

# Variation of Deflection with Measuring Equipment and Load Speed on Test Track

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Deflection is used on the full-scale test track to establish moduli for pavement layers and to provide useful information for strengthening studies and performance models. Results from falling-weight deflectometer and Benkelman beam correlation studies are set out, including an examination of possible factors that could affect the results, such as speed at which the load is applied and pavement deformation. Flexible and semirigid pavements are included.

The Centro de Estudios y Experimentación de Obras Públicas (CEDEX) full-scale pavement test track has novel features compared with other test tracks. Its oval shape provides two straight sections totaling 150 m of testing facilities as opposed to the 10 to 12 m that is the norm for other linear tracks (1,2). Simultaneous comparison between different types of pavement constructed with conventional road equipment is possible given the track's length.

The principal objective of tests carried out on the track is to compare the service life of different pavement sections in a controlled and accelerated manner. Service life is defined on the basis of surface cracking and evenness.

Other parameters also are measured on test tracks to establish the characteristics of pavements tested and to monitor their evolution. One of these is deflection, which is used to establish moduli for pavement layers and to provide useful information for strengthening studies and performance models.

The Benkelman beam (BB) is used in Spain as a standard reference for deflection. On the test track, deflection is measured with a falling-weight deflectometer (FWD) in order to carry out subsequent back calculation for the pavements. It is therefore necessary to carry out studies on the correlation between both types of equipment in order to relate deflection measured with the FWD to standard deflection. Results from such correlation studies are set out in this paper and include an examination of factors that could affect the results (the speed at which the load is applied and pavement deformation). The study also includes a comparison with the Lacroix deflectograph, which is the equipment used most widely in Spain for measuring deflection. Deflection measurements made with the different types of equipment were compared with those from sensors contained within the pavements.

The novel contribution of this work compared with other similar studies is that by carrying it out on test track pavements, it was possible to control the different variables with a high degree of precision.

## DESCRIPTION OF TEST TRACK

The CEDEX test track is oval with two straight sections joined by two curved sections (see Figure 1). Each straight section is approximately 75 m long, and the track has a total circumference of 304 m (1,2). Leaving out the transition areas between the curved and straight sections, 67 m is available on each straight section to carry out pavement testing. Because the minimum length for each test is 20 m, a total of six sections can be tested at the same time. The curved sections are not used for pavement testing but are reserved for studying surface materials, such as paints and wearing courses.

Although the curved sections are laid directly on the natural subgrade, on the straight portions there is a reinforced concrete casing inside which the pavement sections are constructed. This system enables the test sections to be completely isolated from the surrounding ground. It also makes it possible to flood the embankment to simulate different water levels. The concrete casings are 2.60 m deep, enabling embankments of at least 1.25 m to be constructed. They are 8 m wide; therefore, conventional road construction equipment can be used.

A concrete rail has been constructed along the inside perimeter of the track to serve as a guide for the traffic simulation vehicle and to provide control over the trajectory of the load. On the straight sections, the concrete rail rests over accessible underground galleries that are used to house connections for sensor cables installed in the pavement and the permanent data-gathering system. A structure has been built that enables sections of the track to be covered over if desired or water sprinklers to be in-

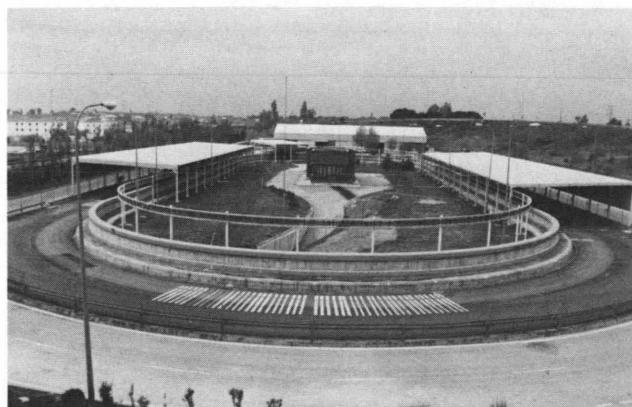


FIGURE 1 CEDEX test track.

stalled to simulate rainfall, along with other equipment to control climatic conditions.

