Road pavements monitoring methodologies

Practical application of Ground Penetrating Radar and of Falling Weight Deflectometer

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Abstract

Road pavements are infrastructures that throughout their life time present a degradative evolution of their functional and structural conditions. Pavements condition monitoring is important in road pavements maintenance, in order to guarantee a quality level that assures safety conditions, comfort, economy and environmental quality.

The most important survey characteristics considered are: bearing capacity, transverse and longitudinal unevenness, drainability, noise, friction and texture. Monitoring equipments are usually used to evaluate these characteristics. In this study the most representative monitoring equipments are identified.

The actual development perspectives in this area involve reliability and accuracy of results by means of monitoring equipments. The main objective is improving road pavements maintenance and therefore developing equipments that can perform at traffic speed and have software which permits a faster interpretation of the results.

This work presents a case study of monitoring equipments application and contribution for structural evaluation of road pavements. From the works developed in this case study of a flexible pavement section, was possible to conclude, that in the determination of pavement structural characteristics, the complementarity of the data obtained in the bearing capacity surveys made with the Falling Weight Deflectometer, together with the results acquired in the tests carried through with the Ground Penetrating Radar and coring, is essential.

Key words: Road pavements; Pavements structural and functional characteristics; Monitoring equipments; Structural evaluation of pavements; Falling Weight Deflectometer; Ground Penetrating Radar.

Introduction

Roads are essential transportation infrastructures for economic, social and cultural development of any country, because they assure the interchange of people and goods in fast, efficient and safe way. Therefore the knowledge of pavements condition is fundamental to provide safety, comfort, economy and environmental quality in order to satisfy road users.

Usually road pavements are classified in three main categories: rigid, semi-rigid and flexible. Flexible pavements represent a very high proportion of the Portuguese road infrastructure. Conceptually, a flexible pavement is constituted by wearing and base course as bituminous material top layers, and by a road base and a sub-base of granular material. Rigid pavements are commonly constituted by a concrete slab and a granular or cement treated sub-base. The main difference between flexible and rigid pavements is the manner in which they distribute the load over the sub-grade. The rigid pavement, because of its stiffness and high modulus of elasticity, tends to distribute the load over a relatively wide area of soil [Yoder & Witczak, 1975]. Semi-rigid pavements present similar characteristics with flexible and rigid pavements.

Pavement materials properties change in time under the effect of traffic, climate and ageing. Consequently distresses occur and may lead to functional or structural failure of the pavement. There are several types of distresses for each pavement referred before, due to their different constitutions.

Survey characteristics are related to the functional and structural condition of the pavement in a given time.

Pavements structural characteristics are related to the bearing capacity for which pavements were designed according to the traffic conditions. Pavements functional characteristics are mainly related with longitudinal and transverse unevenness, drainability, noise, friction and texture.

It is very important to maintain adequate levels for those characteristics during pavements life time. Thus, it is necessary to evaluate pavements condition periodically, through monitoring actions. Pavement maintenance is becoming an important issue, as the construction of new roads tends to decrease, the aggressiveness of traffic loads is increasing and the functional requirements for the existing roads are becoming more demanding [Fontul, 2004].

Furthermore, the degradative evolution of some of those characteristics may turn into very serious and dangerous consequences, like the occurrence in road traffic accidents.

1. Survey characteristics

In order to evaluate the **bearing capacity** and consequently the structural behaviour of a pavement load tests can be performed. The deflection basins measured on the surface of the pavement during load tests allow for analysis of the pavement structure (pavement along with the sub-grade) and the evaluation of the contribution of each layer for its structural behaviour.

Surface distresses observation permits the evaluation of issues related to the functional and structural quality of the pavement. Furthermore, when the surface distresses are identified it is possible to determine the causes associated to their appearance and to predict the development of other distresses and their influence on other survey characteristics.

Road pavements **superficial texture** has a determinative role to provide functional quality. Surface texture is related to the development of skid resistance, to the low frequency noise inside and outside the vehicles and to the tyres consuming. Therefore this is a very important characteristic to be evaluated because of its influence on users safety and comfort, vehicle operation costs and environment [Branco *et al*, 2006].

Unevenness is related with geometrical defects and it may be observed longitudinally and transversally [Fontul, 2006]. Unevenness is considered the characteristic that most influence the users opinion about pavements quality level. Longitudinal profile unevenness occurs when there are deviations on pavement's surface in comparison with the theoretical longitudinal profile, as well as defects on pavement's surface.

Transverse profile unevenness is an important factor to achieve a good road performance. This unevenness affects not only the comfort but also the driving safety particularly when water is present on the road surface.

This parameter can provide an indication of the structural deterioration of the pavement when the deformation is deep within the pavement [FORMAT, 2004].

Pavement surfaces must provide an adequate level of **friction** at the tire-pavement interface to provide safe operation of vehicles.

Friction evolutes in time and depends on several factors.

Some of this factors are related to the pavement's type and condition, for example the polishing of the aggregates caused by the passage of vehicles tyres, the bleeding, the appearance of discontinuities due to cracking, among other factors. The existence of ruts may cause the accumulation of water and .consequently the occurrence of aquaplaning. Other factors are related with the type and condition of tyres, particularly the polishing level, the pressure, the load on wheel. In addition the driving speed, the weather conditions and the season of the year may have influence in friction conditions changes [Pinto, 2003; Santos, 2007].

