Title: Overview of interpretation techniques based on measurement of deflections and curvature radius obtained with the Curviameter.

Author: Carl Van Geem, BRRC

Abstract: In this contribution an overview will be given of the techniques that are used to interpret the results of measurements with the Curviameter.

The Curviameter was developed in the 1970ies and allows measuring the deflection bowl generated by a passing truck. At intervals of 5 meters 100 points on the deflection bowl are registered by a geophone carried by the truck. During the measurements the truck drives at a constant speed of 18 km/h. The Curviameter also measures the curvature of the deflection bowl at the point where the maximum deflection is reached. The BRRC has a Curviameter in use since 1994.

In this contribution we will briefly present the principle of the Curviameter. We will present its precision and its limitations. We will present results of comparisons of maximal deflection measurements with the Benkelman Beam and the FWD.

We will also give an overview, from the literature and from our own experience, of the ways in which the measurements are presented and interpreted. This includes simple criteria on maximal deflection Dm, the exploitation of the radius of curvature R and the product R.Dm, the computation of homogeneous zones, back-calculation of the E-modules of several layers and the detection of Long-Life Pavements.

Contribution:

Principle of the Curviameter

The first Curviameter was brought into service in 1973 on the construction works of the motorways of Rhône-Alpes. The oldest document we have on the Curviameter is a report by the CEBTP of February 1974. A description of the Curviameter and some of the theory behind it was published in the "Revue Générale des Routes et des Aérodromes" (cf. [Paquet77]).

In those days the Benkelman beam was the reference tool for deflection measurements but this device clearly had two drawbacks: the measurement is slow and the radius of curvature is not measured. The Curviameter allows the inspection over long distances in reasonable time (at a speed of 18 km/h) and measures the radius.

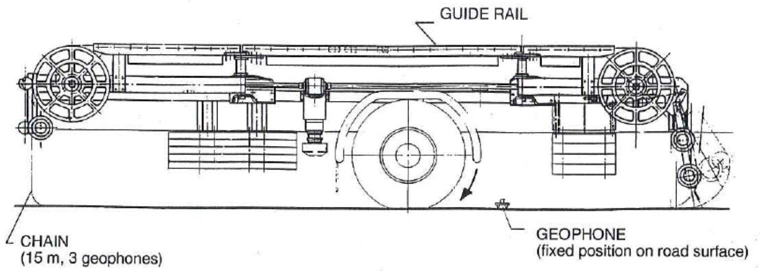

Figure 1: The Curviameter MT-15 principle (cf. [COST325])

The modern Curviameter is equipped with three geophones on a chain (see Figure 1). Only one of the geophones at a time actively registers the deflection bowl observed at a particular position while the lorry moves forward over 4 meters at a constant speed of 18 km/h. The geophone stays in place since the chain is moving in the opposite direction at the same constant speed. The distance between two consecutive points where the deflection bowl is measured, is 5 meters.

The geophone starts registering data as soon as the rear axle is about 1 m away from the geophone's location. The geophone stops registering when the rear axle has passed the geophone's location by approximately 3 m.

Measured data

The signal of the active geophone is stored as a discrete graph of 100 points. This signal can be post-processed and delivers a complete deflection bowl. The electronics and software on board immediately measure the maximal deflection (DmC), the radius of curvature (RC) of the deflection bowl at the moment where the maximal deflection occurs and the indicator λ. The indicator λ is equal to μ/h, where μ is the opening width of the deflection bowl at half-height of the maximal deflection and h is half of the maximal deflection.

Temperature correction

In Spain as well as in France (cf. [Kobisch08]), formulas exist for a corrective action on the values of the deflection on bituminous road surfaces in function of the temperature at which the measurements were executed. In Belgium, we usually do not apply temperature correction on measured deflections, but may apply temperature correction on the E-modules that were estimated by a back-calculation method.

Deflection and load speed

The faster the speed with which the load is applied to the pavement, the less deflection will be generated. The evolution of deflection with respect to load speed also depends on the type of pavement (flexible or semi-rigid). This is illustrated by Figure 2 (cf. [Romero94]).

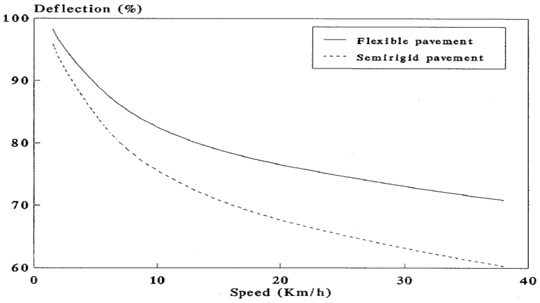

Figure 2: Deflection versus load speed (logarithmic adjustment).

