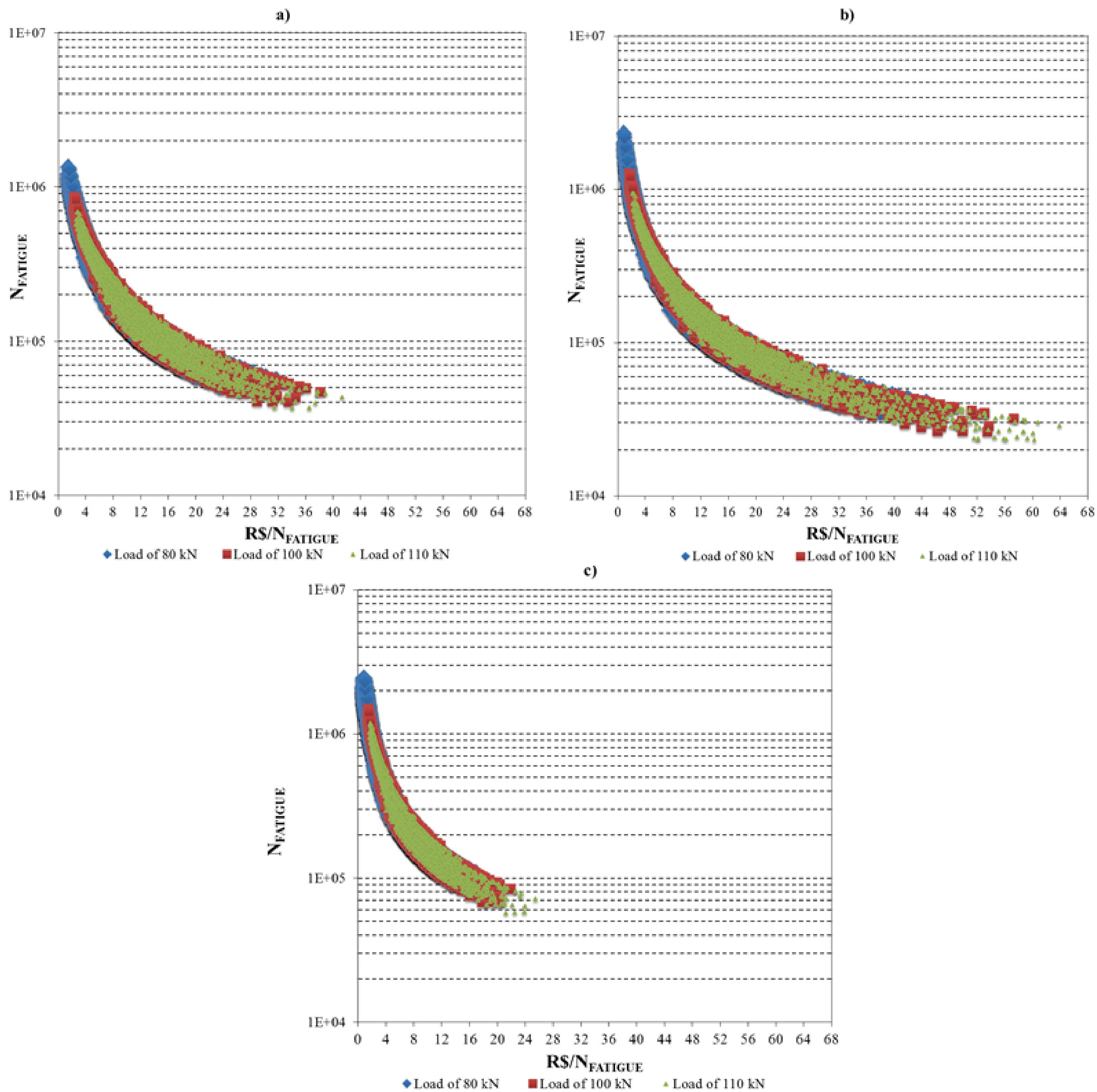

Figure 3. Crossing between cost km $N_{FATIGUE}^{-1}$ and $N_{FATIGUE}$ for the following structures: a) traditional asphalt binder; b) SBS polymer-modified binder; c) asphalt rubber binder.