A tire-pavement's friction can be evaluated by the determination of the longitudinal friction coefficient which is related with break distance and the transverse friction coefficient which evaluates the driving safety on curve zones.

Superficial **drainability** of a pavement is another essential factor to maintain a desirable serviceability level and safety driving conditions.

Poor surface drainage contributes to accidents resulted from aquaplaning and loss of visibility from splash and spray as well as for the appearance of degradations [Mahboub *et al*, 2003].

However, it is also important that underlying layers drainage is adequate, because long-term accumulation of water inside the pavement reduces the strength of unbounded granular materials and sub-grade soils, and

causes pumping of fine materials with subsequent pavement rapid deterioration.

To obtain adequate pavement drainage there are some design techniques like transverse slope, porous superficial layers construction and texturing in rigid pavements.

The most important factors related to the emission and propagation of **noise** produced by vehicles result from the aerodynamic configuration of vehicles, the engine, the exhaustion system and the tyre-pavement contact, that essentially depends on texture and porosity characteristics [Freitas *et al*, 2006; ISO 11819-1, 1997].

The exposure to noise generated by traffic has serious consequences to people's health and quality of life, for example sleep disorders, intellectual performance and communication interference, discomfort, particularly if it is a continuous exposure to sound levels above 65 dB(A) [AEA, 2004].

Current methods to reduce noise include acoustical barriers construction, limitation of traffic speed, changes in vertical and horizontal road design, identification of protected zones, use of modified bituminous mixtures with rubber, which allows the reutilization of tyres and presents advantages not only in matters of noise reduction (about 5/6 dB(A) comparing to traditional pavements) but also increases the resistance to fatigue and to permanent sub-grade strains [RECIPAV, 2007].

2. Road pavement monitoring methodologies

Monitoring equipments assume extreme importance not only in the evaluation of certain characteristics at project level (in little extensions) but mainly at network level in association with management systems related to pavement maintenance. The following road pavement monitoring equipments were identified as representative for the evaluation of structural and functional conditions, taking into account their application in Portugal and internationally.

Superficial distresses may be assessed fundamentally by two methods: visual observation registered in informatics support; visual observation with video or photographic equipment.

Visual observation of pavements condition is mainly performed on the basis of quality indicators of management systems adopted in Portugal.

Determination of pavement deflections, associated to **bearing capacity,** can be accomplished using equipments like the Benkelman Beam, Lacroix's Deflectograph, Curviameter, Falling Weight Deflectometer (FWD) and in the future, high performance equipments that will allow the determination of deflections at traffic speed - *High Speed Deflectometer*.

Structural evaluation also includes the determination of layer constitution, particularly the constituent material and the layer thickness.

In order to achieve this, destructive tests can be done, like coring and test pits or the execution of measurements wells. Non destructive tests can also be done with the Ground Penetrating Radar (GPR).

Preferably, non destructive tests are used, and only when strictly necessary, coring and tests pits are made in order to support results interpretation and laboratorial tests.

Pavement's **unevenness** can be measured by the use of the Longitudinal Profile Analyser (APL), Laser Profilometer or Straightedge.

Local longitudinal friction coefficient can be achieved by the use of British Pendulum. Continuous longitudinal friction coefficient is usually achieved by the use of Grip-Tester.

Transversal friction coefficient can be determined by the use of SCRIM.

Inherent to friction condition are the characteristics of a pavement's texture, which can easily be evaluated at isolated locations through the Volumetric Patch Technique (macrotexture determination) or continuously by using laser technology (microtexture determination) like the Laser Profilometer, the CTmeter and Rugo.

A pavement's surface **drainability** can be determined by the use of Outflow Meter and Permeameter, which have as basic principle the determination of time needed for a given volume of water to dissipate through an area of the surface of the pavement. Therefore it is possible to evaluate the pavement's ability to drain water.

Traffic **noise** can be evaluated by the means of SPB reference method (Statistical Pass-By method), present in standard ISO 11819-1:1997.

It is a stationary and direct method, essentially directed to the comparison of different pavement surfaces which allows for the determination of the sound level of vehicles passage by the use of microphones.

With the objective of continuous noise evaluation, the Close Proximity (CPX) method (ISO/CD11819-2) is being developed [FORMAT, 2004; CEDEX, 2006].

Multifunction monitoring vehicles enable the observation of several pavements characteristics, using at the same time a single vehicle with various integrated technologies, which allows for the reduction of tests time and consequently presents economical advantages due to the use of less human resources.

The future perspectives concern to the development of high performance monitoring equipments, associated to the traffic speed operation and software development inherent to quick results acquisition. It is expected that the network management systems will integrate quality indicators, which take into account several reliable pavements characteristics.

Table 1 presents the most used road pavement monitoring equipments in Portugal their characteristics and their methodologies.

Table 1 – Summary of some characteristics of given equipments used in Portugal.