Deflection and load

The load itself has an impact on the deflection generated. For flexible pavements a correlation is evoked in [Gorski99] between the maximal deflections measured by the Curviameter with loads of 127 kN/axle and 105 kN/axle:

DmC (127 kN) = 1.22 . DmC(105 kN).

Non-destructive testing with high productivity

The Curviameter is a device that can measure a large number of points in a rather short period of time. As a counterpart for its high performance, a certain loss in quality is to be paid: some measurements will fall out; very small deflections (on rigid pavements) cannot be measured accurately since the sensitivity of the sensor does not allow so. Comparisons to punctual measurements (as with FWD or Benkelman beam) must be done with caution since it is very hard to measure at exactly the same spot.

As an alternative, comparisons under less well controlled circumstances can most honestly be done by investigating results like average values and characteristic deflections rather than on a point by point comparison.

Characteristic deflections

The characteristic deflection Dc of a zone is given by the formula $Dc = Da + 2.\sigma$ where Da is the average of the maximal deflections measured in the zone and σ is its standard deviation. The factor 2 is chosen since the number of measures in a zone is considered big enough (at least 10) from a statistical point of view.

For fully flexible roads it was established that there is a relation between the degree of structural damage, the characteristic deflection and the traffic load that already passed on the road (cf. Fig. 6, p. 21 of [BRRC85]). Under certain conditions the ground modulus Es can be estimated accurately in function of the characteristic deflection and the equivalent thickness of the road structure (cf. from p.34 onwards in [BRRC85]).

At the BRRC, another observation was made with respect to the ground modulus Es, establishing a correlation between the deflection D(900) measured by the Curviameter 900 mm after the maximal deflection was registered and Es. The previously obtained relationship was verified again for the study in [Gorski05], from which the graph in Figure 3 is extracted.

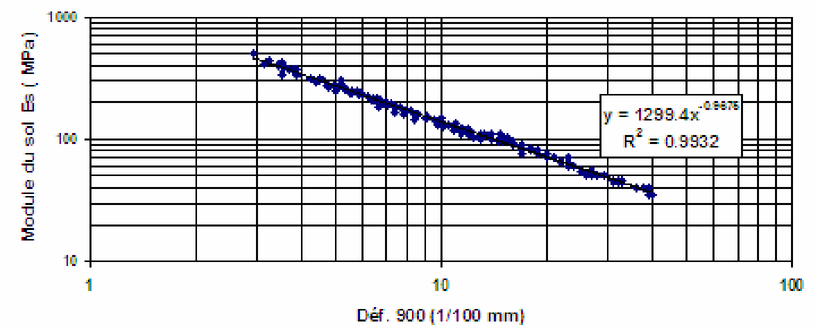

Figure 3: Relationship verified with data from campaign in Italy.

In France, classes are defined based on characteristic deflections corrected in function of the structural design of the road under investigation (cf. [Kobisch08]).

Homogeneous zones

In order to evaluate the measurement results of the Curviameter, it is necessary to cut the monitored road section into "homogeneous zones". A "homogeneous zone" is a zone in which the maximal deflection does not vary significantly. In other words, in a "homogeneous zone" the pavement "responds" in a similar way to the load of the Curviameter. In the end, the road manager will decide to take a particular action on each homogeneous zone separately. Therefore it is not necessary to divide the monitored road section in very short zones and at the BRRC we usually arbitrarily set the minimum length of a zone to 200 m.

The standard method implemented in the software delivered to the BRRC when the Curviameter was purchased, is a statistical analysis of the deflection measurements (cf. [duMesnil84], [Lebeau92]).

Another technique is based on the computation of the sliding average of the characteristic deflection (cf. [BRRC85]). When these are put in a graph, the homogeneous zones are delimited by each change between predefined ranges of deflection values (e.g. 20-40, 40-60,… expressed in 1/100 mm). This technique was already in use for the Lacroix deflectograph data in Belgium before the arrival of the Curviameter.

The technique described in Chapter 4 of the final report of the COST action 336 on FWD measurements (cf. [COST336]) could also be used for Curviameter data.