The traffic simulation vehicle is made up of two parts, the guiding section and the load assembly (see Figure 2). The latter exerts the load by gravity. The total weight (vehicle and ballast) is 6.5 ton, equivalent to a 13-ton half-shaft, which is the maximum permitted limit for simple axles in Spain. It is fitted with twin wheels with conventional tires inflated to a pressure of 8.5 kg/cm<sup>2</sup>. The load assembly contains the driving gear and provides the motive power for the assembly as a whole. An electric motor is used that draws power from a roller path located on the guide rail. When in continuous use, the vehicle has a maximum circulation speed of 50 km/hr, with an average speed of 40 km/hr. The vehicle can move in a sideways direction because of a hydraulic jack within it. The maximum sideways movement is  $\pm 400$  mm; taking into account the width of the tires, that produces a rolling strip with a maximum width of 1.3 m. Vehicle passes are distributed following a normal curve that corresponds with actual distributions measured on roads. Another two vehicles are under construction.

An automatic system has been installed in the control center in the middle of the track to control the vehicle's movements, and instructions are passed to the vehicle by radio. The automatic system for gathering data from the instruments has a maximum capacity of 300 sensors per test, with data gathered in real time and stored in a data base (3).

It should be emphasized that the installation as a whole, and the vehicle and its control system in particular, are purpose-built prototypes.

## PAVEMENTS TESTED

The tests included in this paper were sponsored by Spain's Directorate General for Roads, Ministry of Public Works, Transport and the Environment. The essential purpose of the tests was to compare asphalt pavements with different types of road base and to also study the effects of different types of subgrade.

For this purpose three sections were chosen from directive 6.1 and 2-IC (the Spanish standard pavement catalogue), corresponding to a T2 traffic level (up to 800 trucks daily per lane) resting on subgrades of type E2 [ $10 <$  California bearing ratio (CBR)  $<$

20] and E3 (CBR  $>$  20). The sections studied are shown in Figure 3.

The cement-stabilized soil included 5 percent cement, giving an average simple compressive strength at 7 days of 2.9 MPa. The cement content of the cement-bound granular material was 4 percent with an average simple compressive strength at 7 days of 6.6 MPa. Regarding the asphalt, the bitumen used was B60/70, with an aggregate that had an average binder content of 4.8 percent; the average dynamic modulus at 20°C and 10 Hz was 5300 MPa.

As a result of the tests, it is expected that the relative service life of asphalt pavement sections resting on graded aggregate, cement-stabilized soil, and cement-bound granular material will be determined. In addition, the procedure adopted in the catalog for reducing the thickness of pavements when moving from an E2-type subgrade to an E3-type will be analyzed.

Initial deflection of pavements and their evolution during the first 600,000 load cycles are represented in Figure 4. The deflection is corrected for temperature by calibration carried out on the test track pavements themselves.

## EQUIPMENT USED

A KUAB double mass FWD was used, with a 30-cm-diameter, segmented, flexible-type circular plate. Deflection was measured at the center of the plate and at different distances, although only data obtained from the seismometer located in the center of the plate are included in this study. For each measuring operation, three loads were applied of 2500, 6500, and 6500 kg (in Spain the maximum legal simple axle limit is 13 ton), with the deflection results from the latter two loads averaged out.

The Benkelman beam follows the standing rebound procedure. The truck used has a simple back axle with twin wheels and an axle load of 13 000 kg.

The sensors located in the pavement consist of a rod embedded in the concrete slab at a depth of approximately 2 m and a sensor joined to the pavement, with strain gauges. There are eight sensors of this type (two in Sections 3 and 4 and one in the other sections).

The Lacroix deflectograph has a short chassis and 13 tons per axle with a distance between measurements of approximately 5 m. It works at a measuring rate of 2 to 3 km/hr. It provides measurements 1.9 m apart along two rolling lines corresponding to the back wheels. The sensors are of the linear variable differential transformer (LVDT) type.

All the equipment was calibrated using micrometers before the measurements were carried out.

## COMPARISON BETWEEN FWD AND BB

A comparison between FWD and BB was made, after 50,000 loads had been applied to the pavements, and then again after 600,000 loads had been applied. The first measurements were made for two semirigid pavements (Sections 1 and 3) and one flexible pavement (Section 2). The second measurements were taken only for Sections 1 and 2. In each pavement three points were selected that had a deflection close to the average deflection for the pavement. Measurements were made at each point, first with the BB, then with the FWD, and finally with the BB. An average was taken of the two measurements made with the latter equipment. The operation was repeated three times at each point.