Clearly, it is noted that the higher the loading, the lower the $N_{FATIGUE}$ values and the higher the values for the R$ $N_{FATIGUE}^{-1}$ ratio. For a more objective interpretation of the results, the hundred most economical sets obtained by the R$ $N_{FATIGUE}^{-1}$ ratio were observed for each different situation of applied loading and binder used in the composition of the asphalt concrete layer.

Table 4 presents, through an average percentage, the effect caused by the load increase on the $N_{FATIGUE}$ value. As expected, for the one hundred most economical sets composed of any of the three types of asphalt binders, the load increase causes significant average percentage reduction in $N_{FATIGUE}$. The sets composed of asphalt rubber binder have an intermediate behavior compared with the percentage calculated for the same sets assessed with the other two types of binders; that is, the asphalt rubber binder is slightly more sensitive to load increase than the conventional binder, but less sensitive than the polymer-modified binder.

Table 4. Effect caused by load increase on $N_{FATIGUE}$ of evaluated sets with different asphaltic binders.

Load increase	Effect caused by load increase on $N_{FATIGUE}$		
	Traditional asphalt binder	SBS polymer-modified asphalt	Asphalt rubber binder
80 → 100 kN	↓36.9%	↓46.4%	↓39.2%
80 → 110 kN	↓49.2%	↓59.9%	↓52.1%

Table 5 presents the same average percentage, considering the most economical hundred sets evaluated for each type of asphalt binder, representing the increase in the value of the R$ $N_{FATIGUE}^{-1}$ ratio, when the load was increased from 80 to 100 and from 80 to 110 kN.

Table 5. Effect caused by load increase on the R$ $_{FATIGUE}^{-1}$ ratio of the evaluated sets with different asphalt binders.

Load increase	Effect caused by load increase on $N_{FATIGUE}$		
	Traditional asphalt binder	SBS polymer-modified asphalt	Asphalt rubber binder
80 → 100 kN	↑ 58.9%	↑ 85.3%	↑ 64.3%
80 → 110 kN	↑ 98.4%	↑ 149.4%	↑ 109.0%

It can be seen that the increase percentages of the R$ $N_{FATIGUE}^{-1}$ ratio, caused by the increase in axle load, obtained with the SBS polymer modified binder, rose considerably compared with the structures using conventional binder and asphalt rubber binder. Clearly, the structures composed of the polymer-modified binder are more economically sensitive to the load increase applied on the pavement.

In general terms, the 37.5% load increase (80 to 110 kN) caused approximately a 50% reduction in the $N_{FATIGUE}$ value and average increases of 120% in the R$ $N_{FATIGUE}^{-1}$ ratio, with the three different binders.

Effect of type of binder on $N_{FATIGUE}$ and cost-benefit ratio

At this point, the aim of the study was to identify the effect caused by the type of asphalt binder on the structural and economic performance of the sets. Table 6 presents, through an average percentage calculated with the hundred most economical sets, the effect caused by the change of binders on the assessed $N_{FATIGUE}$ value for each of the loadings applied by the TWSA.

Table 6. Effect caused by changing asphaltic binders on the $N_{FATIGUE}$ value of the evaluated sets with different loads.

Replacement of asphalt binder	Effect caused by changing asphalt binder in $N_{FATIGUE}$		
	80 kN	100 kN	110 kN
Traditional asphalt binder → SBS polymer-modified asphalt	↑ 63.3%	↑ 38.7%	↑ 28.6%
Traditional asphalt binder → Asphalt rubber binder	↑ 92.9%	↑ 85.9%	↑ 81.9%

Modified binders had a very satisfactory performance compared with the $N_{FATIGUE}$ values of the most economical sets. The percentage increase in the $N_{FATIGUE}$ value, caused by the use of rubber asphalt in replacement of the conventional binder, was more than 80% for the three different loadings.

The SBS polymer modified binder also had better results than the conventional one, surpassing the 60% increase in the $N_{FATIGUE}$ value when the loading applied by the TWSA was 80 kN. As the loading is increased, the percentages still show the advantage of using this type of asphalt binder, although in a smaller proportion.

As far as the R$ $N_{FATIGUE}^{-1}$ ratio is concerned, Table 7 presents the average effect caused by changing the type of asphalt binder (calculated by the average of the one hundred most economical sets), with the different applied loadings.