Tests/ Equipments	Human resources required during tests	Testsconditions	Advantages/Disadvantages	Evaluated characteristics	Traffic interference	Safety measures when tests are made on in service pavements
VIZIROAD	1 operator and 1 driver	Diurnal period and without rain	Superficial distresses observation provided by this equipment presents a high performance. However, the reliability of the results is closely depending on the operator's attention. Therefore, this procedure has associated a subjective component.	Superficial distresses	Does not interfere	Superficial distresses observation supported by VIZIROAD does not require special safety measures..
Falling Weight Deflectometer (FWD)	1 operator / driver	Diurnal period preferably, and without rain	Falling Weight Deflectometer presents good performance in spite of its stationary test condition and consequently, its interference on traffic flow. Generally, the results are reliable.	Structural characteristics	Interfere	Because of stationary tests performed by FWD i t is recommended to be accompanied by safety vehicles.
Ground Penetrating Radar (GPR)	1 operator and 1 driver	Diurnal period preferably, and without rain	Throughout Ground Penetrating Radar equipments is possible to determine pavement layers thickness in a continuous way using non-destructive technology. It is always necessary to perform complementary tests like coring. GPR presents a complementary component to bearing capacity test results.	Structural characteristics	Does not interfere	Although, it is a traffic-speed test procedure which does not interfere in traffic flow, it is recommended to be accompanied by safety vehicles.
Laser Profilometer	1 operator and 1 driver	Diurnal period preferably and without rain	Laser Profilometer can be adapted to accomplish measures of rut depth related to transverse unevenness and of longitudinal unevenness. Furthermore, texture depth can be evaluated by means of this equipment in a continuous way. This equipment presents a high performance.	Unevenness and texture	Does not interfere	Although, it is a continuous test procedure, which does not interfere in traffic flow, it is recommended to be accompanied by safety vehicles.
Longitudinal Profile Analyser (APL)	1 operator and 1 driver	Diurnal period preferably and without rain	Longitudinal Profile Analyser may be used for determining longitudinal unevenness in a continuous way by the means of an inertial pendulum. Presents a high performance.	Longitudinal unevenness	Does not interfere	Although, it is a continuous test procedure, which does not interfere in traffic flow, it is recommended to be accompanied by safety vehicles.
Straightedge	1 operator	Diurnal period and without rain	Straightedge permits the obtaining of maximum rut depth among other unevenness. However, this is an equipment used for local measures and therefore represents a low performance test.	Unevenness	Interfere	Because of stationary measurement conditions of tests performed by the Straightedge it is recommended the presence of safety vehicles or other kind of measures that assure the operator's safety.

(Continue)

Volumetric Patch Technique	1 operator	Diurnal period and without rain	Volumetric Patch Technique is used to determine a pavement's texture depth at isolated locations. It is a very simple test procedure but it is low performance.	Texture	Interfere	Because of stationary measurement conditions it is recommended the presence of safety vehicles or other kind of measures that assure the operator's safety
British Pendulum	1 operator	Diurnal period and without rain	By means of the British Pendulum it is possible to determine friction coefficient in a simple way. However the procedure associated with this equipment interferes in traffic. Its low performance is related to its stationary condition.	Friction	Interfere	Because of stationary measurement conditions of tests performed by the British Pendulum it is recommended the presence of safety vehicles or other kind of measures that assure the operator's safety
Grip-tester	1 operator and 1 driver	Diurnal period preferably, and without rain	Grip-tester has the same function of British Pendulum though it measures the longitudinal friction coefficient in a continuous way and with a high performance.	Longitudinal friction	Does not interfere	Although, it is a continuous test procedure, which does not interfere in traffic flow, it is recommended to be accompanied by safety vehicles.
SCRIM	1 operator and 1 driver	Diurnal period preferably, and without rain	With SCRIM it is possible to measure transverse friction coefficient in a continuous way. Some versions of this equipment have a laser which can perform measures of texture depth simultaneously with friction coefficient measures. This equipment has a high performance.	Transversal friction and texture	Does not interfere	Although, it is a continuous test procedure, which does not interfere in traffic flow, it is recommended to be accompanied by safety vehicles.
Outflow meter	1 operator	Diurnal period and without rain	By means of the Outflow meter it is possible to determine drainability of any type of pavement. This is a simple and local test.	Drainability	Interfere	Because of stationary measurement conditions of tests performed by the Outflow meter it is recommended the presence of safety vehicles or other kind of measures that assure the operator's safety
Permeameter	1 operator	Diurnal period preferably, and without rain	Permeameter allows the ability to drain water in pavements with porous characteristics in a rapid and punctual way.	Drainability	Interfere	Because of stationary measurement conditions of tests performed by the Permeameter it is recommended the presence of safety vehicles or other kind of measures that assure the operator's safety
SPB Method	1 operator	Diurnal period preferably	By means of SPB method, noise generated by traffic in a given section of road may be determined. This is a stationary standard method and therefore adequate for project level because of its low performance.	Noise	Does not interfere	Because of stationary measurement conditions it is recommended the presence of safety vehicles or other kind of measures that assure the operator's safety
Coring and Test Pits	1 operator	Diurnal period preferably, and without rain	Both coring and test pits are destructive tests that are performed locally and for this reason only permit the accomplishment of punctual information about pavements constitution. These tests are usually made with the purpose of complement test results of GPR and FWD for example.	Pavement´s constitutions	Interfere	Because of stationary measurement conditions it is recommended the presence of safety vehicles or other kind of measures that assure the operator's safety

3. Practical application of Ground Penetrating Radar and of Falling Weight Deflectometer

3.1. Description of the case study

Under the scope of the protocol of cooperation between Superior Technical Institute (IST) and National Laboratory of Civil Engineering (LNEC) it was possible to accompany a study of the application of monitoring equipments in a flexible pavement structural evaluation. Therefore tests procedures, data processing and results analysis related to the Ground Penetrating Radar (GPR), the Falling Weight Deflectometer (FWD) and coring were carried out.