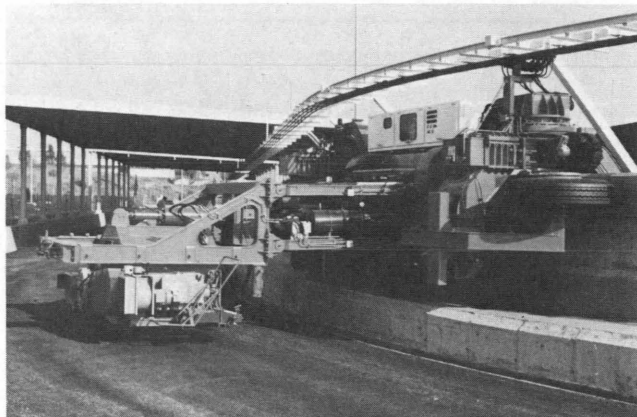


FIGURE 2 Traffic simulation vehicle.

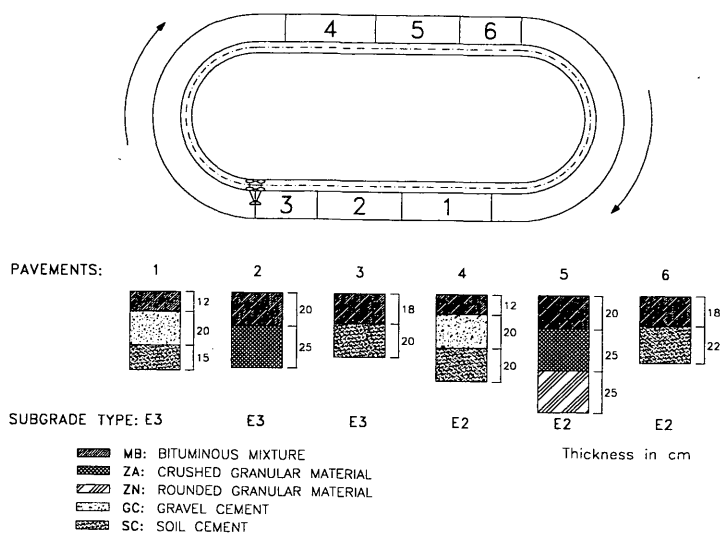


FIGURE 3 Pavements tested.

As a result, coefficient  $\alpha$  was defined as the ratio between the deflection with the BB and that with the FWD. The results are presented in Table 1.

The results varied widely, mostly because of the dispersion of measurements obtained with the BB. If each set of results were represented by their average, it could be said that the ratio between the FWD and the BB depends on pavement type, with higher ratios in the case of flexible pavements as compared with semi-rigid pavements. The same trend appears in the results from the second series of measurements.

During an earlier investigation (4) on different flexible pavements, it was ascertained that the ratio between deflection measured with the two types of equipment also depended on temperature and thickness of the different layers ( $\alpha$  increases both with temperature and with thickness of the asphalt layer) and that the coefficient became gradually less throughout the service life. Furthermore, in the case of flexible pavements with a different com-

position but with the same deflection, different values were obtained for coefficient  $\alpha$ . Specific values for coefficient  $\alpha$  as a whole varied between 0.7 and 2 in the tests carried out.

As a result, it is difficult to establish correlation coefficients between the two sets of equipment. If a conversion needs to be made, the most suitable procedure is to make a comparison on the section to be evaluated, as carried out on the test track. In addition, the lack of consistency obtained in measurements with the BB cast doubt on using it as standard measuring equipment.

### COMPARISON BETWEEN FWD AND LACROIX

Owing to the characteristics of the Lacroix deflectograph, which takes measurements in motion every 5 m, a comparison between the two pieces of equipment could not be carried out point by point. The operation was carried out by repeatedly passing the Lacroix deflectograph over the test sections and staggering the starting point in an attempt to obtain equidistant measurements at 1-m intervals. Maximum positioning errors of  $\pm 30$  cm were measured.

Measurements were carried out after 50,000 loads had been applied to the pavements. As a result of the measurements, coefficient  $\Sigma$  was defined as the result of dividing the average deflection results from the Lacroix deflectograph by the average deflection obtained using the FWD (Table 2). As a comparative example, the specific deflections obtained from both pieces of equipment on Section 1 are shown in Figure 5.

