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Identification of Elastic Response of Asphalt Pavements Layers Using Deflectometric Tests With Different Load Levels

Identificação da Resposta Elástica das Camadas de Pavimentos Asfálticos por Meio de Ensaios Deflectométricos com Diferentes Níveis de Carga

Lucas Dotto Bueno[1], Deividi da Silva Pereira[2], Luciano Pivoto Specht[2], Cleber Faccin[3], Ana Helena Back[1], Elemar Taffe Júnior[4], Fernando Dekeper Boeira[5] & Mauricio Silveira dos Santos[6]

[1]Universidade Federal de Santa Maria, Campus Cachoeira do Sul, Coordenação Acadêmica, Santa Maria, RS, Brasil
[2]Universidade Federal de Santa Maria, Departamento de Transportes, Santa Maria, RS, Brasil
[3]Universidade Federal de Santa Maria, Programa de Pós-Graduação em Engenharia Civil, Santa Maria, RS, Brasil
[4]Pavesys Engenharia Ltda, Porto Alegre, RS, Brasil
[5]CCR Viasul, Porto Alegre, RS, Brasil
[6]Universidade Federal do Pampa, Campus Alegrete, Coordenação Acadêmica, Alegrete, RS, Brasil

E-mails: lucas.bueno@ufsm.br; dsp@ufsm.br; luspecht@ufsm.br; crfaccin@gmail.com; anahback@hotmail.com; taffe@pavesys.com.br; fernando.d.boeira@gmail.com; mauriciosilveira@unipampa.edu.br
Corresponding author: Lucas Dotto Bueno; lucas.bueno@ufsm.br

Abstract

It is a unusual practice in national new pavement designs and rehabilitations to consider the nonlinear elastic behavior of the materials that constitute or will constitute the pavement layers. However, the linear elastic response is a simplification of the actual pavement layers behavior, since the materials used in the structure have stiffness dependent on the stress state (granular layers and subgrade) or on the temperature and time of load application (asphalt concrete). In view of this, this paper aims to study the elastic behavior of the pavement structures of two monitored sites in the city of Santa Maria/RS, through tests with FWD equipment, applying four different levels of loading on the full extension of these two sites. In these structures, the pavements showed a tendency to stiffening with increasing load acting at initial measuring distances (near the FWD load application point), which represent the elastic compression of all layers that make up the pavement. The measuring distances farther from the load application point, referring to the elastic compression of the subgrade, indicated, in most cases, a tendency to linear behavior of the load-deflection relationship in both sites. The backcalculated resilience modulus confirmed the impressions drawn from the load-deflection relationships, indicating the nonlinear elastic behavior of the granular layers (base and sub-base) of the analyzed sites, with resilience modulus directly proportional to the increase of the confining stress. The subgrade of the experimental sites exhibited varied behavior, and could be simplified by linear elasticity, without considerable loss. The same fact happened for the asphalt concrete material used in the pavement of site 1. For site 2, the backcalculated modulus indicated asphalt concrete stiffness dependent on the vertical surface stress increment at the center of the load plate.

Keywords: Falling Weight Deflectometer; Backcalculation; Nonlinearity

Resumo

Não é prática usual, em projetos nacionais de pavimentos novos e restaurações, a consideração do comportamento elástico não linear dos materiais que constituem, ou que irão constituir as camadas do pavimento. Todavia, a resposta elástica linear é uma simplificação do comportamento real das camadas dos pavimentos, já que os materiais empregados na estrutura possuem rigidez dependente do estado de tensões (camadas granulares e subleitos) ou da temperatura e tempo de aplicação de carga (concretos asfálticos). Em vista disso, buscou-se estudar o comportamento elástico das estruturas dos pavimentos de dois trechos monitorados, na cidade de Santa Maria/RS, mediante ensaios com o equipamento FWD, aplicando quatro diferentes níveis de carregamentos em cada estaca que compõe a extensão dos dois trechos. Nessas estruturas, os pavimentos indicaram tendência ao enrijecimento com o aumento da carga atuante

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nas distâncias iniciais de leituras (próximas do ponto de aplicação de carga do FWD), as quais representam a compressão elástica de todas as camadas que constituem o sistema. As distâncias de leitura mais afastadas do ponto de aplicação de carga, referentes à compressão elástica do subleito, indicaram, na maioria dos casos, tendência ao comportamento linear da relação carga-deflexão nos dois trechos. Os módulos de resiliência retroanalisados confirmaram as impressões retiradas das relações carga-deflexão, indicando o comportamento elástico não linear das camadas granulares (base e sub-base) dos trechos analisados, com módulo de resiliência diretamente proporcional ao incremento da tensão confinante. Os subleitos dos segmentos experimentais exibiram comportamento variado, podendo ser simplificados pela elasticidade linear, sem prejuízo considerável. O mesmo aconteceu para o material asfáltico empregado no revestimento do Trecho 1. Para o Trecho 2, os módulos retroanalisados indicaram rigidez do concreto asfáltico dependente do incremento da tensão vertical na superfície no centro da placa de carga.

Palavras-chave: Falling Weight Deflectometer; Retroanálise; Não Linearidade

1 Introduction

A pavement, approached from a mechanistic point of view, can have its structural response estimated by calculating the stresses, strains and displacements generated in the structure. For this to be possible, in addition to the composition of the traffic, the layers must be characterized from their thicknesses and the elastic parameters of the materials that constitute them.

To estimate the efforts originated by the action of traffic, the materials can be considered according to different behaviors of the stress-strain relationship. The elasticity theory is widely used as a calculation tool; however, according to Macêdo (1996); Motta (1991) and Yoder and Witczak (1975), assuming a linear elastic response is a simplification of the real behavior presented by pavement layers, as these materials are often heterogeneous and anisotropic, with discontinuities, cracks and poorly known bonding conditions.