Curviameter Precision

As soon as the first Curviameter was built, the precision and repeatability were verified. Clear reports on this kind of verifications can be found in [Bouche76], [Bouche77a], and [Bouche77b].

The precision of the individual measurements of the Curviameter is of the order of +/- 2/100 mm. The repeatability observed for consecutive passing over the same section of 200 m length varies between 2 and 5/100 mm and depends on the class of deflections as indicated in Table 1.

Deflection class (in 1/100 mm)	20 – 40	40 – 60	60 – 80	80 - 100
Repeatability (in 1/100 mm)	+/- 2	+/- 3	+/- 4	+/- 5

Table 1: repeatability of deflections

In the frame of a normalization procedure in France, the LCPC evaluated the Curviameter MT 15 in 1992. An article in the LCPC Bulletin (cf. [Lepert97]) gives a nice overview of the results. It allowed the Curviameter to be considered as a “deflectometer of class 2” (the class with the highest performance) on all types of roads. Note that it is also mentioned that invalid measurement results were observed for 7 to 24% of the test points, which is reported to be comparable to other deflectometers.

Comparison with Benkelman beam

At several occasions, comparative tests were executed between the Curviameter and the Benkelman beam. Early tests were already reported in [Bouche76], [Bouche77a], and [Bouche77b]. In the period between 1974 and 1978 the first correlation trials were organized in several countries (France, UK, Morocco, and Martinique), and again in 1983 in Cote d’Ivoire both on flexible and semi-rigid road structures (cf. [Liautaud84]). An excellent correlation was published for the maximal deflection.

A test round in Spain under supervision of CEDEX in 1992-1993 (cf. [Lopez94], [CEDEX92]) helped in the acceptance of the Curviameter as a measurement tool in that country. A correlation was established (cf. [Lopez94], [COST324]) for maximal deflections measured with Benkelman beam (DmB) and Curviameter (DmC):

$$DmB = 1{,}38\ DmC\ .$$

A correlation was established for the characteristic deflections (cf. [Lopez94]) measured with Benkelman beam (DcB) and Curviameter (DcC):

$$DcB = 1{,}33\ DcC \text{ or } DcB = 1{,}26\ DcC + 5{,}14\ .$$

Both formulas hold for a load of 127 kN on the Curviameter.

A comparison to the Benkelman beam was also made with the very first Curviameter of the CEBTP on a traditional flexible pavement (cf. [Annales77]). A correlation was established for the radius of curvature measured by the Curviameter (RC) and the radius determined from the measurements with the Benkelman beam (RB):

$$RC = 0.72\ RB.$$

This relationship is very difficult to observe since only the Curviameter measures the radius.

Making a comparison between the Benkelman beam and the Curviameter is very delicate because the speed of the load charge is very different (almost static for the Benkelman beam, at 18 km/h for the Curviameter).

Comparison with Lacroix Deflectograph

A comparative campaign between a Lacroix Deflectograph and the Curviameter has taken place in Belgium on a high number of road sections in 1994, giving an excellent correlation between the maximal deflections as illustrated in Figure 4.

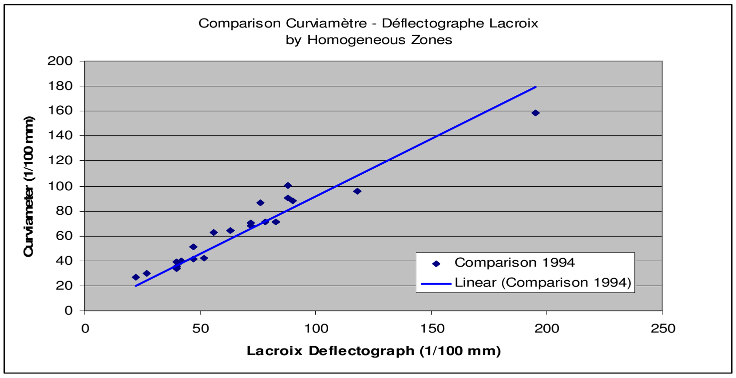

Figure 4: illustration of comparison with Lacroix Deflectograph

Comparison with FWD

One of the first times the older generation Curviameter MT-15 (load of 100 kN/axle) was compared to a Dynatest 8000 FWD (load of 50 kN), was in 1991 in Poland on 7 flexible or semi-rigid road sections, by the CEBTP and IBDiM (cf. [Czarnecki93], [COST324]). In this study only the maximal deflections were compared. The characteristic deflections turned out to be almost identical and it was concluded that both devices could equally well be used for pavement management and maintenance systems. Significant local differences occurred on some sections, for 20 to 30% of the measurements. In the same exercise a Benkelman beam was included on two of the sections, confirming the relationships determined earlier (cf. [CEBTP91]).