A comparison of the measurements made it clear that although average deflection values were comparable, the specific measurements obtained using the Lacroix deflectograph showed a higher dispersion around the mean than did those gathered by the FWD. On the other hand, and unlike the case of the FWD-BB comparison, coefficient  $\Sigma$  is not related to the pavement type and does not show higher values for flexible pavements as compared with semi-rigid types. Results obtained on the two rolling lines of the Lacroix deflectograph are presented in Figure 6, and it can be seen that the deflections follow the same trend on both lines. For that

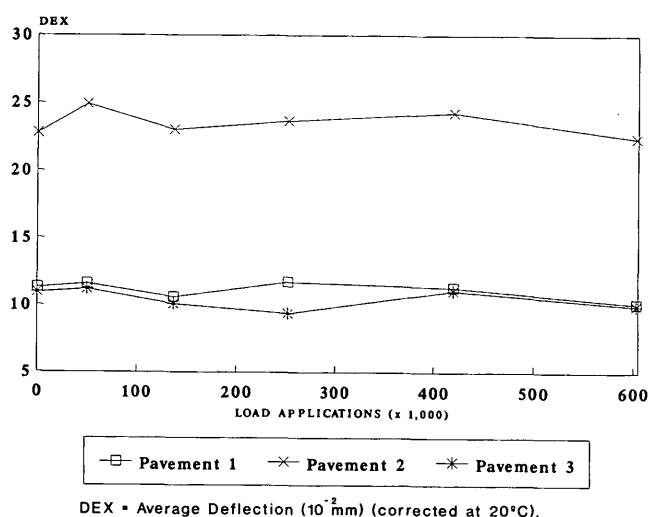


FIGURE 4 Deflections along the test track.

TABLE 1  $\alpha$  Values

LOADS APPLIED	50,000			600,000	
DATE	MAY 1992			APRIL 1993	
PAVEMENT TEMPERATURE	14 - 15			9 - 10	
PAVEMENT No	1	2	3	1	2
DEX	10.2	20.8	9.0	8.7	17.9
$[\alpha]$	0.82 - 1.54	1.35 - 1.71	0.92 - 1.65	0.72 - 1.29	1.22 - 1.65
$\alpha$	1.03	1.51	1.19	0.92	1.44

DEX = AVERAGE DEFLECTION (FWD) ( $10^{-2}$  mm) $[\alpha]$  = INTERVAL $\alpha$  =  $\alpha$  AVERAGE

$$\alpha = \frac{\text{BB DEFLECTION (6,5t)}}{\text{FWD DEFLECTION (6,5t)}}$$

reason, the difference between these results and those obtained with the FWD is not attributable to the differences in the measuring points because of errors in positioning the equipment. Possible causes of the differences that were considered included the effect of the position of the beam tip between the twin wheels and the effect of the dynamic load applied by the vehicle.

The average deflection value measured with the Lacroix deflectograph shows the difference between low and high deflection, but it could give rise to significant deviation from FWD results if specific values or characteristics are used, particularly with deflections of less than  $20 \cdot 10^{-2}$  mm.

The FWD clearly seemed to be a more reliable and consistent piece of equipment, with better characteristics for precision work such as that on test tracks or for working with specific values such as those used with back calculation models. The deflectograph appears to be suitable for large-scale work because of the large quantity of information it supplies, provided that average values are used because specific values show a considerable dispersion.

#### COMPARISON BETWEEN FWD OR BB AND SENSORS

The comparison between the FWD and the sensors was carried out by placing the circular FWD plate in such a way that the central seismometer point rested on the sensor embedded in the pavement. Three loads were then applied (2.5, 6.5, and 6.5 ton), and in each case deflection measured by the embedded sensor was recorded. One of the deflection curves obtained is presented in Figure 7, in which deflection can be seen as a result of the first blow and those blows caused by subsequent bounces. The shape of the wave sequence is similar for all measurements that were made.