Asphalt mixtures and granular materials do not exhibit linear elastic behavior and their stress-strain relationships have already been interpreted by tests that approximate the stress state and loading conditions to which they will be subjected on the road. In existing pavements, an alternative to obtain the elastic parameters of the materials, in order to avoid the collection of samples on the road, is the process of backcalculation, consolidated as an important tool in the analysis of pavements structural condition since the 1980s, with the pioneering work of Ali and Khosla (1981); Bush III and Alexander (1985); Hoffman and Thompson (1982); Ullidtz and Stubstad (1985), among others.

Backcalculation procedure is performed based on results from non-destructive deflectometric tests, usually performed with Falling Weight Deflectometer (FWD) equipment. According to Ullidtz and Stubstad (1985) and Wang and Lytton (1993), the form of the load transmitted to the pavement by FWD equipment is similar to that obtained from a moving wheel load; that is, this type of device is able to reproduce displacements similar to the real ones, produced by the passage of heavy vehicles over the surface of the structure. Thus, from tests with FWD, performed with various load levels, it is possible to verify the behavior of the linear or nonlinear relationship between load and deflection.

The interpretations can also be transferred to the results determined with backcalculation procedures, performed from the deflection basins tested, with different loads, identifying their consequences on the resilience modulus of the pavement layers, according to the conditions existing in the field. The linear elastic behavior of the structure is identified when the backcalculated modulus does not vary according to the basins determined after different loading levels. If the stiffness of the materials changes according to the loads, the response of one or more layers of the pavement is nonlinear (Bueno 2016).

In the rehabilitation design of existing pavements, the techniques obtained from the backcalculated resilience modulus and the possibility of calculating stresses, strains and displacements through computer programs, brought new possibilities for designers, replacing the purely empirical methodologies. In the current technical scenario, the road sector mostly considers the behavior of the materials that make up the pavement structure as linear elastic. However, laboratory tests often provide results of material stiffness dependent on the stress state (in the case of cohesive soils and granular materials) or temperature conditions and load application time (in the case of asphalt mixtures), indicating a trend towards nonlinear elasticity, or even viscoelasticity of one or more layers of the structure. Within this context, it is possible to employ, in mechanistic analyses, modeling based on the response of materials when subjected to dynamic laboratory tests or non-destructive tests performed with FWD in the field.

In order to contribute to this discussion, the present study aims to determine the behavior of the relationship between load and deflection, as well as its consequences on the backcalculated resilience modulus, referring to the layers that constitute two different pavements, monitored in the city of Santa Maria, in the state of Rio Grande do Sul, through the variation of applied load with Falling Weight Deflectometer (FWD) tests.

2 Materials and Methods

To reach the objective proposed by this study, two sites (new pavement structures), located in the city of Santa Maria (RS), were monitored by performing deflectometric tests with FWD equipment.

The monitoring of sites implementation, in the different stages of pre-execution, execution and post-execution, as well as the complete characterization of the traffic, materials and construction methods employed in the two sites, are described in detail in the works of Bueno (2016, 2019); Bueno et al. (2020) and Santos (2015). Table 1 summarizes the main characteristics of the two sites monitored during this research.

2.1 Deflectometric Evaluation

Every six months, deflectometric tests were performed with FWD equipment in all the extension of the two monitored sites (280 meters). The testing campaigns were carried out over a period of two years, totaling four campaigns of surveys with the FWD.

In this study, the KUAB FWD 50 model was used, according to the requirements contained in the ASTM D4695-03 (2020a) and D4694-09 (2020b) specifications. This equipment allows the determination of the deflectometric basin in seven points and has attached to its structure a distance meter (digital odometer) with a resolution of 1.0 m, automatic air and pavement temperature meter with a resolution of 0.5 °C and accuracy of +/- 1 °C (between -18 °C and +70 °C), and a metric precision GPS with geographic coordinates. Field tests were performed with FWD equipment from Pavesys Engenharia S/S Ltda - Epp (partner throughout the development of this research) (Figure 1).

Four different loads (20, 40, 60, and 80 kN) were applied to each site, transmitted to the pavement by a plate with an application radius equal to 150 mm. For each load, two tests were replicated in sequence, at the same position.

The LVDTs of the FWD equipment obeyed the distances shown in Table 2, adopted as standard for these tests in the two monitored sites. It is understood that this form of positioning reflects the contribution of the various layers in the total pavement displacement, defining completely the basin geometry.

To identify the behavior of the structure load-deflection relationship, the deflectometric basins measured in the two monitored sites were evaluated. Every 20 meters, in the different sites, it was tested eight deflectometric basins, two of them referring to each load applied by FWD. The respective basins were interpreted separately, with the seven sensors, from the load application point, where the LVDTs took the deflection measuring. The objective was to identify, at each of the sensors, the linearity or nonlinearity of the structure's load-deflection behavior.

To evaluate the behavior of the deflectometric basins as the FWD equipment loading is increased, Macêdo (1996) suggests Equation 1, that was applied to determine the pavement structure degree of linearity (GL) in the monitored sections.

$$GL = \frac{R_D}{R_C} \quad (1)$$

where:

GL = degree of linearity;

R_C = ratio between applied loads P2/ P1;

R_D = ratio between the deflections (D2/D1) due to P2 and P1;

The following criteria (with their respective abbreviations) were therefore defined to identify the trend of the structures' behavior globally:

Degree of linearity between 0.95 and 1.05 = tendency to linear behavior of the structure (L);

Degree of linearity greater than 1.05 = tendency for the structure to soften with increasing load (A);

Linearity degree lower than 0.95 = tendency to stiffening of the structure with the increase of the acting load (E).