A comparison between Lacroix Deflectograph, FWD Dynatest 8000 and Curviameter versus a reference was organized in France by the LCPC in 1993-1994 (cf. [COST324]). The results of these tests however gave formulas with poor correlation coefficients. The European-wide COST action 324 did give recommendations on deflection measurements for use in future long-term pavement performance studies on European level (cf. [COST324], pp.117-118).

In the frame of the PARIS project (Performance Analysis of Road Infrastructure), a comparative test was executed between the Curviameter of the BRRC (load 104.5 kN) and the FWD Dynatest 8000 of the DWW. The results were published in a technical memorandum (cf. [PARIS98]). The first result concerns the deflections measured by both devices, given in Table 2.

Deflection distance from maximum (in mm)	Linear correlation coefficient (R)	A1 (DCurvia = A1 . DFWD)	A2 (DFWD = A2 . Dcurvia)
0	0.919	1.024	0.955
300	0.962	1.315	0.753
600	0.916	1.662	0.590
900	0.728	1.810	0.514

Table 2: FWD vs. Curviameter in PARIS project

The second result of the PARIS comparison concerns the radius of curvature. It was observed that there is a relationship between the Surface Curvature Index at 600 (SCI_{600}, also IDK_{600}, in 1/100 mm) computed from FWD measurements and the radius of curvature (RC, in m) measured by the Curviameter:

$$SCI_{600} = 1.3827\ RC.$$

Norms

There exists a norm in France related to the measurement of deflections generated by a rolling load (cf. [NF91]) and in particular one related to the Curviameter (cf. [NF97]). In Belgium, a method for deflection measurements is defined for Lacroix Deflectometer and Curviameter (cf. [CME02]) and an extension of this text to the FWD is under discussion.

Evolution of deflections in time

By definition, the residual life is equal to the total life time of a road minus the time the road has been in service. The total life time of a road is defined as the number of years from its construction until the moment the road reaches a degree S of damage in terms of fatigue and deformations of the pavement. For main roads S = 50%. Often, the life time is expressed in “equivalent standard axle loads” (ESAL) rather than in time. The relation between ESAL (of 80 kN) and the characteristic deflection determined by the Curviameter (at 100 kN) is given in graphical format in Figure 5 (cf. [BRRC98], [BRRC85], [Veverka80]).

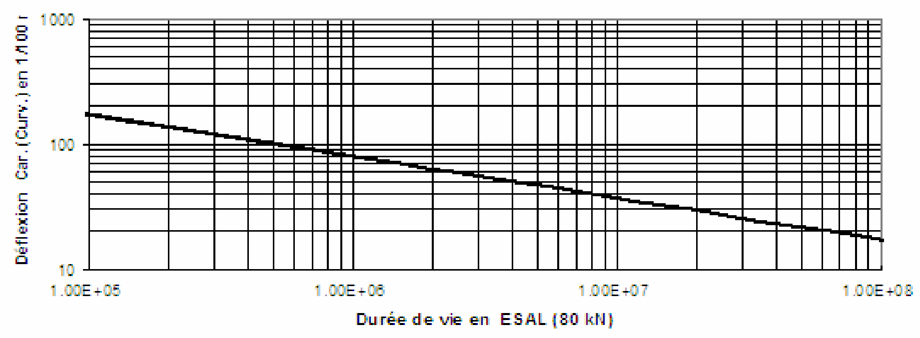

Figure 5: ESAL vs. Dc (ref. BRRC)

For characteristic deflection determined with the Benkelman beam, the relation is expressed by the formula (cf. [Gorski99]):

$$N_{ESAL} = 2.46 \times 10^{12} / (DcB)^3.$$

This graph and formula are in agreement with relations obtained earlier by AASHO (in the US) and TRRL (in the UK) and verified through a campaign of the Curviameter in the North of Italy (cf. [BRRC97]).

In [Gorski99] a simple approach is presented that allows translating deflections measured by the Curviameter into remaining life time: determine homogeneous zones, compute characteristic deflections, transform into ESAL life time, extract the number of ESAL that already circulated on the pavement and deduce the remaining life time.