Values for deflection measured by the FWD and the sensors are presented in Table 3, along with coefficient  $\beta$ , obtained by dividing the first by the second and multiplying the result by 100. The deflections measured correspond with a difference of about 5 percent, which is within the range of calibration error for both pieces

TABLE 2 FWD Versus Lacroix Deflectometer Results

PAVEMENT	INTERVAL ( $10^{-2}$ mm)		AVERAGE ( $10^{-2}$ mm)		$\sigma$		$\Sigma$
	DI	DL	DI	DL	DI	DL	
1	9-13	4-18	10.2	10.4	1.1	4.1	1.02
2	19-24	15-36	21.1	24.2	1.2	6.5	1.14
3	8-10	5-20	9.1	11.5	0.5	4.7	1.27

 $\sigma$  = Standard Deviation

DI = FWD Deflection

DL = Lacroix Deflection

$$\Sigma = \frac{(DL)}{(DI)}$$

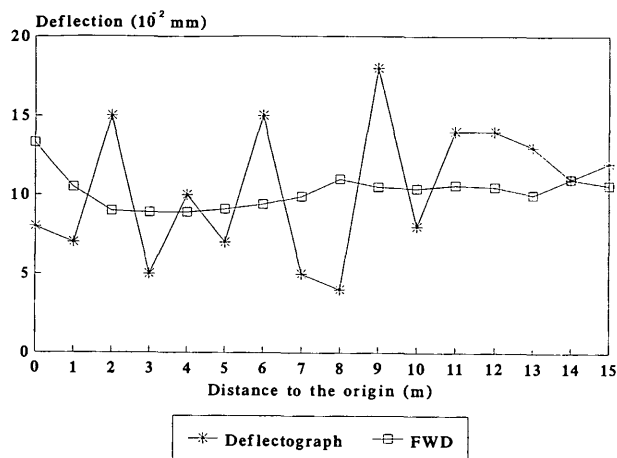


FIGURE 5 Lacroix deflectograph versus FWD deflections (Pavement 1; 50,000 load applications).

of equipment. All sections, regardless of their type, showed similar values for  $\beta$ .

A comparison of the BB and the sensors was then made. The twin wheels of the truck were positioned in such a way that the sensor was between them, and the beam tip of the BB rested directly over the sensor.

In Table 4, the results obtained from all sections are indicated along with coefficient  $\lambda$ , which was obtained by dividing the two deflections (BB and sensor). The value of this coefficient is 92 and 96 in the case of flexible sections and varies between 64 and 80 in the case of semirigid pavements. In the latter case, error brought in by the Benkelman beam therefore could be considerable.

The difference between the two measurements must be based on the fact that the BB's support is partly within the deformation bowl produced by the load. The effect of the deformation factor is much greater for semirigid sections than for flexible sections.

The half-length of the deformation bowl obtained in the test with the load simulation vehicle moving at 1 to 2 km/hr is 500 cm in Section 1 (semirigid) and 350 cm in Section 2 (flexible).

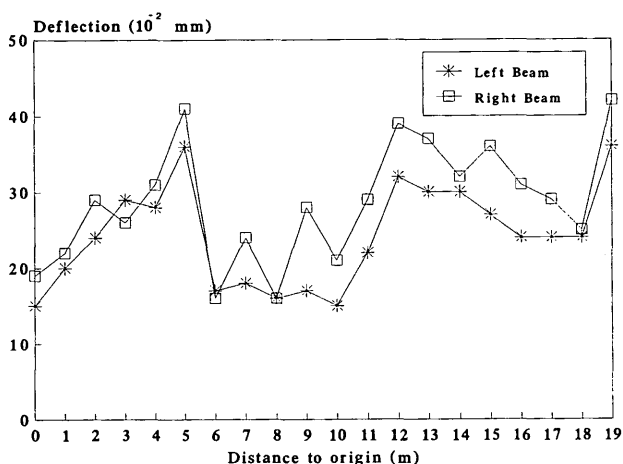


FIGURE 6 Deflections measured with Lacroix deflectometer (Pavement 2).

Because the BB's support is 240 cm from the beam tip, the latter is located in the middle of the half-length of the deformation bowl on the semirigid sections and 1 m from their beginning on flexible sections.

## INFLUENCE OF SECOND SET OF REAR WHEELS

Whereas the FWD applies only to a single load, deflection measured with the BB is produced by the whole set of wheels on the track used in the test. If the effect of the front axle is ignored, since it is of minor importance to the total deflection, the main effect comes from the second assembly of the rear axle wheels.