Table 7. Average effect caused by changing asphaltic binders on the R$ $N_{FATIGUE}^{-1}$ ratio of the evaluated sets with different loads.

Replacement of asphalt binder	Effect caused by changing asphalt binder in relation to R$ $N_{FATIGUE}^{-1}$		
	80 kN	100 kN	110 kN
Traditional asphalt binder → SBS polymer-modified asphalt	↓ 32.6%	↓ 21.4%	↓ 15.2%
Traditional asphalt binder → Asphalt rubber binder	↓ 44.8%	↓ 42.9%	↓ 41.8%

The replacement of asphalt concrete with conventional binder with AC with modified binders (both SBS polymers and rubber) caused an average percentage reduction in the R$ $N_{FATIGUE}^{-1}$ ratio for the three different loadings applied by the TWSA.

When the conventional binder was replaced with asphalt rubber binder, it was noted that the change in binders alone reduced the cost per repeated load by over 40% for the three different applied loadings. When the conventional binder was replaced with the polymer-modified binder, there was also higher performance, but to a lesser extent as the loading was increased.

Structures with the best cost-benefit ratio

Table 8 presents the layer thickness and the resilience modules of the extreme sets with the best and worst performances for the R$ $N_{FATIGUE}^{-1}$ ratio, considering all cases evaluated for asphalt concrete with conventional binder, SBS polymer modified binder and rubber asphalt binder. It is worth pointing out that the sets with the best and worst performances, considering all cases evaluated for the polymer-modified asphalt binder and the rubber asphalt binder, were not the same for the three different levels of axle load applied. However, the assessment of five cases of best and worst performances, found in the results of each of the three different axle loads evaluated, showed extreme sets that are repeated in the three loadings.

Table 8. Sets of best and worst performances for the R$ $N_{FATIGUE}^{-1}$ ratio.

	Traditional asphalt binder						
	Structures			Resilient Modulus			
	AC (cm)	GG (cm)	DM (cm)	RM AC (MPa)	RM GG (MPa)	RM DM (MPa)	RM SG (MPa)
Best performance	12.5	12	16	5.278	208	400	150
	12.5	12	21	5.278	208	400	150
	12.5	12	16	5.278	208	400	150
Worst performance	5	18	32	3.283	117	200	150
	5	18	32	3.283	117	200	100
	5	18	32	3.283	117	200	50
	SBS polymer-modified asphalt						
	Structures			Resilient Modulus			
	AC (cm)	GG (cm)	DM (cm)	RM AC (MPa)	RM GG (MPa)	RM DM (MPa)	RM SG (MPa)
Best performance	12.5	12	21	5.278	208	400	150
	12.5	12	16	5.278	208	400	150
	12.5	12	32	5.278	208	400	150
Worst performance	5	18	16	3.283	117	200	50
	5	18	21	3.283	117	200	50
	5	18	32	3.283	117	200	50
	Asphalt rubber binder						
	Structures			Resilient Modulus			
	AC (cm)	GG (cm)	DM (cm)	RM AC (MPa)	RM GG (MPa)	RM DM (MPa)	RM SG (MPa)
Best performance	12.5	12	16	5.278	208	400	150
	12.5	12	21	5.278	208	400	150
	12.5	12	16	5.283	208	400	150
Worst performance	5	18	21	5.278	117	200	50
	5	18	32	5.278	117	200	100
	5	18	32	5.278	117	200	50

It can also be seen that the asphalt concrete module affects the classification of the data set; for the conventional binder, over 85% of cases have the most resilient moduli (5278 MPa) used when the applied load was 80 kN; the situation was repeated when axle loads were 100 and 110 kN. The first hundred sets obtained by using the polymer-modified binder followed the same pattern: more than 70% of the cases showed the greatest resilient modulus adopted in three different evaluated loadings. When the asphalt rubber binder was used, the behavior of the sets changed; the greatest resilient modulus (5278 MPa) appear in less than 40% of the occurrences for the three different loading levels. There is also an intermediate modulus (4.280 MPa) in the AC layer for more than 30% of the cases, for the three loads applied on the pavement.