Earlier studies showed that indeed the increment of the characteristic deflection is negligible for about the first 70% of the life time of a pavement, period after which the deflection however will increase by 10% as shown in Figure 6 (cf. [DTC71]). With this in mind, the road manager may want to distribute consecutive deflection measurements, spacing the measurement by shorter intervals of time when the time of operation approaches the life time considered at the design stage.

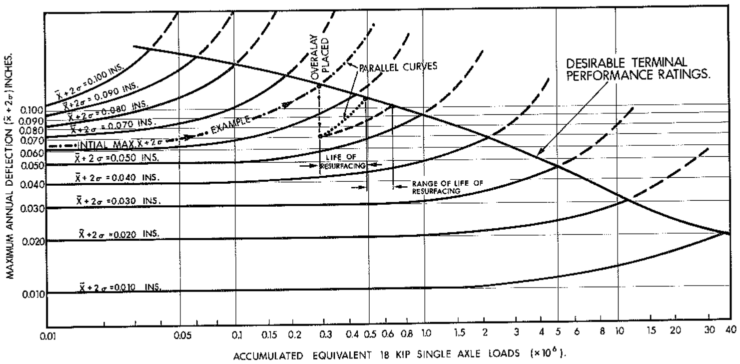

Figure 6: ESAL vs. Dc (cf. [DTC71]).

Recently a study of the evolution of the maximal deflection over time has been done based on real data collected (with the Lacroix deflectograph) over a very long period of time in France. (cf. [Lepert06]). It was observed that the maximal deflection has the tendency to stay constant or to decrease slightly over time. High traffic load incites slow introduction of micro-cracks in the base course. Low traffic roads may benefit from late extra stabilization due to the traffic and bituminous top layers can get somewhat more rigid over time. Therefore the maximal deflection will not change much over time for well designed roads.

R.Dm for flexible pavements

The product of the maximal deflection Dm and the radius of curvature R is mainly been studied in France. For fully flexible bituminous roads, a good relation is established between the product and the fraction E2/E3 of the elasticity modules E2 of the sub-base layer and E3 of the base course. If the structure of the road is in a good condition then the product R.Dm is constant and proportional to E2/E3 as long as the thickness of the sub-base layer is constant. Under such conditions the product R.Dm is independent from the actual values of the modules. The most detailed publication on the product R.Dm was certainly written in April 1969 by P. Autret (cf. [Autret69]). This study was based on measurements with the Benkelman beam, on theoretical models of the deflection bowl and on a structural road model of three layers.

Back-calculation of E-modules and estimation of residual life

Early publications mention the use of the software Alizé III for back-calculation of E-modules from Curviameter data. In Belgium we now use the back-calculation module of the software DimMET© (cf. [Lemlin06], [Maeck09]). Usually the deflections D(0), D(300), D(600) and D(900) are extracted from the deflection bowl measured by the Curviameter and they are used for back-calculation using a 3-layer model of the road (where D(x) is the deflection measured by the Curviameter x mm after the maximal deflection was registered).

In order to make the back-calculation computations as realistic as possible, the "footprint" made by the tyre of the Curviameter on the road surface has been measured by the BRRC, and the pressure in the tyres during measurements is regularly checked. The contact surface is indeed an input parameter for DimMET©.

Radius of curvature

In France, the radius of curvature is considered to give an indication on the quality of the bounding between layers and a division in classes is made (cf. [Kobisch08], [Chea06]). The radius is more sensible to temperature variations for bituminous surface layers and to variations in the quality of base or sub-base layers (cf. [Kobisch08]).

Noise: is this extra information?

It was already stated at the conception of the Curviameter that the road or the vehicle itself could cause noise in the signals and that this noise has to be filtered in order to exploit the measurements (cf. [Paquet77]). This does not prevent the presence of invalid measurement results at some of the numerous points a Curviameter produces (cf. [Lepert97]). From our long experience with the Curviameter at the BRRC we observed that the noise in the rejected signals is often very regular and similar to signals observed on viaducts. This makes us to express the hypothesis that there may very well be a signature of bad bounding between the top layer and the base layer of the road structure in the noise of rejected signals. So far, this hypothesis was never contradicted to other observations or by coring but a more rigorous verification is still necessary.

Curviameter in practice

An example of the use of back-calculation of E-modules is given by the exercise described in [Gorski05]. The context was the realization of a rehabilitation project of a motorway in Italy making use of cold recycled material based on bitumen and cement.

