Correlation between deflections measurements on flexible pavements obtained under static and dynamic load techniques

Corrélation entre les déflexions de revêtements flexibles mesurées sous chargement statique et dynamique

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ABSTRACT: Over the last 40 years several nondestructive techniques have been developed for determining the structural capacity of flexible pavements as a function of the deflections produced by the application of a load. The techniques most used in Colombia to measure pavement deflections are the Falling Weight Deflectometer (FWD) and the Benkelman beam, the first one works under dynamic loading and the second device under static loading. However, for over 10 years, the use of devices under static loading has not been recommended by several design methodologies, including AASHTO, but these are still used widely in many countries, for this reason it was necessary to establish the correlation between the deflections obtained from FWD and Benkelman beam, specially on deteriorated pavement structures; for this purpose, it was selected a section of flexible pavement road with presence of different types of deterioration. The influence of type of deterioration, the temperature of the asphalt layer and the presence of nearby drainage structures and vegetation in the measurements were evaluated. The obtained results showed that both devices have high correlation, and it is possible to obtain FWD deflections as a function of Benkelman beam deflections.

RÉSUMÉ : Dans les quarante dernières années plusieurs techniques ont été utilisées pour déterminer la portance des chaussées en utilisant les bassins de déflection générée par l'application d'une charge. Le déflectomètre FWD est devenu aujourd'hui l'appareil de référence international pour la détermination de la portance des chaussées. Cependant, en Colombie, la poutre Benkelman est la technique plus utilisée, bien que l'utilisation d'appareils sous charge statique n'ait pas été recommandée par plusieurs méthodologies. Par conséquent, il était nécessaire d'établir la corrélation entre les déflexions obtenues à partir de la poutre Benkelman et le FWD. Plusieurs tests ont été menés afin de réaliser la comparaison entre les déflections obtenues par la charge statique ainsi que la charge dynamique. Les essais ont été réalisés sur chaussée souple avec différents types de détérioration. L'influence du type de déficience, la température, la végétation ont été pris en compte. Les résultats ont montré qu'il est possible d'établir une corrélation entre les deux appareils.

KEYWORDS: Non-destructive test, Benkelman beam, FWD, deflections, flexible pavement, structural number, resilient modulus, backcalculation.

1 INRODUCTION

Most of the road network in Colombia has a significant level of deterioration and therefore requires major rehabilitation projects; in general, most of these rehabilitation activities involve a new asphalt layer on the original pavement structure; knowledge and analysis of structural capacity of the pavement is essential to perform a durable and economical rehabilitation design.

It is possible to quantify the structural capacity of the pavement by means of the structural number (SN), which, in this case, is obtained in function of the deflections generated on the surface of the pavement by a process of backcalculation. The most used equipment in Colombia for measuring deflections on pavement structures are the Falling Weight Deflectometer (FWD) which works under dynamic loading and the Benkelman beam which works under static loading.

The Benkelman beam was one of the first methods developed for measuring deflections on pavements, is economical, readily available and has been widely used in the world, however, its performance is slow, has high degree of uncertainty taking data and mainly it operates under a static load which does not really represent the effects exerted by moving vehicles, presenting low reliability of results. On the other hand the FWD, although it is more expensive, has a high performance, is automated and operates under a dynamic load, this is the most efficient equipment and advanced technically exists to measure the deflections of a pavement structure simulating the action of a moving load.

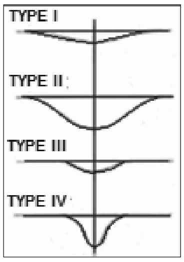
Different associations like the AASHTO do not recommend the use of deflectometers under static load, but in several countries, including Colombia which presents damage in the most of the road network, these devices are still in use especially the Benkelman beam, not only for structural evaluation but also for design of pavement structures; this is due especially to difficult acquisition, unfamiliarity and cost of falling weight deflectometer.

Therefore, it is important to determine the degree of correlation between these two devices to be able to obtain FWD deflections as a function of Benkelman beam deflections.

2 DEFLECTOMETRY

The deflection of an asphalt pavement structure is the vertical displacement of the surface in response to application of an external load. When this load is applied on the surface, all layers are deflected, developing stress and strain in each layer, as shown in Figure 1.

The shape and dimension of the deflection basin covers important information about the structural characteristics of both the pavement and subgrade. Deflections measured towards the end of the basin reflect the condition of the subgrade, while the measurements taken in the center of load application reflect the condition of the surface layer.Figure1 shows the evaluation of the pavement according to the length (Lo) and a maximum depth (Do) of the basin.