Table 1 Monitored sites summary characteristics.

Location		Site 1	Site 2
		Hélvio Basso Avenue	BR-158
Annual Traffic		NUSACE = 1.06x10^6	NUSACE = 1.20x10^6
Structure	Asphalt Concrete	60 mm	75 mm
	Granular Base	200 mm	150 mm
	Granular sub-base	400 mm	150 mm
	Subgrade Reinforcement	–	400 mm
	Subgrade	A-6 (TRB)	A-6 (TRB)

Figure 1 FWD equipment used to perform the deflectometric tests.

Table 2 Sensors positioning for the formation of deflectometric basins.

D_0 (mm)	D_1 (mm)	D_2 (mm)	D_3 (mm)	D_4 (mm)	D_5 (mm)	D_6 (mm)
0	200	300	450	600	900	1200

It is worth highlight that this evaluation provides only an index and not an absolute value, because it considers only two load levels. Even with the use of FWD equipment, which provides a more sensitive measurement system than that present in the Benkelman Beam, there are still inaccuracies in the deflection measurements and, therefore, the results should be interpreted with care. In a complementary way, an evaluation of the linearity or non-linearity of the load-deflection relationship was also performed by using the criterion proposed by Rocha Filho (1996), which consists in graphically comparing the measured deflections and the loading levels, aiming to identify a linearity relationship, or not.

2.2 Backcalculation

In order to obtain the resilience modulus of the pavements layers, the backcalcultion procedure was performed. The backcalculation is characterized by the best fit between the basin measured in the field and the one calculated with the help of the computer program. The stiffness values were determined following the stopping criterion that proposes the reliability analysis of the values obtained through the relative error calculated for each point of the deflection basin, as suggested by Bueno (2016).

The iterative procedure was carried out with the BAKFAA program, developed by the Federal Aviation Administration (FAA), by adjusting the deflectometric basins obtained from the FWD, with the values fully corrected for the reference temperature (25 ºC) through Equation 2, proposed by DER-SP (2006), as an adaptation of the abacus developed by AASHTO (1993).

$$D_{25} = \frac{Dp}{\left(\left(\left(\frac{h_{CA}}{1000}\right) * (T - 25)\right) + 1\right)} \qquad \mathbf{(2)}$$

Where:
D = corrected deflection to a temperature of 25 ºC (0.01 mm);

Dp = deflection measured on the field (0.01 mm);
h_{CA} = asphalt layer thickness (cm);
T = temperature of the pavement surface at the time of the test (ºC).

In this step, the resilience modulus was obtained for every 20 meters in the two monitored sites (from the two hits performed by the FWD equipment with each of the four loads).

To start the iterations, the program requires the user to inform the pavement cross section (layers and respective thicknesses), the Poisson ratio of each material, the deflectometric basins obtained in the field, the load applied by the FWD equipment, its application radius, and the interface parameters (bonded or unbonded layers).

The Poisson ratio adopted for the materials used in the pavement layers of the two monitored sites followed the recommendations of Balbo (2007) and Bernucci et al. (2010). As for the bonding conditions between the pavement layers, the concept of Huang (2004) was used, which describes that typical flexible pavements are formed by one or more asphaltic layers bounded to each other, over unbonded granular layers. In the monitored sites 1 and 2, due to the existence of only one asphalt layer, all materials were considered with their interface conditions unbonded. To define the characteristic resilience modulus of the layers, the statistical analysis procedure described by PRO 011/79, of the former DNER, was applied, as detailed by Bueno (2016).

To identify the behavior of the pavement layers resilient parameters, models were determined by combining the linear modulus, obtained from the backcalculation, and the efforts generated from the field situation simulated in the AEMC (multilayer elastic analysis) tool, a component of the MeDiNa software (using the stiffness of the layers determined in the backcalculation), developed by Franco and Motta (2020).

For the pavement asphalt concrete, the regression of the resilient modulus was performed from the vertical stress (σ_v), at the load plate center, on the surface. Therefore, data from the AEMC output results were not used. Only the vertical stress was calculated from the loading and its application radius.

For the granular layers (base and sub-base), the stiffness model was applied as a function of the confining stresses (σ_3). These were calculated using AEMC, simulating the loads exerted by the FWD with the structural and modular configuration of each of the sites. Thus, the confining stresses in the center of the layers of granular base and sub-base were evaluated.

Regarding the subgrade systems, the confining stress (σ_3) and deviator stress (σ_d) were calculated by AEMC at a position located 300 mm below the interface with the granular sub-base. The models applied to the granular layers and subgrade were chosen because they are commonly used in the analysis of the resilient modulus of these materials, in the repeated load triaxial test. Thus, it was possible to verify if the backcalculated resilience modulus of each layer, from the different loads, presents a behavior dependent on the stress state generated by the load application.

3 Results and Analysis

Presentation of this study results was fragmented into two parts. The first part presents the results concerning the behavior of the structure load-deflection relationship, by using the concept of the Degree of Linearity (GL) in each of the sensors with the FWD equipment. In a second step, the nonlinear resilient modulus models are presented and determined for the pavement layers of sites 1 and 2, as a function of the vertical stress generated on the surface by the acting load (asphalt concrete) and the stress state in the central part of the granular layers (bases and sub-bases) and subgrade.

3.1 Behavior of the Load-Deflection Relationship

As described in item 2.1, the behavior of the load-deflection relationship of the structures was evaluated using the equation suggested by Macêdo (1996), to determine the degree of linearity (GL) of the two monitored sites pavements.