For the base of simple graded gravel (SGG), when the three different types of asphalt binders were used, smaller thicknesses (associated with higher AC thicknesses) was produced the best cost-benefit ratios. A condition of very thick granular layers and low stiffness does not contribute to pavement performance against fatigue cracking. In the case of the asphalt layer with conventional binder, approximately 43% of the occurrences of the first one hundred positions had the thickest granular base used in the data sets (12 cm) for the 80, 100 and 110 kN loads. In addition, it is noteworthy that in the three different loadings, over 30% of the cases had intermediate thickness (15 cm). For the other evaluated binders, the occurrences showed similar behavior to that of the conventional binder, with only minor percentage differences.

Regarding the resilient modulus of SGG, as expected, for the structures of conventional asphalt binder, 53% of events had the highest determined resilient modulus (208 MPa) for graded gravel at three different loading levels applied on the surface. For the sets of polymer-modified asphalt binder and those with rubber asphalt, about 60 and 70%, respectively, have the highest RM adopted for the granular base evaluated for the three different axle loads.

The dry macadam sub-base (DM) showed that good results in the cost-benefit ratio might be obtained with small thicknesses. Approximately 40% of sets with conventional asphalt binder have a thinner determined granular sub-base (16 cm), for loadings of 80, 100 and 110 kN. In the first hundred positions of the sets comprised of rubber asphalt binder, the behavior was analogous to that of the conventional binder, while in sets with polymer-modified asphalt binder, it should be noted that approximately 35% of cases have the lower thickness deployed for the sub-base and 35% have intermediate thickness (21 cm).

Regarding the RM of the dry macadam, more than 50% of cases have the greatest resilient moduli determined for the material (300 MPa) in the three loadings for the sets with conventional and polymer-modified asphalt binder. For groups with asphalt rubber binder, over 60% of cases have the dry macadam with resilient modulus of 300 MPa.

The subgrade resilient modulus was an important factor in the cost-benefit analyses, and for sets with conventional binder as well as for sets with polymer-modified binder, over 70% of cases have the highest resilient modulus determined (150 MPa) for the three axis loads. For groups with rubber asphalt, 84% of the occurrences presented resilient modulus of 150 MPa for all three loads, and showed a significant increase of over 10% compared to the previously discussed binders.

Conclusion

Based on the numerical simulations carried out in accordance with the methodological procedures of the present study, it was concluded that:

a) The increased load applied by the studied axle (TWSA) from 80 to 110 kN (within the load range allowed by the new law enacted by Contran) implies in a reduction of approximately 50% (mean decrease of assessed sets) in the $N_{FATIGUE}$ value. This reduction occurred for the two assessed sets with three different types of asphalt binders used in the composition of the coating layer. The economic impact of this increase also has a significant magnitude, and the same load increase by the TWSA caused an average increase of 120% in the cost per repeated load applied to the pavement. For structures with polymer-modified binder, this percentage was more than 140%. Nevertheless, the increased load from heavy vehicles is a point of no return in the face of technological advances in the automotive industry. The increase in the maximum legal axle load, regulated by the recent legislation, just follows this trend. Road engineers must be prepared for that, and use more robust structures and better asphalt mixtures to adequately support the new road loads.

b) In terms of performance of the modified binders, both the rubber asphalt and the polymer-modified binder showed better economic and structural performance over conventional asphalt binder, especially the asphalt rubber binder, which has increased by over 80% the $N_{FATIGUE}$ value in three different loads, and reduced by more than 40% the cost per repeated load as compared with structures with conventional binder. The percentages generated by the structures with polymer-modified binder were also higher, resulting in an increase of over 60% in $N_{FATIGUE}$ and reduction of more than 30% in the cost per repeated load when the applied axle load was 80 kN.

c) Among the best combinations analyzed for the cost of repeated load, it was determined that the largest measured asphalt concrete thickness (12.5 cm) is the best option for structures with any one of the three evaluated binders. Regarding the granular layers (base and sub-base), it was observed that lower thicknesses, associated with thicker AC layers, result in better R$ $N_{FATIGUE}^{-1}$ ratios with the three different asphalt binders. As for stiffness of the materials, it was observed that all layers showed the best cost-benefit results (for three different asphalt binders) when the pavement components were evaluated with their maximum resilient moduli.