Type	Do	Lo	EVALUATION
I	Low	High	Good subgrade soil/ Good pavement
II	High	High	Poor subgrade soil/ Good pavement
III	Low	Low	Good subgrade soil/Poor pavement performance
IV	High	Low	Poor subgrade soil /Poor pavement performance

Figure1.Characteristics of deflection basin

2.1Admissible deflection value

The maximum values of deflection for design purposes estimated by Hveem (1995) are presented in Table 1.

Table 1. Maximum deflection values estimated by Hveem, 1995.

Type of pavement structure	Thickness (mm)	Maximum deflection value (microns)
Concrete pavement	200	300
Cement treated base	150	300
Asphalt pavement	100	425
Asphalt pavement on base course (plant mixed)	75	500
Asphalt pavement on base course (plant mixed)	50	625
Asphalt pavement on base course (In-situ)	25	925
Surface treatment pavement	13	1250

3 BACKCALCULATION METHODOLOGY

Table 2 shows the basics of back calculation methodology.The back calculation outputs are the modulus of elasticity of the pavement structure, effective structural number of the pavement layers, and subgrade soil resilient modulus.

Table 2. Representation of back calculation methodology

DIRECT CALCULATION		
E, Di,μ	⟶	d,σ,ε
BACKCALCULATION		
E,σ,ε	⟵	d, Di,μ

whereE: elastic modulus of the materials, μ: Poisson's ratio, d: deflection of the pavement structure, σ: stress on each layer of the structure, ε: strain, and D: layers thickness.There are several backcalculation methodologies, most of them carried out in function of the deflections obtained only under dynamic load including the AASHTO and SASW methodology which was used for the analysis of the deflections obtained from FWD.(Murillo et al, 2009).
There exist few methodologies developed from deflections under static load, because these procedures do not simulate adequately the real effects of moving loads. Mario Hoffman, in 1975, presented a methodology based on the "Hogg Model", which was used in the present study for backcalculation procedure based on the deflections obtained using the Benkelman Beam.

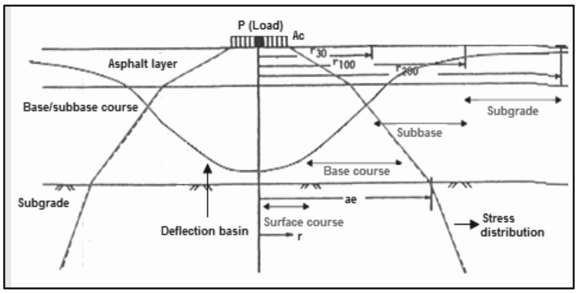


Figure 2.Algorithm backcalculation of M_R- AASHTO.

3.1. *AASHTO Methodology (for FWD)*

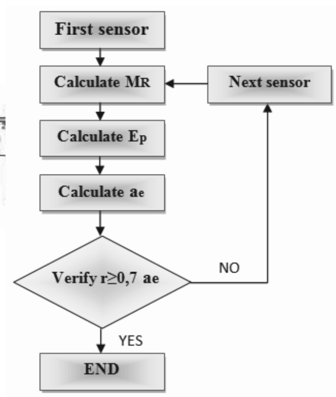
The guide for designing of pavement structures AASHTO establishes a procedure to calculate the resilient module (M_R)and thereafter the effective structural number (pavement structural capacity) as shown in the flowchart of Figure 2.

$$M_R = \frac{0,24\,P}{d_r\, r}$$

$$d_o = 1,5\,p\,a \left\{ \frac{1}{M_R\sqrt{1+\left(\frac{D}{a}\sqrt[3]{\frac{E_p}{M_R}}\right)^2}} + \frac{1-\frac{1}{\sqrt{1+\left(\frac{D}{a}\right)^2}}}{E_p} \right.$$

$$a_e = \sqrt{\left[a^2 + \left(D\sqrt[3]{\frac{E_p}{M_R}}\right)^2\right]}$$

$$r \geq 0,7\, a_e$$



whereMR: resilient modulus of the subgrade (psi), P: applied load (pounds), r: distance from the center of the load (inch), d_r: deflection at a distance "r" from the center of the load (inch), a_e: radius of the bulb of pressure representing the subgrade level (inch), a: radius of the loading Ring (inch), D: thickness of the pavement structure above the subgrade (inch), Ep: equivalent modulus of all pavement layers above the subgrade (psi), d_0: deflection at the center of the load plate, adjusted to a temperature of 20 ° C (inch), p: pressure of load plate (P/πa2).The effective structural number (SN_{eff}) is calculated based on the total thickness of the pavement and its effective modulus as shown below.

$$SN_{eff} = 0,0045\, H_T (E_P)^{1/3} \quad (1)$$

where H_T:total thickness of the pavement structure (in), Ep: equivalent modulus of pavement structure above the subgrade (psi).