For the two sites investigated, the degrees of linearity were calculated from all possible load combinations (ratio between 40 and 20 kN; 60 and 20 kN; 60 and 40 kN; 80 and 20 kN; 80 and 40 kN; 80 and 60 kN), which generated their respective deflectometric basins on the pavement.

Tables 3 and 4 show the averages of the deflectometric relationships between the loads, considering all the extension of the evaluated sites in all four campaigns of deflectometric surveys with FWD equipment.

Before performing the analyses of Tables 3 and 4, it is necessary to interpret which layers are represented by the displacements measured in the seven FWD sensors. For this purpose, the concept of Lytton and Smith (1985) was used, who state that the pavement structure is usually represented by elastic layers of known thickness.

Table 3 Linearity degrees of Site 1 structure. Averages of the four campaigns highlighted in bold.

Ratios	D_0	D_1	D_2	D_3	D_4	D_5	D_6
Average GL (80/60)	0.95	0.95	0.96	0.96	0.97	0.96	0.94
Average Behavior	E	E	L	L	L	L	E
Average GL (80/40)	0.85	0.88	0.90	0.93	0.96	0.96	0.99
Average Behavior	E	E	E	E	L	L	L
Average GL (80/20)	0.71	0.77	0.83	0.91	0.97	0.97	1.08
Average Behavior	E	E	E	E	L	L	A
Average GL (60/40)	0.89	0.91	0.93	0.95	0.98	0.99	1.03
Average Behavior	E	E	E	L	L	L	L
Average GL (60/20)	0.73	0.79	0.85	0.92	0.98	1.01	1.10
Average Behavior	E	E	E	E	L	L	A
Average GL (40/20)	0.82	0.87	0.91	0.97	1.00	1.02	1.07
Average Behavior	E	E	E	L	L	L	A
Average GL	**0.82**	**0.86**	**0.90**	**0.94**	**0.97**	**0.98**	**1.04**
Standard Deviation	**0.09**	**0.07**	**0.05**	**0.02**	**0.01**	**0.02**	**0.06**
CV	**11%**	**8%**	**5%**	**3%**	**1%**	**2%**	**6%**
Average Behavior	**E**	**E**	**E**	**E**	**L**	**L**	**L**

Table 4 Linearity degrees of Site 2 structure. Averages of the four campaigns highlighted in bold.

Ratios	D_0	D_1	D_2	D_3	D_4	D_5	D_6
Average GL (80/60)	0.92	0.92	0.93	0.93	0.94	0.96	0.99
Average Behavior	E	E	E	E	E	L	L
Average GL (80/40)	0.80	0.81	0.83	0.86	0.91	0.96	1.04
Average Behavior	E	E	E	E	E	L	L
Average GL (80/20)	0.64	0.68	0.72	0.79	0.88	0.95	1.17
Average Behavior	E	E	E	E	E	L	A
Average GL (60/40)	0.86	0.88	0.89	0.92	0.96	0.99	1.03
Average Behavior	E	E	E	E	L	L	L
Average GL (60/20)	0.69	0.73	0.77	0.84	0.92	1.01	1.14
Average Behavior	E	E	E	E	E	L	A
Average GL (40/20)	0.80	0.83	0.87	0.92	0.96	1.02	1.11
Average Behavior	E	E	E	E	L	L	A
Average GL	**0.78**	**0.81**	**0.84**	**0.88**	**0.93**	**0.98**	**1.08**
Standard Deviation	**0.10**	**0.09**	**0.08**	**0.06**	**0.03**	**0.03**	**0.07**
CV	**13%**	**11%**	**9%**	**6%**	**3%**	**3%**	**6%**
Average Behavior	**E**	**E**	**E**	**E**	**E**	**L**	**A**

Thus, the characteristic resilience modulus of the site, obtained from the backcalculation with the BAKFAA program (later presented in item 3.2), were inserted in the AEMC program (MeDiNa package tool), along with the thicknesses and Poisson ratios of the layers, to obtain the vertical stresses in the bottom fiber of each of the layers that make up the structure. It is important to note that the interfaces between layers were considered with unbonded conditions. It was therefore interpreted that at the horizontal distance where vertical stresses no longer acted in a given layer, the deflections measured at sensors positioned from that point on would no longer evaluate the elastic compression of the respective layer, representing only the elastic compression of the layers located below it.

Figures 2 and 3, referring to a 40 kN application on the pavements of Sites 1 and 2, respectively, during FWD tests, allow a better view of the stress distribution along the pavement structural system, as an example.

It is worth noting that for the other loads (20, 60 and 80 kN), the vertical stress distribution was significantly similar, allowing analogous interpretations. As the stiffness of the layers is dependent on the applied load and, consequently, on the stress state generated in the structure, the resilient modulus changes with the load change. Therefore, the existence of vertical stresses acting in a given layer does not change much when the load is increased, since the stiffness also increases, allowing the vertical stresses to be distributed in a similar way to those originated by a lower load, with less stiff layers.

For example, with the resilience modulus of Site 1, backcalculated from the deflectometric survey with the FWD in Campaign 1, considering the unbound layers to each other, the vertical stress originated by the load of approximately 20 kN stops acting on the asphalt concrete 460 mm away from the load application point. When the load is increased to 60 kN, vertical stress is non-existent in the asphalt concrete 470 mm away from the point of load application (considering the new set of resilient moduli, obtained from deflections generated by the application of 60 kN with FWD). This interpretation also extends to the distribution of vertical stresses in Site 2.