Modules were estimated by back-calculation based on continuously measured deflections by the Curviameter and layer thicknesses with a Ground Penetrating Radar. In parallel, modules were determined in a laboratory from a few cores. Very similar values were obtained with both methods but back-calculation and continuous non-destructive measurements allowed to explain variations in the E-module for the layer of recycled material by the more heterogeneous composition of the lower part of that layer.

A particular interpretation of Curviameter results was done for a case study on long life pavements (cf. [Gorski07]). In this paper a criterion used in the UK and based on maximal deflection and layer thickness of the bituminous material was verified with data obtained by a campaign of measurements on an Italian motorway. Layer thicknesses were determined with a Ground Penetrating Radar. It turned out that some sections with less bituminous material were still “long life pavements”, probably due to the quality of the lower layers. It is suggested that further investigation of another criterion is based on the product R.Dm would have great potential.

A comparison between the homogeneous zones determined from deflection measurements on the one hand and Ground Penetrating Radar images on the other hand were presented in [VanGeem05]. The radar images allow dividing a section in structurally homogeneous zones whereas the Curviameter measurements allow dividing a section into zones with similar structural performance characteristics. It turned out that the borders of the zones determined from radar images coincided with borders of zones determined from maximal deflections.

References

[Annales77] Annales de l'institut technique du bâtiment et des travaux publics, N°356, December 1977 (fig. 12 : chaussée souple traditionnelle).

[Autret69] *Utilisation du produit Rd pour l'auscultation des chausses à couche de base traitée*, P. Autret, Bulletin de liaison des Laboratoires des Ponts et Chaussées N° 42, Déc. 1969, Réf. 740, pp.67-80.

[Bouche76] *Le Curviamètre CEBTP*, Maurice Bouche, Fédération Routière Internationale (I.R.F.), III Conférence Routière Africaine, Abidjan, 24-30 October 1976.

[Bouche77a] *Le Curviamètre CEBTP*, Maurice Bouche, Conférence Pan Africaine sur l'Entretien et la Réfection des Routes, Ghana, November 1977.

[Bouche77b] *Le Curviamètre CEBTP*, Maurice Bouche, Annales de l'institut technique du bâtiment et des travaux publics N°356, série Essais et measures N°154, December 1977.

[BRRC85] *Handleiding voor de versterking van flexibele wegen met bitumineuze materialen*, OCW Aanbevelingen A56/85 – *Code de bonne pratique pour le renforcement des chausses souples à l'aide de matériaux bitumineux*, Recommandations CRR R56/85.

[BRRC97] *Equipes de mesure du CRR en point de mire*, bulletin CRR – OCW mededelingen N°33, 1997

[BRRC98] *Evaluation de la durée de vie résiduelle des chausses souples et semi-rigides*, bulletin CRR – OCW mededelingen N°34, 1998

[Chea06] *Détection des défauts d'interfacesentre couches de chaussées à l'aide de la déflexion de surface,* S. Chea, J.Martinez, 24èmes Rencontres Universitaires de Génie Civil, La Grande 1-2 juin 2006.

[Czarnecki93] *Comparative Measurements of Pavement Deflections. FWD – Curviameter*, K. Czarnecki, S. Szpinek, D.Godlewski, B.Heritier, The East-West European Road Conference Proceedings, Vol. 1, 1993, pp.66-70.

[CEBTP91] *Mesures de déflexions. Etude comparative Benkelman – FWD – Curviamètre*, technical document of CEBTP (in French), Dec. 1991.

[CEDEX92] *Estudio comparative de los resultados provisionales obtenidos con el curviámetro MT-15 y la viga Benkelman*, CEDEX, Madrid, Dec. 1992.

[CME02] *54.26 - Portance (déflexion du revêtement au passage d'un essieu)*, Chapitre 54 du Catalogue des Méthodes d'Essais, annexe au Cahier de Charges Type du Ministère de la Région wallonne, version 2002.

[COST324] *COST 324, Long Term Performance of Road Pavements, Final Report of the Action*, 1997 (ISBN 92-828-0308-2).

[COST325] *COST 325, New Pavement Monitoring Equipment and Methods, Final Report of the Action*, 1997 (ISBN 92-828-0307-4).

[COST336] *COST 336, Use of Falling Weight Deflectometers in Pavement Evaluation - Final Report of the Action*, Main Report, 2nd Edition, April 2005.