3.2. *Hogg Model Methodology (for Viga Benke.)*

In 1944, Hogg presented the mathematical solution of the model which is known by his name. This assumes that the pavement layers are characterized by a thin plate with a certain bending stiffness.
The subgrade is represented by an elastic, linear, homogeneous and isotropic medium (Figure 3).Hoffman, in 1977, presented the computerized solution of the model, which is summarized below in Figure 5.

Figure 3. Scheme of Hogg mode
Hoffman, Mario. 1985

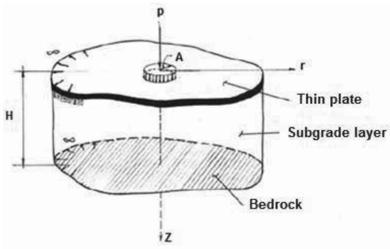


Figure 5. Methodology of Hogg Model for calculation of subgrade modulus

$$A = \sqrt{\frac{P/2}{\pi p}} \longrightarrow R_5 = R\frac{A^C - B}{\left[A\left(\frac{D_O}{D_R}-1\right)\right]^C - B} \longrightarrow l_0 = \frac{Y R_5 + \sqrt{(Y R_5)^2 - 4 A X R_5}}{2}$$

$$E_0 = \left(\frac{K * I * P}{l_0 * D_0}\right)\frac{S_0}{S} \longleftarrow \frac{S_0}{S} = 1 - M\left(\frac{A}{l_0} - 0{,}1\right)$$

where A: radius of the contact circular footprint, P: load on the double rim (1/2 of the load on back axle. Example 80 KN / 2 = 40KN), *p*: inflation pressure, R: distance which deflection D_R is measured, D_0: maximum deflection, D_R: deflection at a distance R, R_5: distance from the geometric center of the double rim along until obtaining the relation D_R/D_0=0.5, lo: characteristic length of the deflection basin, S_0: stiffness for theoretical point load, S: stiffness of the pavement, E_0: modulus of subgrade (kg/cm^2). I, K, M, X, Y, A, B, C: numerical coefficients developed for the model (see Ref 5).

The effective structural number (SN_{eff}) is calculated depending on the characteristic length and the modulus of subgrade as shown below:

$$SN_{eff} = 0{,}0364\, l_0\, (E_0)^{1/3} - 0{,}5$$

where E_0: modulus of subgrade (MPa), l_0: characteristic length (cm).

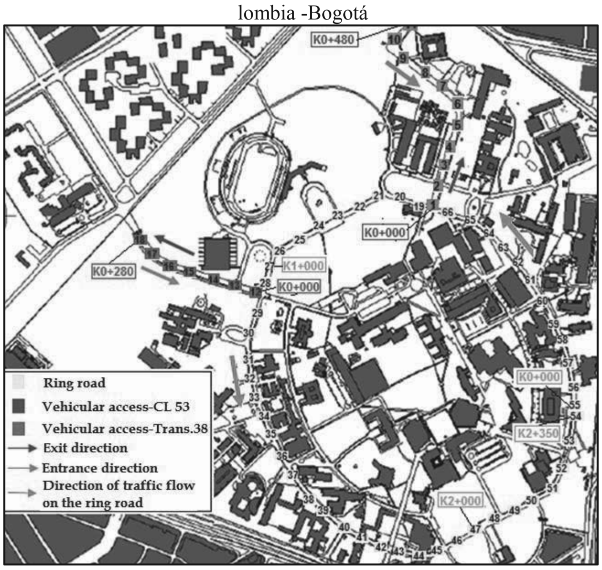
It is possible to calculate the equivalent modulus of pavement layers by means of Ullidtz proposal.

4 STUDY AREA

The study area is located on the campus of the Universidad Nacional de Colombia-Bogotá, it includes three sections of flexible pavement structure which are part of the road network of the university, these are: the main Ring road with a length of 2375 meters, vehicular access Calle 53 with length of 480 meters and vehicular access Transversal 38 with a length of 280 meters.