Specifically for Site 1, it can be stated that, upon analysis of Figure 2, only the deflections measured at sensors D0, D1 and D2 represent the elastic compression of the entire set of layers. Consequently, the values determined at sensors D3 and D4 represent the elastic compression of the layers under the overlay and sensors D5 and D6 represent the elastic compression of the granular sub-base and subgrade. This interpretation is analogous for all the surveys performed in Site 1, for all the loads applied by the FWD equipment.

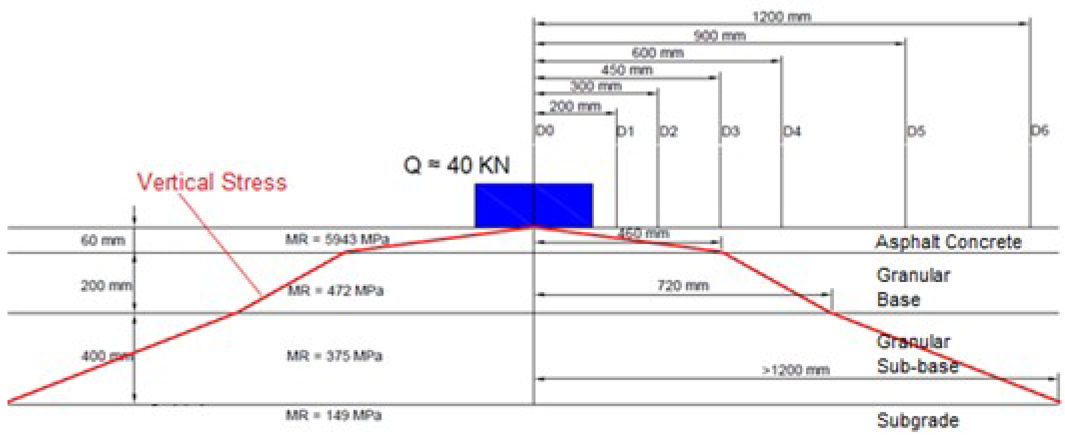

Figure 2 Example of the vertical stress distributions in the Site 1 pavement.

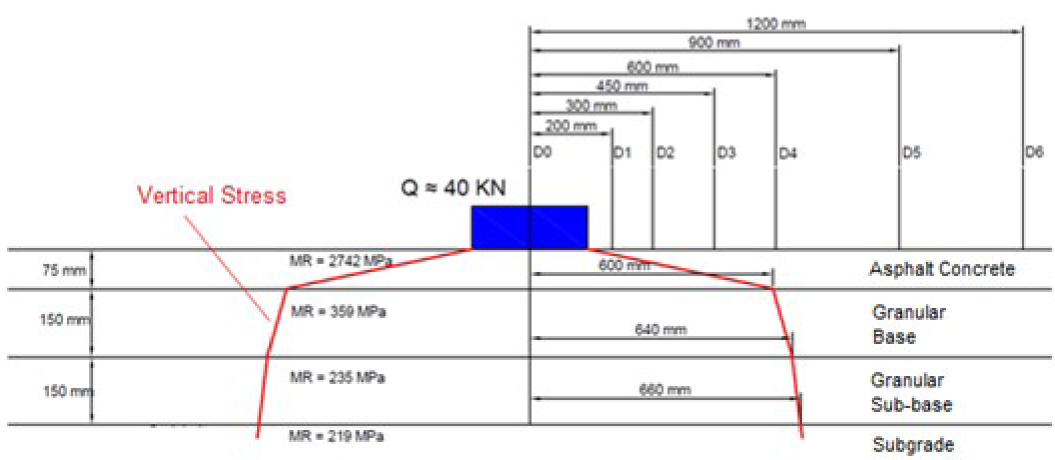

Figure 3 Example of the vertical stress distributions in the Site 2 pavement.

Therefore, it is possible to relate Table 3 with Figure 2 identifying that the deflections measured in the first three sensors (D0, D1 and D2), referring to the complete structural system of site 1, showed a tendency to stiffening the structure with increasing load. The deflections measured at sensor D3, referring to the elastic compression of the base, sub-base and subgrade layers, maintained the pattern of the previous sensors, showing a tendency to stiffening.

However, the deflections measured at sensors D4 and D5 indicated linear behavior of the structure layers located below the granular base in all surveys performed. Sensor D6, which mostly represents the elastic compression of the subgrade, also indicated a tendency towards linearity of the system under the sub-base, with increasing load.

Aiming to perform a more accurate evaluation, considering the four loading levels simultaneously, the most representative basin of Site 1, determined in the field in Campaign 4 (campaing with the lowest coefficient of variation in the degree of linearity values) was outlined in the graph shown in Figure 4, following the nonlinearity evaluation method proposed by Rocha Filho (1996), which consists in graphically comparing the measured deflections and the loading levels, aiming to identify a linearity relationship, or not.

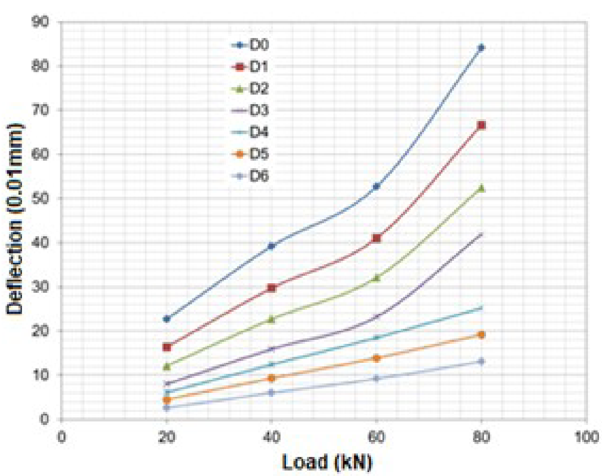

Figure 4 Linearity analysis of the Site 1 structure according to Rocha Filho's criteria (1996).