Results analysis was performed in a demonstrative way with the selection of representative sections. The representative sections selected present different properties and consequently allow for the application of several important concepts. Furthermore it was possible to conclude about the importance of the

complementarity of GPR and FWD together with coring. The case study concerned 13 km of a national road rehabilitation in the North of the country. This two-way road, with two lanes in a carriageway does not have pavement shoulder.

In this case study was not possible to indicate more detailed elements about the road section analysed due to its confidentiality character.

The 13 km of pavement studied were very heterogeneous. Along the pavement there were some sub-sections of new structure consisting of a bituminous macadam base course layer and granular layers of extended grading crushed aggregates (ABGE). There were also sections that had been reinforced or widened, and consisted of bituminous macadam base and pre-base course layers, with a geotextile at the interface between them, overlaying the old pavement structure.

The upper layer of wearing course in asphalt concrete was not constructed at the time this study was made. The construction of this layer depends on the final report of LNEC.

Table 2 presents the layers material elastic moduli as well as the corresponding Poisson's ratios.

Table 2 – Elastic moduli (E) and Poisson's ratios (υ) of pavement's layers (2005 project's data).

	E (MPa)	υ
Betuminous concrete	4500	0.35
Bituminous macadam	5500	0.35
Road base ABGE	240	0.35
Sub-base ABGE	130	0.35
Sub-grade	70	0.40

3.2. Monitoring equipment applied

LNEC´s **FWD** was used to determine the pavement's bearing capacity by means of the registered surface deflection values.

With the knowledge of the deflections at given distances, the pavement's constitution and geometry it becomes possible to evaluate the pavement's structural characteristics: elastic moduli and Poisson's ratios of each layer.

This equipment generated a load pulse (peak impulse load of 50 kN) by dropping a weight on a damped spring system mounted on a loading plate with 30 cm of diameter [COST 336, 2002].

The peaks of the vertical surface deflections were measured at the centre of the loading plate and at 7 radial positions by a series of deflection sensors: D_0 – 0 cm; D_1 - 30 cm; D_2 – 45 cm; D_3 – 60 cm; D_4 - 90 cm; D_5 -120 cm e D_6 – 180 cm (distances from the centre of the loading plate). The bearing capacity tests were performed each 75 m in a stationary way. For several test points were made measurements of the air and the surface of the pavement temperatures.

GPR is an equipment that uses a non-destructive method to supply the pavement's layer thickness structure changes in a continuous way. Although its high performance GPR operation principle has some limitations. GPR results were then used as a complement of the deflection test results obtained with the FWD.

The GPR transmits short duration electromagnetic pulses from a transmitting antenna into the object being tested and picks up the reflected energy in the receiving antenna. The reflected wave gives information about the structure. The wave amplitude is related with the difference in dielectric properties of two adjacent layers, while the travel time gives the interface location beneath the surface. The GPR measures the travel time, which is post-processed and converted to layer thickness [Fontul, 2007]. So it was possible to determine flexible pavement layers thickness for the 13 km of a pavement under study.

Tests were performed with two different types of horn coupled antennas, each pair with central frequencies associated of 1.0 GHz and 1.8 GHz, respectively. However only the data obtained with the lower frequencies pair of antennas were taken into account. The 1.0 GHz antennas despite of obtaining data with less resolution achieve higher penetration. In this case study the resolution obtained with the 1.0 GHz and the 1.8 GHz were not very different with the disadvantage that this last ones achieved a lower depth penetration.

The antennas were suspended at 0.45 m height above the pavement's surface, allowing the operation at traffic speed without any limitation, and therefore they are suitable for the evaluation of in service pavements

without major disturbance to road users. In this study, 4 scans per meter were performed (one each 25 cm).

The tests with GPR were performed at a traffic speed of approximately 50 km/h.

From the results obtained with GPR and FWD was possible to identify different zones and singular points and **core drilling** beeing performed at selected sites. Cores had the main purpose of confirm pavement's constitution (bounded layers thickness). Furthermore cored specimens are used to perform laboratory tests to determine parameters such as density, aggregate gradation, percentage of bitumen, bitumen's penetration at 25ºC, bitumen's ring and ball temperature, among others.

In Figure 1 it is shown GPR and FWD performing tests in the case study road.

Figure 1 – Tests performed with the FWD (left) and with the GPR (right).

3.3. Analysis of results

The deflection values registered with the FWD device were normalized to the peak pulse load of 50 kN. Figures 2 and 3 present the deflection values obtained for each sensor at every test point.