The deflection measurement was taken in 66 points, as shown in Figure 4.The area presented various types of damage including longitudinal failures, fatigue cracking (alligator cracking), interventions of asphalt patching, edge cracking and small potholes. Moreover vegetation influence is quite evident negatively causing transverse and block cracks by the action of the root system.

Figure 4.Study area. Road network at Universidad Nacional de Colombia -Bogotá



5 MEASUREMENT DEVICES

5.1 Benkelman beam

Benkelman beam (Figure 5) is a device which operates on a simple lever arm principle, the unit consists of a rigid support beam, pivot, one or two measurement probe beams and dials indicator. It is a convenient and practical device for measuring deflection of flexible pavements under the action of wheel loads and works in conjunction with a suitable loaded vehicle (back axle loaded with 80 KN).The probe beam is placed between the dual tires of a test vehicle, and deflection is measured as the vehicle passes over the test area to beyond the end of the probe beam.

Figure 6.Benkelman beam (two-part probe beam)

The measurements were taken at 0 (Lo), 75, 150 and 300 cm, the end of the two probe beams were separated 25 cm each other, which means the readings were estimated at 0, 25, 75, 100, 150, 175, 300 and 325 cm from the center of load application. The temperature was taken with a manual thermometer.

4.2FWD

The falling weight deflectometer, FWD works by dropping a controlled weight and transmitted to the pavement structure through a circular plate as shown in Figure 6. A set of geophones (deformation sensors) mounted radially from the center of the load plate measure the deflection in response of load pulse. The distribution of deflection sensors are shown in Table 3.

The FWD used in the tests was model JILS-20, programmed with a load pulse of 9000 pounds and three impact tests at every point. The equipment had an infrared sensor to measure the temperature of the asphalt layer.

Figure 6.FWD a) Equipment mounting b)Load cell and deflection sensors system

a)

b)

Table 1. FWD - Sensor configuration

FWD Geophones configuration									
FWD Sensor number	# 9	# 1 (do)	# 2	# 3	# 4	# 5	# 6	# 7	# 8
Offset from FWD load plate (cm)	-20	0	20	30	45	60	90	120	150

5 EXPERIMENTAL RESULTS

5.1 *Deflection basins*

Figure 7 shows representative results of deflection basins acquired in the study. The tendency of the deflection curves are deep and of short length, which means that the subgrade corresponds to a poor quality soil and deficient pavement performance.It was observed that the deflection basins obtained from the Benkelman beam are much deeper (12 to 232 mm^{-2}) than those obtained using FWD (31,29 to 164,14 mm^{-2}) giving more critical quality of the structure, although largely this is due to static charging system (Figure 8); that is, the analysis performed with the Benkelman Beam is more unfavorable, being that a deeper deflection curve indicates a deficient performance not only of the pavement structure but also of the subgrade.

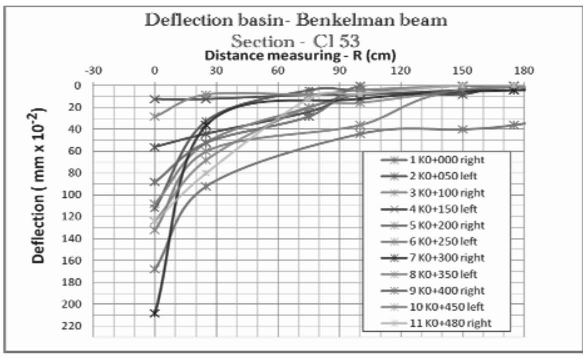


Figure 7. a) Deflection basin -Benkelman Beam, CL 53.

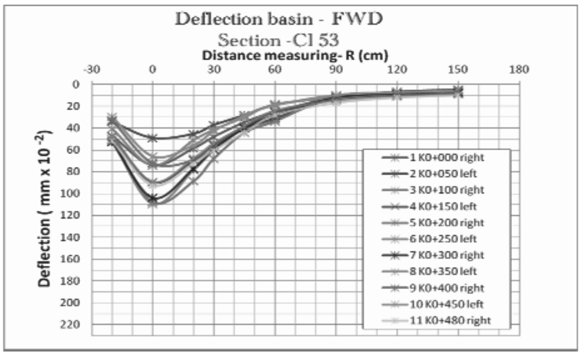


Figure 7. b)Deflection basin-FWD, CL 53.