Figure 4 supplements the results discussed above, exemplifying what happens in a generalized manner in the section. The layer system of site 1 exhibited a nonlinear behavior of the load-deflection relationship in the first sensors. At further distances, a linear behavior or a behavior significantly close to linearity is observed.

For the pavement structure of site 2, it was possible to note from Figure 3 that the distribution of vertical stresses was significantly different from that determined for site 1. The sensors positioned at distances D0, D1, D2 and D3 represent the elastic compression of the complete structural system. However, at sensor D4, the stress diagram suffers a significantly sharp inflection, allowing the interpretation that sensors D5 and D6 represent only the elastic compression of the subgrade.

Regarding the relationship between Figure 3 and Table 4, it can be seen that, for site 2, the sensors D0 to D4 show a tendency to stiffening of the structure with the increase of the acting load. As seen previously, D0 to D3 represent the elastic compression of the entire structure, and the overall system may be classified as convergent to stiffening. The readings obtained with sensor D4 still represent a small contribution of the intermediate layers in the vertical stress diagram, also indicating a tendency to stiffening the layers with increasing load in all surveys.

Sensors D5 and D6 represent exclusively the elastic compression of the subgrade. In all surveys, D5 exhibited linear behavior. Sensor D6 were evaluated with a tendency to softening with increasing load.

The linearity analysis was also performed following the interpretation method of Rocha Filho (1996). The result, shown through the representative basin of Site 2 (Figure 5), refers to Campaign 4.

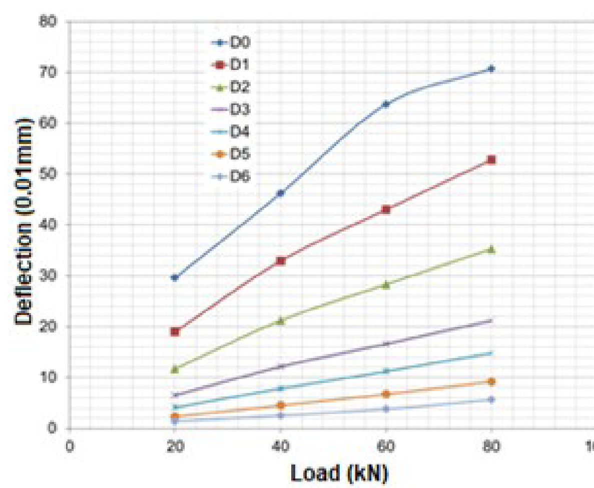

Figure 5 Linearity analysis of the Site 2 structure according to Rocha Filho's criteria (1996).

It is identified, as in Site 1, compatibility between the graph in Figure 5 and the results exposed in Table 4. Again, the initial sensors exhibit nonlinear elastic behavior of the load-deflection relationship. In comparison with the results obtained for Site 1, it can be seen that the nonlinearity obtained for Site 2, at the first distances, is not as pronounced, but it does exist. Again, the sensors far from the point of load application indicated, as occurred in Site 1, linear or near-linear behavior in the load-deflection relationship.

3.2 Stiffness Models for the Pavement Layers on Monitored Sites

The models determined for site 1 and site 2 used the backcalculated stiffness results obtained with the four different loading levels employed by the FWD equipment. To evaluate the results, Table 5 shows the resilience modulus models for each layer that makes up the structural system of site 1, obtained in each of the four survey campaigns performed with the FWD. The regressions were calculated from the vertical surface stress at the center of the load plate (asphalt concrete), confining stress at the center of the granular layers (granular base and sub-base), confining stress and deviator stress 300 mm below the interface with the granular sub-base (subgrade). In addition to the detailed equations for each of the survey campaigns in Site 1, Table 5 also highlights the average model of behavior for the four grouped test campaigns.

It was noticed that the evaluation of the models together, using the data from all the surveys (average model), makes the coefficients of determination (R^2) low, especially for the models of of the asphalt concrete and subgrade.

For the subgrade resilient modulus, it can be seen that in the results generated from the first three test campaigns, the positive values of the parameter k3 indicate that the resilient modulus increases in direct proportion to the increase in the deviator stress. This effect does not occur with the increase of the confining stress, due to the negative values of k2.

The regression performed from the last survey (Campaign 4) describes an inverse behavior to the previous ones for the subgrade. This behavior is analogous to that found by Santos et al. (2019), by applying composite models in the pairs of stresses with which the authors performed triaxial test of repeated loads to determine the resilient modulus of four soils employed in road subgrade in the state of Rio Grande do Sul.

The authors concluded, in three of the four materials studied for them, that in the application of the composite model, the increase in confining stress causes an increase in resilient modulus, an effect that does not occur for the deviator stress, due to the negative values of k3 obtained by the authors.

It is also noteworthy that the average regression (considering all survey campaigns) describes a practically linear elastic resilient behavior. This variability in the behavior of the pavement subgrade of Site 1, with different influences of the stress state on the resilience modulus determined from the four backcalculation surveys, allows the interpretation of the material, in mechanistic analyses, as linear elastic. The adoption of linearity is also supported by the linear behavior of the load-deflection relationship of the sensors referring mostly to elastic compression of the subgrade (distances far from the load application point), discussed in site 3.1.

For granular materials, there is an increase in stiffness value caused by the increase in confining stress, both for granular base and sub-base. The results obtained for the k2 coefficient describe a different proportion from that determined by Silva et al. (2006), referring to the equivalent modulus (single layer of base + sub-base), obtained by the authors for granular materials. In their research, with a methodology analogous to this one, the backcalculated

Table 5 Resilient modulus models for Site 1 layers. Averages of the four campaigns highlighted in bold.