[DTC71] *Pavement Investment Decision Making and Management System*, Report RR174, Dept. of Transportation and Communications, Ontario, Oct. 1971.

[duMesnil84] *Traitement automatique des résultats de mesure en continu*, M. du Mesnil-Adelée, J.Peybernard, Bulletin de liaison des Laboratoires des Ponts et Chaussées N° 130, March-April 1984, pp. 76-81.

[Lepert97] *Evaluation du Curviamètre MT 15*, Ph.Lepert, G.Aussedat, J-M.Simonin, Bulletin des Laboratoires des Ponts et Chaussées N° 209, May-June 1997.

[Gorski99] *Residual Service Life of Flexible Pavements an dits Impact on Planning and Selecting Priorities for the Structural Strengthening of Road Networks - La durée de vie résiduelle des chaussées souples et son impact sur la planification et le choix* *des priorités en matière de renforcement structurel des réseaux routiers*, M. Gorski, XXI Congres Mondial de la Route (AIPCR), Kuala Lumpur, Malaisie, 3-9 octobre 1999.

[Gorski05] *Détemination de modules de couches recyclées a froid*, M. Gorski, XXème congrès belge de la route, 2005.

[Gorski07] *Investigating long life pavements. A case study*, M. Gorski, R.Benetti, M.Garozzo, M.Mori, in Advanced Characterisation of Pavement and Soil Engineering Materials, Loizos, Scarpas & Al-Quadi (eds), 2007.

[Kobisch08] *Guide CFTR diagnostic et conception des renforcements de chaussées*, R. Kobisch, presentation at the LCPC Séminaire "Durabilité structurelle des chausses: pathologies et entretien", 9 Sept. 2008.

[Lebeau92] *Traitement automatique de mesures pour un découpage de routes en zones homogènes* », rapport de stage de DESS, J.Lebeau, étudiant de l'Université Paris VI sous la direction de Y.Lerolle du CEBTP, Octobre 1992.

[Lemlin06] *Walloon Design Method for Concrete Pavements, Improvements since 2003*, Proceedings 10th International Symposium on Concrete Roads, 18-22 Sept. 2006, Brussels.

[Lepert06] *Evolution de la déflexion observée sur les chausses souples modernes*; Ph. Lepert, Bulletin des Laboratoires des Ponts et Chaussées N° 265, Oct.-Dec. 2006.

[Liautaud84] *Routes et développement – comptes rendus du Colloque International, Paris, 22-25 mai 1984*, organized by l'Ecole Nationale des Ponts et Chaussées.

[Lopez94] *Comparacion entre las deflexiones medidascon el curviametro MT15 y con la viga Benkelman*, B.Sanchez Lopez, F.Achutegui Viada, Rutas N°41, March-April 1994.

[Maeck09] *Dimensionering van wegen met behulp van de software DimMET*, J. Maeck, XXIe Congrès belge de la Route, Gand, 22-25 septembre 2009.

[NF91] *Mesure de la déflexion engendrée par une charge roulante*, norme française, NF P 98-200-1, juillet 1991.

[NF97] *Mesure de la déflexion engendrée par une charge roulante. Détermination de la déflexion et du rayon de courbure avec le curviamètre*, norme française, NF P 98-200-7, décembre 1997.

[Paquet77] *Un nouveau appareil d'auscultation des chausses : le Curviamètre*, J. Paquet, in Revue Générale des Routes et des Aérodromes N°530, April 1977 (translated in English and published as technical note by the CEBTP in 1978): ISBN 2-902722-0-1).

[PARIS98] *Normalisation of Deflection Measurements*, Technical Memorandum T2 of the PARIS project, 22 September 1998.

[Romero94] *Variation of Deflection with the Measuring Equipment and with the Load Speed in a Test Track*, R.Romero, A.Ruiz, R.Rodil, M.A.Lechuga, Transportation Research Record, Issue 1448, 1994, p. 53-60 (also Preprint of Paper N° 940891 for the Transportation Research Board 73th Annual Meeting, Washington DC, 1994).

[VanGeem05] *The use of FWD measurements in Belgium*, C. Van Geem, L. Heleven, 4th European FWD UGM, Trondheim, 2005.

[Veverka80] *Renforcement des chaussées à revêtement hydrocarboné*, Compte rendu de recherche CR12/80, Centre de Recherches Routières, 1980.