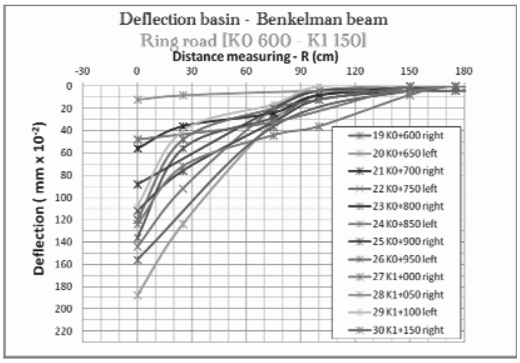


Figure 7c) Deflection basin-Benkelman Beam, Ring road (K0+600-K1+150).

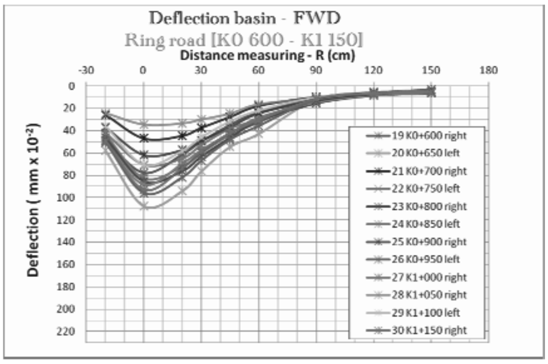


Figure 7d) Deflection basin-FWD, Ring road ((K0+600-K1+150)

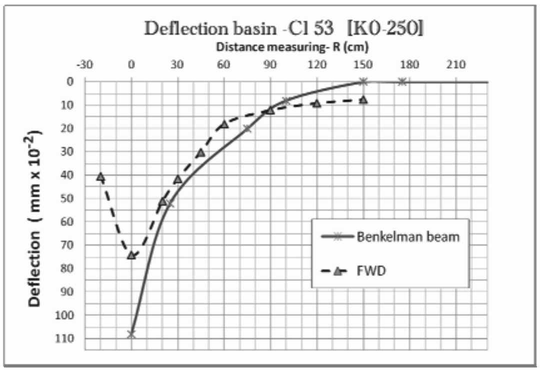


Figure 8. Typical deflection basin throughout the area, obtained using Benkelman beam and FWD

Figure 9 shows that presence of damages such as block and transverse cracking (mostly caused by tree roots) strongly affect the measurement resulting deflection values lower than average. The Benkelman beam technique is more susceptible to this cause.

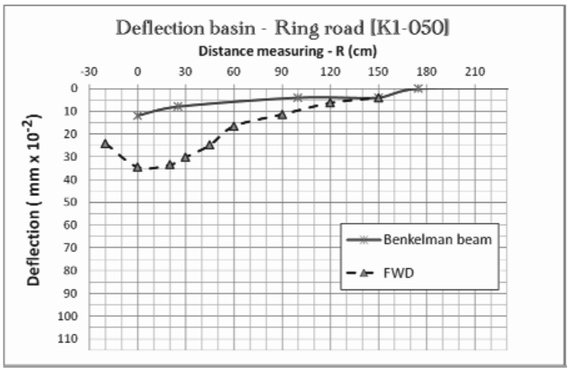


Figure 9.Deflection basin on areas affected by block cracking

In areas intervened with asphalt patching also the curve tends to be shallower than the average (Figure 10). In contrast, Figure 11 shows that on areas with longitudinal failuresthe deflection measurements resulted be higher than average, over 0.8 mm. The presence of other type of damage or drainage structures also caused high deflection measurements, over 1 mm.