According to multilayer simulation, these rear wheels contribute 44 to 55 percent of the deflections in the semirigid sections and 24 to 34 percent in the flexible sections. From the deflection curves measured with the vehicle moving at 2 km/hr, these figures have an average of 33 and 20 percent, respectively. The values with the vehicle stopped would be a little bit higher than those, but other measures not being available, these values were used.

On the basis of these results, BB/FWD deflection ratios can be calculated, eliminating the effects of the deformation bowl and the second set of wheels. The results are indicated in Table 5 for Sections 1 (semirigid) and 2 (flexible) in the form of variable  $\omega$ . In making this calculation, the average of values obtained for semirigid sections was applied to Section 1 and the average for flexible sections to Section 2. Taking average values at 15°C, the deflection produced by BB is greater than the deflection produced by the FWD by 50 percent (on semirigid pavements) and 70 percent (on flexible pavements).

## VARIATION IN DEFLECTION WITH LOAD SPEED

In order to carry out this study, deflections from sensors embedded in the pavements were measured as the load simulation vehicle passed over them at different speeds. The data shown here relate to the position of the vehicle with the sensor midway between the two wheels. Values for the resulting deflections are indicated in Table 6. Figure 8 shows an example of the results and their adjustment using logarithmic equations.

The deformation bowl half-length (the distance from the start to the point of maximum value) is between 350 and 400 cm on the flexible sections (Sections 2 and 5) at speeds of 1 to 2 km/hr and decreases as the speed increases to values of 230 to 260 cm. On semirigid pavements, the variation is 400 to 500 cm at low speeds and 300 to 350 cm at higher speeds. Deflections decrease as speed increases. Contrary to what might be expected, the decrease is always greater on semirigid sections than on flexible sections. In the former, the variation is high, up to 15 to 20 km/hr, but then decreases more slowly. In the case of flexible pavements, the greater decrease occurs at up to 10 km/hr (Figure 9).

On flexible and semirigid pavements, the vehicle speed that produces a deflection similar to that of the BB is between 1 and 2 km/hr, whereas in the case of the FWD there is a considerable difference in the equivalent speed for the two types of pavement. On flexible pavements the speed is around 25 km/hr; on semirigid pavement it is between 1 and 2 km/hr. These speed values are obtained by calculating the vehicle speed that produces a deflection on pavements similar to that of the FWD, which gives a ratio

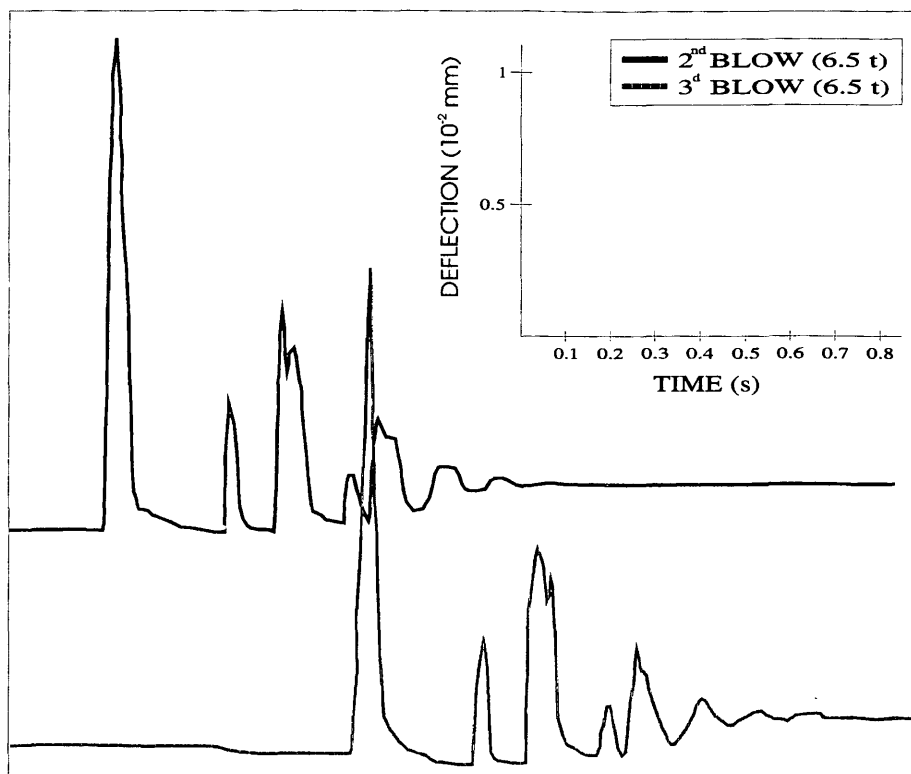


FIGURE 7 FWD deflection-time curve measured by the sensor.