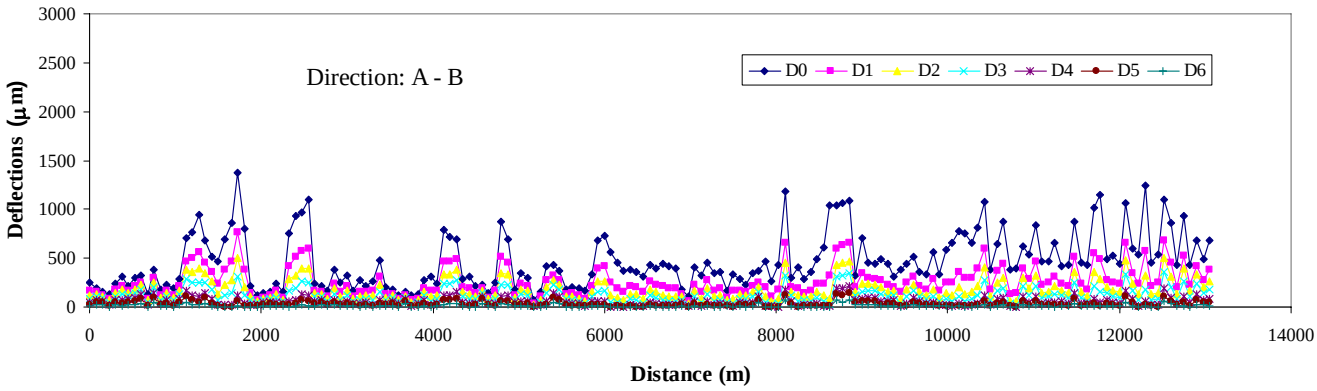

Figure 2 – Deflections measured in FWD tests perform in the direction A – B.

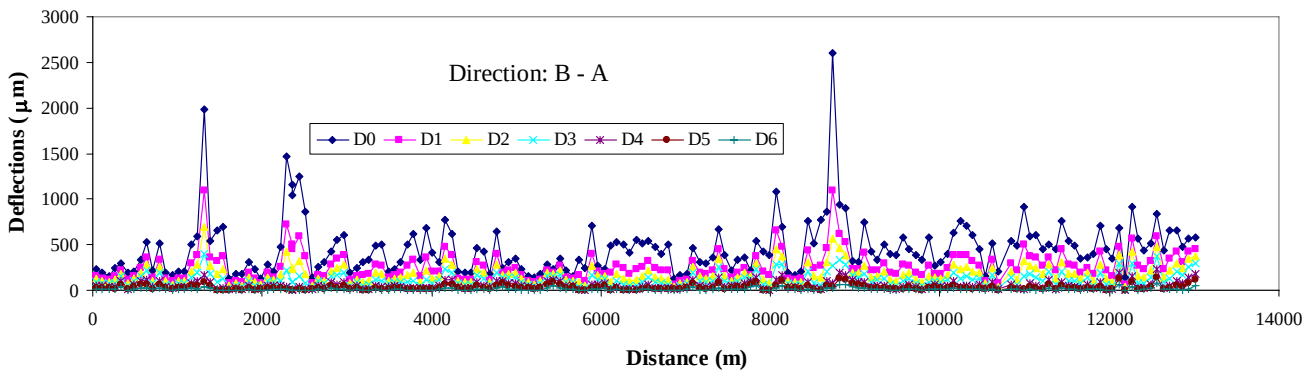

Figure 3 - Deflections measured in FWD tests perform in the direction B – A.

In general it was possible to observe that the registered deflections are similar in both lanes along the 13 km. However it was also possible to identify only by the observation of Figures 2 and 3 that along the 13 km of pavement there were distinguished zones with different structural behaviours.

For flexible pavements it is generally considered that deflections up to 500 µm to a load of 50 kN are pavements with poor structural capacity.

Nevertheless, it was noticed that in given zones there were some high deflection values in comparison with the rest. For example, at the test point (Pk) 8+737 (lane of the direction B – A) it was registered a high deflection value (2.6 mm) for the position of the D_0 sensor.

The core obtained in Pk 8+737 presented cracking of the base course bituminous layer. A possible cause is the lack of support capacity of the granular layers or even of the sub-grade in this location (see Figure 4).

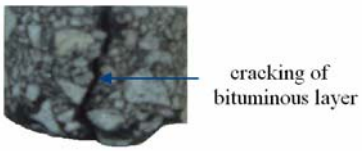

Figure 4 - Core 18 of Pk 8+737.

Based on the deflection graphics obtained for each lane of circulation (Figures 2 and 3) and using the AASHTO cumulated difference method, several zones of different structural behaviour were determined (division into homogeneous zones).

Afterwards, for each zone of each lane it was identified the test point which corresponded to the representative deflection bowl. The representative deflection bowl for each zone was selected regarding an adopted confidence level of 85%.

For the data interpretation with GPR it was used RADAN 6.5 software.

The files obtained by GPR were splited into sub-sections of similar constitution and geometry. Thus, it was possible to proceed to the files interpretation. This interpretation consists of defining expected location of interfaces between different materials and subsequently to identify the reflexion points considered as significant. Reflexion points considered to be insignificant were either anomalous elements or points that the software identified in the wrong interface. Sometimes it was necessary to introduce reflexion points that were not initially identified by the program but which were visible in the GPR file, in order to obtain the continuation of the observed reflexion recorded by the GPR.

For each lane a given zone was selected in order to demonstrate the adopted methodology and to perform comparisons of the obtained results. The two zones selected had different pavement structures.

Furthermore, the methodology applied for the other zones of homogeneous structural behaviour was similar with the one that follows.

It was selected and analysed a reinforced pavement zone (zone 1 of direction A – B, between Pk 0+000 and Pk 1+050) and a new pavement zone (zone 8 of direction B – A between Pk 6+112.5 and Pk 6+787.5).