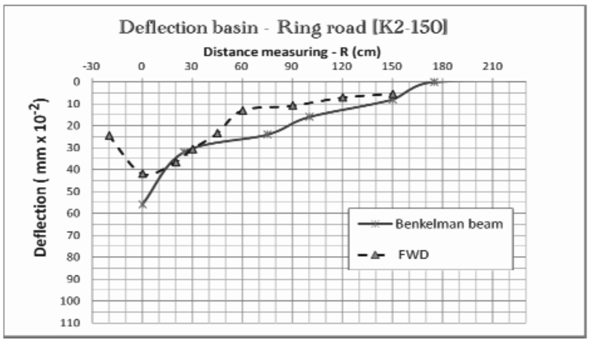


Figure 10. Typical deflection basin on areas with asphalt patching interventions

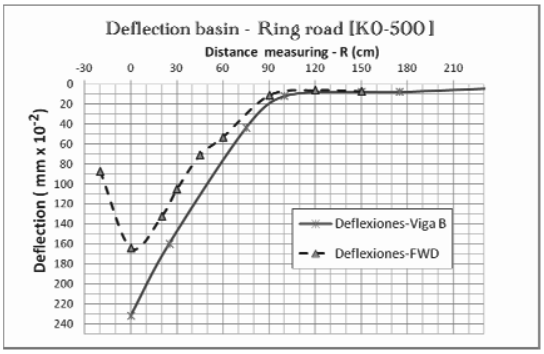


Figure 11.Typical deflection basin on areas with presence of longitudinal cracks

5.2 *Maximum deflection value(D_0)*

The pavement structure of the test roads has an asphalt layer thickness of 100 mm on average, according to Table 1 the permissible maximum deflection value corresponds to 42,5 mm^{-2}. Figure 14 shows the maximum deflectionprofile in the Ring road and the permissible value.

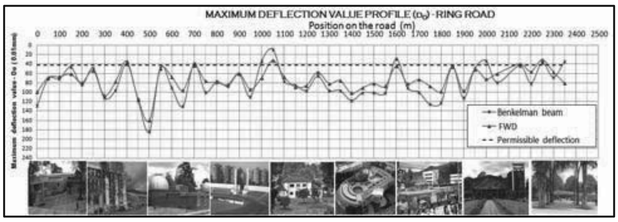


Figure 12. Maximum deflection value profile (d_0) - Ring road.

Figure 12 clearly shows deflections obtained from both devices follow the same trend. Both deflection profiles obtained using the Benkelman and FWD are outside the range of the maximum allowable deflection. The deflection values furthest from the trend correspond to test points affected by transverse cracking (usually caused by tree roots), mainly those measurements values obtained with the Benkelman beam.

Table 4. Maximum deflection - average per section

MAXIMUM DEFLECTION NORMALIZED TO 20^{O} C			
SECTION	Position on the road	Benkel. Beam	FWD
		0,01 mm	0,01 mm
Acceso Cl 53	[K0+000 - K0+480]	78.46	72.43
Acceso Trans. 40	[K0+000 - K0+280]	96.44	77.50
Anillo vial	[K0+600 - K1+150]	78.96	71.40
Anillo vial	[K1+200 - K1+750]	93.85	78.93
Anillo vial	[K1+800 - K2+350]	71.53	59.55
Anillo vial	[K0+000 - K0+550]	87.54	81.02

The average of maximum deflection values (Do) is around 0.8 mm, which means a pavement structure of low stiffness and sub-grade of low-bearing capacity. As shown in Table 4, the section in best condition is the Ring road [K1+800 – K2+350].

5.3 *Comparison between Benkelman beam and FWD measurements*

The correlation between the deflection data obtained from FWD and Benkelman beam is shown in Figure 15. Equations (3) and (4) were obtained in order to convert Benkelman beam deflections to FWD deflections taking into account falling weight deflectometers simulate better the real effects made by moving loads.

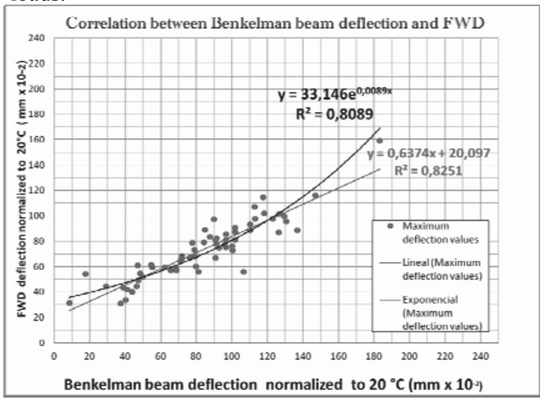


Figure 12. Correlation between deflections obtained with Benkelman beam and FWD

$$FWD = 33,146\ e^{0,0089B} \quad \ldots \quad (3)$$

$$FWD = 0,6374\ B + 20,097 \quad \ldots \quad (4)$$

where FWD: maximum deflection value (Do) obtained fromFWD normalized to a standard temperature of 20°C (68°F), B =

maximum deflection value (Do) obtained fromBenkelman beam normalized to a standard temperature of 20°C (68°F).The correlation equations (3) and (4) are optimal for deflections measurements taken on flexible pavement structures of low stiffness, it is possible to use them in deteriorated structures, preferably without presence neither transverse nor block cracking (especially that caused by surrounding vegetation). These equations are recommended for deflections between 0.3 and 1.8 millimeters.