Campaigns	Asphalt concrete		Granular Base		Granular Sub-base		Subgrade	
	$MR = k1*\sigma_v^{k2}$ (MPa)	**R^2**	**$MR = k1*\sigma_3^{k2}$ (MPa)**	**R^2**	**$MR = k1*\sigma_3^{k2}$ (MPa)**	**R^2**	**$MR = k1*s_3^{k2}*\sigma_d^{k3}$ (MPa)**	**R^2**
1	$MR=6,312.3\ \sigma_V^{0.274}$	0.55	$MR=1,279.4\ \sigma_3^{0.323}$	0.80	$MR=1,645.2\ \sigma_3^{0.337}$	0.49	$MR=74.62\ \sigma_3^{-1.323}\ \sigma_d^{1.447}$	0.37
2	$MR=8,309.8\ \sigma_V^{0.328}$	0.80	$MR=1,929.1\ \sigma_3^{0.377}$	0.70	$MR=3,433.0\ \sigma_3^{0.401}$	0.62	$MR=102.08\ \sigma_3^{-1.753}\ \sigma_d^{1.985}$	0.51
3	$MR=8,187.0\ \sigma_V^{0.325}$	0.92	$MR=1,786.6\ \sigma_3^{0.394}$	0.81	$MR=1,959.6\ \sigma_3^{0.338}$	0.76	$MR=27.34\ \sigma_3^{-3.169}\ \sigma_d^{3.428}$	0.61
4	$MR=7,891.2\ \sigma_V^{0.178}$	0.49	$MR=2,119.8\ \sigma_3^{0.406}$	0.81	$MR=3,090.8\ \sigma_3^{0.338}$	0.57	$MR=166.72\ \sigma_3^{0.155}\ \sigma_d^{-0.215}$	0.19
Average	**$MR=6,692.5\ \sigma_V^{0.058}$**	**0.021**	**$MR=1,480.3\ \sigma_3^{0.344}$**	**0.48**	**$MR=2,005.0\ \sigma_3^{0.330}$**	**0.30**	**$MR=163.18\sigma_3^{-0.078}\ \sigma_d^{0.078}$**	**0.0008**

stiffness for the equivalent layer, from deflectometric basins, exhibits behavior inversely dependent on the confinement simulated in the central part of the layer. However, it is understood that this type of evaluation is dependent on the type of material used and the conditions of the structure evaluated.

Regarding the pavement surface, it is known that asphalt materials have a resilience modulus dependent on temperature and frequency of load application. By backcalculation, it is not possible to determine the stiffness of asphalt layers considering the viscoelasticity of the material. Even so, the models developed from the increment of the vertical stress on the road surface, generated by the acting load, described reasonably (considering the proper objectives) the material behavior.

It can be seen that, applied the regression models separately for each of the surveys, the resilience modulus of the asphalt concrete increases proportionally with the increase of the vertical stress on the surface under the load (positive k2 coefficient in all regressions). The average model considering all four surveys describes a practically linear behavior (absolute value of k2 very small).

Addressing the practical application of the models determined in this item, for site 1, based also on the load-deflection relationships obtained during the approach in item 3.1, the assignment of the resilient modulus of the site through linear elasticity is not detrimental to the pavement, in terms of structural reliability. As already verified, the resilience modulus of granular materials (the only nonlinear elastic materials in this site, according to this study) has a behavior directly proportional to the increase in confining stress, which also increases with the increase in the acting load.

When the stiffness of the granular base, sub-base and subgrade materials are higher, in mechanistic analyses of stresses, it is possible to identify lower horizontal tensile strains in the bottom of the asphalt concrete layer and lower vertical compressive strains in the top of the subgrade. With this approach, based only on the concepts of classical pavement mechanics, it would not be reckless, aiming at the structure durability, to adopt granular layers also with linear resilience modulus. It should be noted that these findings could not be transferred to the stiffness values determined by laboratory tests, due to the differences in the way of obtaining the result in relation to the backcalculation process.

The same regressions and determinations of the resilient models for the overlay, base, sub-base and subgrade layers, performed in Site 1, were applied to the linear modulus, obtained from the backcalculation with deflectometric basins generated by varying loads in Site 2. Table 6 shows the values obtained from the regressions for the layers. Again, the regressions were calculated from the vertical surface stress at the center of the load plate (asphalt concrete), confining stress at the center of the granular layers (granular base and sub-base), confining stress and deviator stress 300 mm below the interface with the granular sub-base (subgrade).

According to Table 6, it can be seen that the coefficients k1 and k2, determined by the regressions of the resilient modulus for granular materials, are similar to those found for the base and sub-base layers of Site 1. Again, for the four surveys, both separately and in the average regression model, the resilient modulus of the base and sub-base layers increases with rising confining stress.

For the subgrade, the average regression, considering data from the four surveys, determined a practically linear stiffness value, little dependent on the stress state. However, the models generated separately, for each of the surveys, followed the behavior mostly verified in Site 1, where an increase in the resilient modulus was identified with the

Table 6 Resilient modulus models for Site 2 layers. Averages of the four campaigns highlighted in bold.