TABLE 3  $\beta$  Values

GENERAL DATA	
DATE	MARCH 1993
LOADS APPLIED	600,000
PAVEMENT TEMPERATURE	7 - 9°C

PAVEMENT	2 <sup>nd</sup> BLOW (6,5t)			3 <sup>rd</sup> BLOW (6,5t)		
	DI	SE	$\beta$	DI	SE	$\beta$
1	8.3	8.1	102	8.2	8.0	102
2	19.7	18.9	104	19.1	18.6	103
3	8.2	7.6	108	8.2	7.7	106
4	6.6	5.9	111	6.5	5.9	110
5	26.7	25.9	103	26.0	25.0	104
6	7.6	7.5	101	8.0	7.6	105
AVERAGE			105			105

DI = FWD Deflection ( $10^2$  mm)  
SE = Sensor Deflection ( $10^2$  mm)  
 $\beta$  = (DI/SE) x 100

TABLE 4  $\gamma$  Results

GENERAL DATA	
DATE	FEBRUARY 1993
LOADS APLIED	550,000
PAVEMENT TEMPERATURE	6 - 8°C

PAVEMENT	BB	SE	$\gamma$
1	8	10.0	80
2	30	31.3	96
3	9	11.6	78
4	6	8.3	73
5	36	39.3	92
6	8	12.5	64
AVERAGE 1,3,4,6	7.8	10.6	74
AVERAGE 2,5	33	35.5	94

BB = BB Deflection ( $10^2$  mm)  
SE = Sensor Maximum Deflection ( $10^2$  mm)  
 $\gamma$  = (BB/SE) x 100



TABLE 5  $\alpha$  Versus  $\omega$ 

PAVEMENT	TEMPERATURE $\approx 15^{\circ}\text{C}$		TEMPERATURE $\approx 10^{\circ}\text{C}$	
	$\alpha$	$\omega$	$\alpha$	$\omega$
1	1.03	0.98	0.92	0.87
2	1.51	1.34	1.44	1.28

\* = Pavement average temperature

$$\alpha = \frac{\text{BB Deflection (6,5t)}}{\text{FWD Deflection (6,5t)}}$$

$$\omega = \frac{\text{BB Deflection (6,5t)}}{\text{FWD Deflection (6,5t)}}$$

between the speed assigned to the FWD and the BB speed of 1 on semirigid pavements and 15 to 20 on flexible pavements.

Response times to the load, measured with the sensors located in the pavements and made with the BB, are approximately 15 sec for flexible pavements and 25 sec for semirigid types. In the case of measurements made with the FWD, 0.12 sec for both types of pavements. The ratio between the deflection response times of the two pieces of equipment is therefore 125 for flexible pavements and 210 for semirigid types. A comparison of these values with earlier ones, even taking into account possible errors in measurement, indicates that a consideration of speed and deformation is not enough to explain the difference between deflections measured with the two types of equipment, particularly in the case of semirigid pavements.

## CONCLUSIONS

- The ratio between deflections measured with the BB and the FWD depends on the pavement temperature, the thickness of the asphalt layer, the pavement type, and the point in the lifetime of the pavement at which the measurements are made.

- Higher ratios are obtained with flexible pavements than with semirigid pavements. The ratio increases with temperature and thickness of the asphalt and decreases over the lifetime of the pavement.