5.4 *Subgrade soil modulus*

Both subgrade soilresilientmodulusand effective structural numbers obtained using AASHTO methodology prove to be higher than those obtained using the methodology of the Hogg Model; that is the results obtained with the Benkelman beam still are more unfavorable just as in the analysis of the deflection basins.

Table 5. Subgrade soil modulus obtained in each section

SECTION	Position on the road	SUBGRADE MODULUS (Mpa)			
		BENK. BEAM	c (%)	FWD	c (%)
Acceso Cl 53	[K0+000 - K0+480]	42.2	59.8	77.9	14.2
Acceso Trans. 40	[K0+000 - K0+280]	38.3	39.3	63.4	29.5
Anillo vial	[K0+600 - K1+150]	44.4	25.0	55.1	20.0
Anillo vial	[K1+200 - K1+750]	35.1	41.0	62.3	26.3
Anillo vial	[K1+800 - K2+350]	42.5	56.6	59.8	17.4
Anillo vial	[K0+000 - K0+550]	40.7	33.4	50.9	26.0
AVERAGE		40.5	42.5	61.6	22.2
c: Variation coefficient					

As shown in Table 5, on average in all test area, the modulus of subgrade were 40,5MPa (5880 psi) obtained using the Benkelman Beam and 61,6 MPa (8931 psi) with FWD. Thesesubgrade modulus values correspond to a fine-grained soft soil such as fat clays and silts.

5.5 *Effective structural number (SNeff)*

On average, the effective structural number (SNeff) was 1,6 obtained using the methodology of the Hogg Model for Benkelman beam measurements and 2,4 obtained using AASHTO methodology for FWD measurements; it is demonstrated that the structural assessment carried out with the Benkelman beam is more critical than the one carried out with the FWD, this is because the deflections obtained usingBenkelman beam are higher for being taken under static load.

As shown in Table 6, these effective structural number values are very low, representing the low pavement structural capacity and the need for implementation of a rehabilitation project.

Table 6. Effective structural number obtained with both techniques

SECTION	Position on the road	EFFECTIVE STRUCTURAL NUMBER, SNeff			
		BENK. BEAM	c (%)	FWD	c (%)
Acceso Cl 53	[K0+000 - K0+480]	1.6	104.2	3.0	11.9
Acceso Trans. 40	[K0+000 - K0+280]	1.0	76.7	2.3	11.9
Anillo vial	[K0+600 - K1+150]	2.0	44.3	2.3	11.7
Anillo vial	[K1+200 - K1+750]	1.6	51.7	2.4	20.0
Anillo vial	[K1+800 - K2+350]	1.6	87.9	2.2	11.3
Anillo vial	[K0+000 - K0+550]	1.9	39.4	2.3	16.0
AVERAGE		1.6	67.4	2.4	13.8

6 CONCLUSIONS

-Deflections under static load are higher than those generated by dynamic load; this is due to longer duration of load application. Therefore, the results obtained from deflection values under static load do not represent accurately the effects made by moving loads (moving vehicles), so the structural analysis made using static loading equipment may generate higher costs in rehabilitation projects.

-Most deflection basins obtained are deep and short extension, which means presence of poor subgrade soils and low performance of pavement layers (low structural pavement capacity).

-Backcalculation of subgrade soil modulus is a simple non-destructive procedure, more practical and faster than calculation by laboratory tests; and more reliable than using correlations based on other parameters as CBR.

-Exist a correlation (R^2=0,82) between the deflections obtained from Benkelman beam and FWD. The estimated equations are recommended to use in structural analysis of low stiffness pavement. It is possible to use them on deteriorated structures, preferably without presence neither transverse nor block cracking (especially that caused by surrounding vegetation).

-It was observed that presence of damages such as block and transverse cracking (mostly produced by the effect of tree roots) as well as asphalt patching interventions markedly influence the measurement, resulting deflection values lower than average. In contrast, presence of longitudinal failures as well as drainage structures nearby causedeflection measurements higher than average. It is not recommended to take deflections measurements on these areas.

-The standard deviation and coefficient of variation of data obtained using Benkelman beam are higher than those obtained using FWD.

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