The representative bowl determined for zone 1 (direction A – B) corresponded to test point Pk 0+600 and for zone 8 (direction B – A) corresponded to test point Pk 6+187.

Figures 5 and 6 present fragments of RADAN interpreted files with the respective identification of the interfaces detected. Is it important to mention that in RADAN file related to interval of kilometric points [0+000; 1+000] of direction A – B, the first interface was only detected because of the presence of the geotextile film placed between the bituminous macadam adjacent layers of base and pre-base course. The geotextile film presented a very well defined reflexion of the electromagnetical waves during GPR tests otherwise it would have been very difficult to identify this interface, because these two adjacent layers are constituted of the same material with similar dilelectric characteristics.

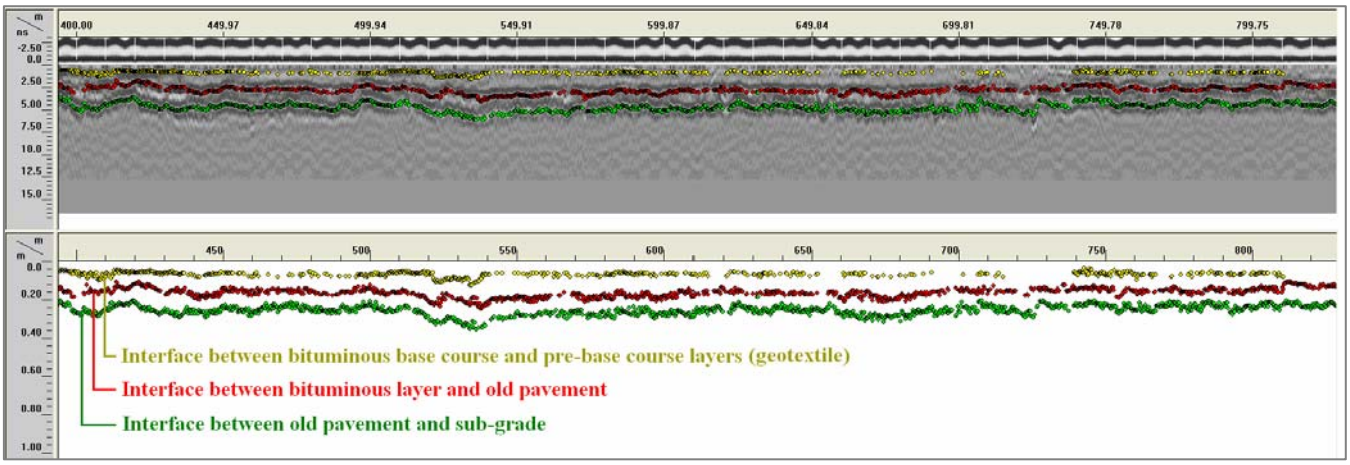

Figure 5 – Fragment of RADAN interpreted file of section from Pk 0+000 to Pk 1+000 of direction A – B.

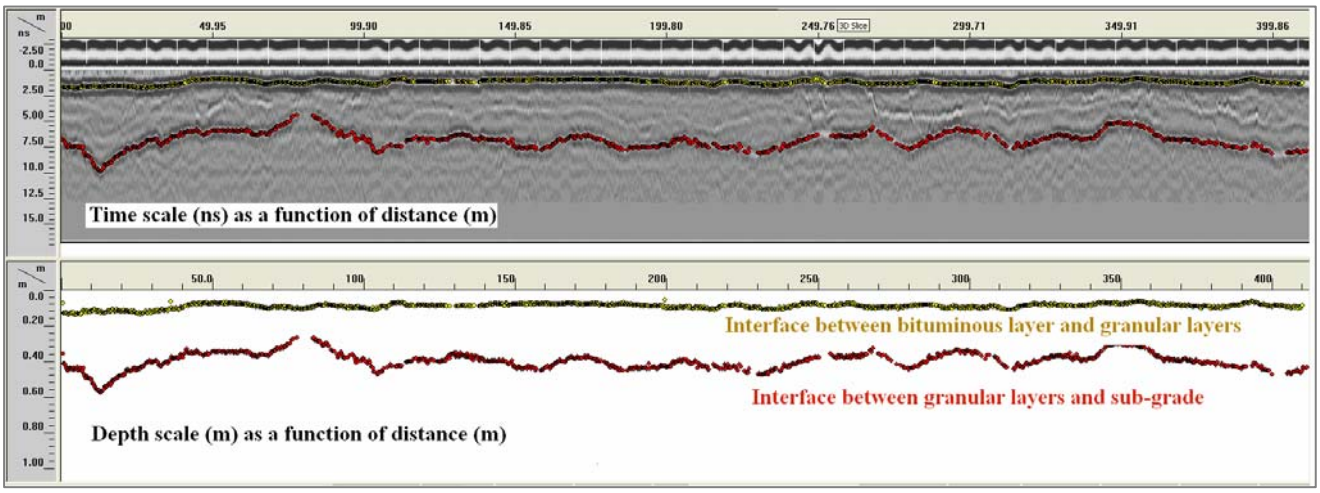

Figure 6 – RADAN interpreted file of section from Pk 6+176 to Pk 6+598 of direction B – A.