TABLE 6 Deflections at Different Speeds (Test Track Vehicle;  $7^{\circ}\text{C}$ ; 550,000 Load Applications)

PAVEMENT	SPEED (km/h) (*)							
	1.5	1.8	5.2	10	15	20	30	38
1	10.7	10.4	7.9	7.4	7.9	7.0	7.0	7.0
2	30.0	30.0	26.7	24.8	25.4	24.3	23.1	21.2
3	11.1	9.6	8.4	7.4	7.7	7.3	6.6	6.1
4	8.3	8.0	7.1	6.4	6.7	5.9	5.6	5.2
5	40.7	39.3	30.8	30.8	32.2	30.4	30.1	27.4
6	11.9	11.0	9.1	8.4	8.8	8.1	--	--

(\*) Deflection in  $10^{-2}$  mm

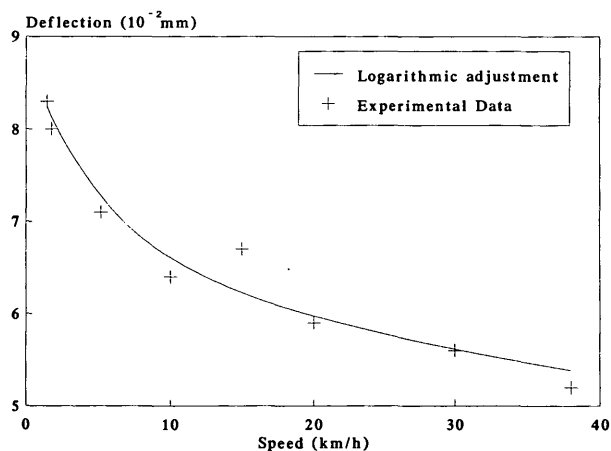


FIGURE 8 Deflection versus load speed (Pavement 4).

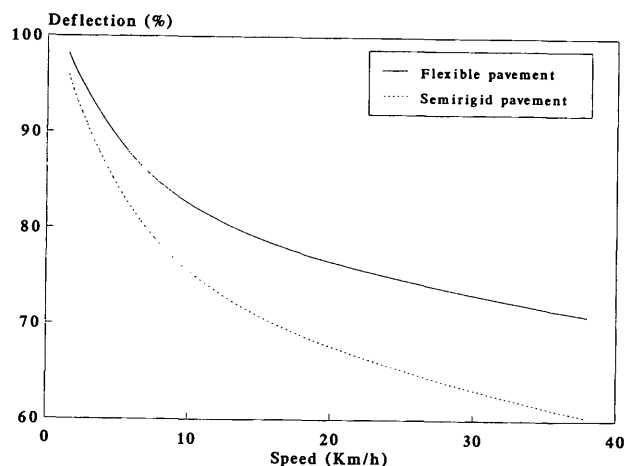


FIGURE 9 Deflection versus load speed in flexible and semirigid pavement (logarithmic adjustment).

- Compared with the deflectograph, the deflectometer is more reliable and consistent and more suitable for precision work such as that done on test tracks or for working with specific values such as those used in back calculation models.

- The deflectograph appears suitable for high-capacity work but could give rise to considerable error if specific values or characteristics are used, particularly with deflections of less than  $20.10^{-2}$  mm.

- The FWD measures the same deflection as sensors embedded in the pavement. The BB, on the other hand, gives lower deflection measurements because its support legs are within the area of pavement deformation. The deviation is greater in the case of semirigid pavements (20 to 35 percent) than with flexible pavements (4 to 8 percent).

- Taking average values at a pavement temperature of  $15^{\circ}\text{C}$ , FWD deflection on sections tested should be increased by 50 percent (before corrections) or 35 percent (after corrections for deflection bowl and second set of wheels), in the case of flexible pavements, to obtain the deflection produced by the BB. Deflections produced by both instruments for semirigid pavements are practically the same.

- Decrease in deflection with an increase in speed of load application depends on the pavement type.

- On semirigid pavements tested between 1 and 40 km/hr, the deflection decreased between 35 and 45 percent. The rate of decrease was greater during the first 15 to 20 km/hr; it then became more gradual.

- For the flexible pavements tested, the decrease in deflection between 1 and 40 km/hr was around 30 percent, with the greatest decrease occurring up to 10 km/hr.

- Deformation bowl length decreased as load application speed increased. On the flexible pavements tested, deformation varied

from 700 to 800 cm at 1 to 2 km/hr to 460 to 520 cm from 20 km/hr onward. On semirigid pavements, deformation values of 800 to 1,000 cm for low speeds and 600 to 700 cm at higher speeds were obtained.

- Different load application times between the FWD and the BB alone do not explain the differences obtained between the deflections produced by the two types of equipment, especially in semirigid pavements.

## ACKNOWLEDGMENT

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