Acknowledgements

The author would like to thank ANP/Petrobras, CNPq and Capes for financial support and grants.

References

Benevides, S. A. S. (2000). *Análise comparativa dos métodos de dimensionamento de pavimentos asfálticos: empírico do DNER e da resiliência da COPPE/UFRJ em rodovias do estado do Ceará* (Dissertação de Mestrado). Universidade Federal do Rio de Janeiro. Rio de Janeiro, RJ.

Comissão Europeia de Normalização. (2004). *EN 12697 – 24. Bituminous mixtures. Test methods for hot mix asphalt. Part 24: Restistance to fadigue*. Bruxelas, BE: CEN.

Conselho Nacional de Trânsito. (2014). *Resolução n° 489. Fixa metodologia de aferição de peso de veículos, estabelece percentuais de tolerância de dá outras providências*. Brasília, DF: Cotran.

Dantas Neto, S. A., Farias, M. M., Leite, L. F. M., & Santos, C. C. (2001). *Estudo da influência do tipo de ligante nas características mecânicas das misturas asfálticas*. In 33ª Reunião Anual de pavimentação – ABPv. Florianópolis, SC.

Departamento Nacional de Infraestrutura de Transportes. (2009a). *Pavimentos flexíveis – Concreto asfáltico com asfalto-borracha via úmida, do tipo "Terminal Blending". Norma 112/2009 – ES*. Rio de Janeiro, RJ: Dnit.

Departamento Nacional de Infraestrutura de Transportes. (2009b). *Pavimento flexível – Cimento asfáltico modificado por borracha de pneus inservíveis pelo processo via úmida, do tipo "Terminal Blending". Norma 111/2009 – EM*. Rio de Janeiro, RJ: Dnit.

Departamento Nacional de Infraestrutura de Transportes. (2011). *Cimento asfáltico de petróleo modificado por polímero elastomérico. Norma 129/2011 – EM*. Rio de Janeiro, RJ: Dnit.

Departamento Nacional de Infraestrutura de Transportes. (2014). *Custos e pagamentos - SICRO II/ Sul (março de 2014)*. Retrieved from: http://www.dnit.gov.br/servicos/sicro/sul

Franco, F. A. C. P. (2007). *Método de dimensionamento mecanístico-empírico de Pavimentos asfálticos – SisPav* (Tese de Doutorado). Universidade Federal do Rio de Janeiro. Rio de Janeiro, RJ.

Huang, Y. H. (1993). *Pavements analysis and design*. Englewood Cliffs, NJ: Prentice-Hall.

Marques, G. L. O., Motta, L. M. G., & Leite, L. F. M. (2001). *Exemplos de dosagem SUPERPAVE no Brasil*. In 33ª Reunião Anual de Pavimentação – ABPv. Florianópolis, SC.

Pinto, S. (1991). *Estudo do comportamento à fadiga de misturas betuminosas e aplicação na avaliação estrutural de pavimentos* (Tese de Doutorado). Universidade Federal do Rio de Janeiro. Rio de Janeiro, RJ.

Preussler, E. (1983). *Estudo da deformação resiliente de pavimentos e aplicação ao projeto de camadas de reforço* (Tese de Doutorado). Universidade Federal do Rio de Janeiro. Rio de Janeiro, RJ.

Ramos, C. R., Láo, V. L. E. S. T., & Farah, H. (2000). *Avaliação do desempenho de asfalto de alto índice a nível de laboratório e de campo*. Rio de Janeiro, RJ: IBP.

Salini, R. B. (2000). *Utilização de borracha reciclada de pneus em misturas asfálticas* (Dissertação de Mestrado). Universidade Federal de Santa Catarina. Florianópolis, SC.

Soares, J. B., Motta, L. M. G., Paiva, J. P., & Branco, J. V. C. (2000). *Propriedades mecânicas de misturas asfálticas com variação de granulometria e de CAP*. Rio de Janeiro, RJ: IBP.

Yoder, E. J., & Witczak, M. W. (1975). *Principles of pavement design*. New York City, NK: John Wiley e Sons.

Received on July 11, 2015.
Accepted on April 6, 2016.