The tests performed with GPR provided information about the layers thickness of the pavement structure by means of an interpretation procedure of the data obtained using RADAN [GSSI, 2005].

Cores were very helpful to calibrate GPR data files.

Afterwards, with the information of layers thickness, provided by GPR results together with cores information, and with the knowledge of the structural response, obtained with FWD bearing capacity tests, an iterative procedure was performed.

The automatic calculation program BISAR was used in order to estimate the pavement's structural characteristics (elastic moduli) for the two selected zones. BISAR program is based on the Burmister model which considers that materials are homogeneous, isotropic and linear elastic. In this model the pavement layers are considered to be continuous and infinite horizontally with a finite thickness and settled in a semi-infinite layer. At the surface of the group of layers a vertical load is applied uniformly distributed over a circular area [SHELL, 1995].

To perform the iterative procedure in BISAR it was necessary to define inputs related to four issues: load applied on pavement's surface (50 kN load in a 0.15 m radius circle); pavement layers (layers thickness, elastic moduli and Poisson's ratios); the boundary between layers (cores provided the information that the layers were bounded); and the location where it deflection values were to be determined (the location of sensors of FWD device in bearing capacity tests).

This procedure consisted of determining, for the two selected zones of homogeneous structural behaviour, the layers elastic moduli which led to an approximation of the calculated bowl (by means of BISAR) to the deflection bowl of the representative points acquired on the FWD tests.

The criteria RMS (Root Mean Square) was adopted to define the approximation between calculated and measured deflection bowls [Domingos, 2007].

It was considered that for values of RMS less than 10% the group of elastic moduli obtained give an acceptable approximation grade.

Throughout the iterative procedure mentioned before it was possible to identify the contribution of each layer to the deflection bowl measured in load tests for the flexible pavement in study.

Therefore, the deflection values measured by the sensors that were closer to the load application local were a reflex of the structural response of the whole pavement together with the sub-grade. Furthermore in the further sensors the structural response was conditioned by the deeper layers of the pavement together with the sub-grade. In conclusion, the deflection values measured by sensor D_0 were the response of total structure set (pavement plus sub-grade) on the other hand the deflection values measured by sensor D_6 reflected almost exclusively of the structural response of the sub-grade to the load applied.

It is also important to mention that with the purpose of approximate as much as possible the model of reality,

the sub-grade was divided into two layers: the first one was a superior layer with 1 m of thickness; the second one was an inferior layer with semi-infinite thickness with "rigid layer" properties, in another words, with a elastic moduli significantly superior to the first one [Antunes, 1993].

The results obtained through this procedure are presented in Tables 3 and 4.

Table 3 – Layers characteristics defined in BISAR as a model of structural behaviour (last iteration for the point 0+600 of direction B - A).

Layers characteristics	Thickness (m)	E (MPa)	υ
1 – base and pre-base course layers	0.17	4800	0.40
2 – old pavement	0.13	1500	0.35
3 – sub-grade superior layer	1.00	65	0.35
4 - sub-grade inferior layer	-	300	0.35

Table 4 – Layers characteristics defined in BISAR as a model of structural behaviour (last iteration for the point 6+187 of direction B - A).

Layers characteristics	Thickness (m)	E (MPa)	υ
1 – base course layer	0.09	5800	0.40
2 – granular layers of ABGE	0.30	110	0.35
3 – sub-grade superior layer	1.00	160	0.35
4 - sub-grade inferior layer	-	720	0.35

In order to correct bituminous layers elastic moduli to the project temperature it was used an expression developed by LNEC, which establish a correlation between the elastic modulus for a given temperature T (E_T) and the elastic modulus for the 20 ºC reference temperature [LNEC, 2005]:

$$(E_{20}): {E_T}/{E_{20}} = -0{,}0282T + 1{,}5562 \,.$$

The purpose of the application of the previous procedure was to determine the elastic moduli of the bituminous layers (bituminous macadam) for the 24 ºC project temperature and therefore to perform a comparison between the estimated moduli and the moduli indicated in the project.

Although temperature measurements were performed at the pavement surface during FWD tests, it is necessary to determine the temperature of the bituminous layers for a given depth chosen as representative. In this case half depth was considered as the representative depth of bituminous layers.

By the means of BELLS3 method bituminous layers temperatures at the intended depth were determined using the following expression [Stubstad, R.N. *et al*; 1998]:

$$T_d = 0{,}95 + 0{,}892 \times IR + (\log(d) - 1{,}25) \times (-0{,}45 \times IR + 0{,}62 \times \times (1 - day) + 1{,}83 \times sen(hr_{18} - 15{,}5)) + 0{,}042 \times IR \times \times sen(hr_{18} - 13{,}5).$$

Table 5 presents some values that were necessary for determining bituminous layers temperatures at the intended depth.

Table 5 – Necessary information for determination of bituminous layer temperature at the intended depth.