Campaigns	Asphalt concrete		Granular Base		Granular Sub-base		Subgrade	
	MR = k1*σ_v^{k2}	**R^2**	**MR = k1*σ_3^{k2}**	**R^2**	**MR = k1*σ_3^{k2}**	**R^2**	**MR = k1*σ_3^{k2}*σ_d^{k3}**	**R^2**
1	MR=3,238.3 $\sigma_v^{0.324}$	0.68	MR=838.73 $\sigma_3^{0.307}$	0.53	MR=1,290.5 $\sigma_3^{0.536}$	0.43	MR=38.81$\sigma_3^{-1.778}$ $\sigma_d^{1.923}$	0.48
2	MR=5,260.2 $\sigma_v^{0.651}$	0.92	MR=1,870.0 $\sigma_3^{0.443}$	0.72	MR=2,322.3 $\sigma_3^{0.514}$	0.67	MR=81.36$\sigma_3^{-1.730}$ $\sigma_d^{2.072}$	0.74
3	MR=5,420.4 $\sigma_v^{0.417}$	0.82	MR=1,452.3 $\sigma_3^{0.378}$	0.76	MR=2,764.2 $\sigma_3^{0.626}$	0.71	MR=65.39$\sigma_3^{-1.612}$ $\sigma_d^{1.843}$	0.78
4	MR=5,031.9 $\sigma_v^{0.360}$	0.86	MR=1,320.5 $\sigma_3^{0.363}$	0.80	MR=4,177.2 $\sigma_3^{0.757}$	0.78	MR=142.70$\sigma_3^{-0.718}$ $\sigma_d^{0.797}$	0.17
Average	**MR=3,975.6 $\sigma_v^{0.215}$**	**0.13**	**MR=985.44 $\sigma_3^{0.290}$**	**0.29**	**MR=2,111.1 $\sigma_3^{0.588}$**	**0.38**	**MR=333.37$\sigma_3^{0.050}$ $\sigma_d^{0.048}$**	**0.13**

increase of the deviator stress and the opposite effect with the increase of the confining stress.

For the asphalt concrete, the regressions performed in Site 2 resulted in models with better determination coefficients than those obtained from the resilient modulus of Site 1. The resilient behavior was found to be directly proportional to the increase in vertical surface tension at the center of the load plate. It is noteworthy that the average model for asphalt concrete stiffness, unlike Site 1, resulted in a significant k2 parameter, together with an acceptable coefficient of determination for the amount of data evaluated, making clear the nonlinearity of the material.

Verifying, as performed for the stiffness models proposed for Site 1, the practical applications of the nonlinear resilience modulus found for Site 2, the interpretations are similar. For granular materials, the stiffness directly dependent on the increase of the confining stress does not cause, when adopted the linear elasticity of resilient modulus, structural damage to the pavement when analyzed from the classical perspective of pavement mechanics. However, the use of the nonlinear model provides a representative characterization of the material, allowing the designer to work with the stiffness curve appropriate to the field behavior.

For the asphalt mixture used in the pavement of Site 2, the behavior directly proportional to the increase in vertical stress on the surface, in the center of the loading plate, also allows, based on interpretations of classical pavement mechanics, to state that higher values of asphalt concrete stiffness imply lower horizontal tensile strains at the bottom of the evaluated asphaltic layer, when subjected to loading. Thus, it is considered acceptable, in terms of basic level design, to consider the asphalt mixture of Site 2 as linear elastic.

4 Conclusions

From the results obtained in accordance with the methodological outline of this study, it was possible to conclude that:

a) The non-linear behavior of the relationship between load and deflection was clearly identified in the initial sensors (D0, D1, D2 and D3) from tests with FWD equipment applying four different levels of loading in sites 1 and 2. In these structures, the pavement indicated a tendency to stiffen with increasing load acting at the initial sensors, which represent the elastic compression of all layers that constitute the system. The sensors far from the point of load application, referring to the elastic compression of the subgrade, indicated, in most cases, a tendency to linear behavior of the load-deflection relationship in both sites;

b) The resilience modulus of the granular layers in sites 1 and 2, obtained from backcalculation of deflectometric basins measured with FWD, by applying four load levels, exhibited a nonlinear elastic behavior, with stiffness varying in direct proportion to the increase in the confining stress. Based on the results, it could be concluded that, for granular materials, the stiffness directly dependent on the increase of the confining stress does not cause, when adopted the linear elasticity of resilient modulus, structural damage to the pavement when analyzed from the classical perspective of pavement mechanics. However, the use of the nonlinear model provides a representative characterization of the material, allowing the designer to work with the stiffness curve appropriate to the field behavior.

c) Regarding the subgrade, the results of the resilient modulus in sites 1 and 2 showed behavioral variations in the different surveys performed. Therefore, it is considered prudent to determine the subgrade of the two pavements as linear elastic.

d) Regarding the asphalt concrete, the backcalculated resilience modulus for site 2 indicated a behavior directly proportional to the increase in vertical stress on the surface. The pavement of site1 followed the same path, but with modulus less dependent on the increase of load applied to the surface by the FWD equipment, and can be admitted as linear elastic. The behavior directly proportional to the increase in vertical stress on the surface, in the center of the loading plate, also allows, based on interpretations of classical pavement mechanics, to state that higher values of asphalt concrete stiffness imply lower horizontal tensile strains at the bottom of the evaluated asphaltic layer, when subjected to loading. Thus, it is considered acceptable, in terms of basic level design, to consider the asphalt mixture as linear elastic.

5 Acknowlegedgments

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Author contributions

Lucas Dotto Bueno: conceptualization; formal analysis; methodology; validation; writing-original draft; writing – review and editing; visualization. **Deividi da Silva Pereira:** conceptualization; formal analysis; methodology; supervision. **Luciano Pivoto Specht:** conceptualization; formal analysis; methodology; supervision. **Cleber Faccin:** methodology. **Ana Helena Back:** methodology; writing – original draft; writing – review and editing. **Elemar Taffe Júnior:** methodology. **Fernando Dekeper Boeira:** methodology. **Mauricio Silveira dos Santos:** methodology.

Conflict of interest

The authors declare no potential conflict of interest.

Data availability statement

All data included in this study are publicly available in the literature.

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