	Pk 0+600 direction A - B	Pk 6+187 direction B - A
Air temperature (ºC)	9	17
Pavement´s superficial temperature (ºC)	11	21
Bituminous layers thickness (cm)	17	9
Test time	6:51	11:32
Decimal test time (hr_{18})	6.85	11.53
$hr_{18} - 15{,}5$	-8.65	-3.97
$hr_{18} - 13{,}5$	-6.65	-1.97
$(hr_{18} - 15{,}5) \times 18/2\pi$ (rad)	-3.02	-1.38
$(hr_{18} - 13{,}5) \times 18/2\pi$ (rad)	-2.32	-0.69
$sen(hr_{18} - 15{,}5)$	-0.12	-0.98
$sen(hr_{18} - 13{,}5)$	-0.73	-0.63
d – depth at which mat temperature is to be predicted (mm)	85	45
IR - surface temperature (ºC)	$9 + 4 = 13$	$17 + 3 = 20$
1-day – average of the previous day's high and low air temperature (ºC)	11.0	15.1

After estimating bituminous layers temperatures it became possible to determine the elastic moduli for the 20 ºC reference temperature. Bituminous layers elastic moduli for the 24 ºC project temperature were determined by means of the elastic moduli determined first for the 20 ºC reference temperature (see Table 6).

Table 6 – Estimated elastic moduli of the bituminous layers for the project temperature.

	Pk 0+600 direction A - B	Pk 6+187 direction B - A
Bituminous layers test temperature	13 ºC	18 ºC
E_T (test)	4800 MPa	5800 MPa
E_{20}	3925 MPa	5449 MPa
E_{24} (project temperature)	3430 MPa	4760 MPa

After correcting the elastic moduli to the project temperature, it was verified, as expected, a decrease of the moduli values, since the calculated temperatures to the bituminous layers were inferior to the ones of the project (24ºC).

The elastic moduli specified in the project for the bituminous macadam was 5500 MPa. In the performed calculus regarding the bearing capacity tests, were obtained inferior values than the one specified in the project, to the points corresponding to the representative deflection bowls for each zone in study. In order to structurally characterize each zone, it would be useful to estimate elastic moduli corresponding to other points of each zone.

The values estimated for the elastic moduli, were lower than the ones specified in the project. This difference may have origin in bad execution and application of bituminous mixtures. However, to justify this difference it would be necessary do characterize the bituminous mixture by doing laboratorial tests, especially bitumen characterization tests, for example, penetration at 25ºC and bitumen's ring and ball temperature.

Conclusion

The knowledge of pavement conditions, throughout its life time, is fundamental to guarantee safety conditions, comfort, economy and environmental quality.

In order to evaluate pavements functional and structural conditions, several methodologies associated with monitoring equipments are used.

The case study accompanied in LNEC, appeared as an opportunity to structurally evaluate a flexible road pavement section, by the means of monitoring equipment.

However, the structural evaluation of a road pavement can not be resumed in the analysis made in this paper.

A structural analysis of a pavement with a given constitution should include the use of behaviour models and the bearing capacity tests, associated with de pavement's structural response.

These tests must be complemented with others which allow for the determination of various layers constitution and respective thickness, such as GPR tests, core drilling and also laboratorial tests. These last ones were not studied in this paper, because they were not in this approach scope, and also because they have not been performed up to date.

GPR working technology can not by itself produce conclusive results about pavements constitution. Therefore, GPR should not be used in an isolated way, but rather as a complement to identify pavement layers. Although GPR has a great potential of achieving results, their interpretation is not easy therefore it should be done by experienced personnel with precaution and conscientiously.

Cores allowed to verify the real constitution of pavements namely of the bituminous layers. The core drilling was fundamental because it allowed for the calibration of the GPR results and, in this way, for confronting reality with the results achieved in the tests made with the GPR and FWD.

Using the tests results it was possible to clearly identify two types of constitutions in the pavement in study. In some sub-sections, were identified two interfaces and in others were found three.

In the reinforced pavement sub-sections, the interface between the base course and pre-base course layers, both in bituminous macadam, was only identified due to the existence of a geotextile film applied between these layers.

Comparing the division into homogeneous sub-zones done in both ways (from A to B and from B to A), using the cumulated difference method, was possible to verify that, in general, there is a coincidence between different structural behaviour zones. In general, the zone changing corresponded to the change in pavement constitution. In the majority of zones of the new pavement structure, the deflections values measured are higher than the ones measured in reinforced pavement zones.

It also noticed that in the lane which was mainly in excavation (direction B - A), the capacity of support was slightly inferior, and this difference may be caused by drain problems or other problems related to geotechnical differences of the sub-grade terrains.

By the means of the procedure performed in order to determine the elastic moduli to the project temperature (24 ºC), it was observed that temperature had an important influence in the deformability of the bituminous mixtures. After the adjust of de elastic moduli to the projects temperature (24 ºC), it was verified a reduction of these values since the test temperatures were inferior to the project temperatures (13 ºC to the Pk 0+600 of direction A - B and 18 ºC to Pk 6+187 of direction B - A).

Regarding the results achieved from the tests performed with the FWD, the GPR and the core drilling, the calculated elastic moduli were inferior to the ones referred in the project to the bituminous macadam.

Nevertheless, it is necessary to estimate elastic moduli values taking into account more points for each zone.

In order to analyse the pavements conformity to what was specified in the project, it is necessary to make laboratory tests on the cores drilled in the field.

After accompanying this case study in LNEC, it was possible to understand the utility of monitoring equipments and the interaction between the achieved results in order to evaluate de structural pavement condition. Because of the fact that the studied road section was constituted by a so heterogeneous flexible pavement, it was possible to do comparative analysis. In case it had been a pavement with an homogeneous constitution, these comparative analysis would not be possible.

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