THE INFLUENCE OF CONSTRUCTION QUALITY CONTROL DATA VARIABILITY ON PAVEMENTS EVOLUTION

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ABSTRACT: Predicting pavement evolution is a fundamental component in pavement maintenance and rehabilitation management work. However, it is very complex to carry out due to several drawbacks, namely a common use of inadequate quality control procedures or a lack of reproducibility of quality control data. This paper describes the main conclusions of a study on the influence of construction quality control data on pavement evolution. It was possible to develop a methodology for this purpose based on stiffness modulus evolution, which will also allow for the assessment of the pavement's design. The study involved the establishment of a statistical analysis procedure in order to analyse construction quality variability data, and the use of deflection tests, stiffness modulus tests, back-analysis of FWD data and the development of a procedure to correct the effect of temperature within the pavement on stiffness modulus. Results analysis showed that control quality data variability has an important influence on pavements' evolution prediction. It is expected that the integration of the proposed methodology on quality control plans will improve the data accuracy and all the decisions based on it.

KEY WORDS: quality control, variability, evolution, methodology, statistical analysis, temperature, accuracy

1. INTRODUCTION

Pavement performance prevision constitutes one of the most important components in pavement maintenance and rehabilitation management work. It depends on field data which should be reliable and show little variability. Nevertheless, a common use of inadequate quality control procedures or a lack of reproducibility of quality control data contribute to poor data quality, making previsions complex.

There are several possibilities to assess pavement performance. Calculation of the residual live is an example of one of the most used methods. Another method consists of comparing moduli in different stages of pavement's life with a reference modulus, obtaining in this way residual life and fatigue damage. This method is very useful since different references may be used, such as design modulus and modulus at the time of construction, allowing for the evaluation of design data and its effect on behaviour, as well as for the evaluation of construction quality.

To study bituminous mixtures modulus behaviour over time by comparison, two decisions must be taken beforehand. The first and the most important is the establishment of a reference modulus. The second is the reference temperature. Immediately after construction is the most appropriate time in a pavement's life to take modulus as a reference. This way, all changes may be studied. The reference temperature depends on the location and should allow for the mechanical characterization of asphalt concrete layers in such a way that it represents the real mechanical behaviour of the pavement.

The objective of the study reported herein is to assess the influence of construction quality control data on the pavement's behaviour. The assessment is made by means of a parameter which relates to the stiffness modulus at different times of pavement life. A study methodology was established for this purpose, constituting a base for a proposal of an improved methodology to integrate in the quality control procedures.

2. RESEARCH METHODOLOGY

The assessment of the influence of construction quality control data on a pavement's behaviour relies on the establishment of a parameter defined as Evolution (EV). This parameter relates the stiffness modulus at different times of pavement life according to Equation 1.

$$EV(T_r) = \frac{M_i(T_r)}{M_{ir}(T_r)} \times 100 \qquad (1)$$

with:

$EV(T_r)$ = Evolution at reference temperature (T_r), (%);
$M_i(T_r)$ = Layer i modulus at reference temperature (T_r);
$M_{ir}(T_r)$ = Layer i reference modulus at reference temperature (T_r).

In this study, the establishment of the evolution (EV) concerns the modulus determined after eight years in service and the modulus at the time of construction. Since in Portugal it is not common practice to backcalculate the stiffness modulus at the time of construction, the latter was calculated using the Shell's modulus since it had been used in the design. This has the advantages of not only allowing for the analysis of the construction quality parameters effect but also the design decisions. The study methodology comprises the six main phases presented hereafter and detailed in the next sections.

In the first phase, the statistical analysis procedure was set up and applied to data. It consisted of a group of statistical tests which allow for the assessment of construction quality variability. This procedure also considers the possibility of calculating conformity probabilities of each construction quality parameter and the establishment of behaviour relations between different road sections.

In the second phase, FWD tests were performed over the total length of the road and 9 homogenous sections were defined. Then, the corresponding pavement's model was determined using a backanalysis procedure. The modulus obtained this way, after temperature correction, can be related to the modulus taken as a reference.

Material extracted from one stretch, which incorporates two homogeneous sections, has been submitted to stiffness tests under a wide range of temperatures, in the third phase. It aimed at establishing a modulus-temperature law. In this phase tests to determine grading, binder content (bc) and void content (e) have also been performed.

Correction of backcalculated modulus to the reference temperature constitutes the fourth phase. This was achieved by means of a computer program developed to calculate temperature inside the pavement, from temperature measured at the surface, and the modulus-temperature law.

The fifth phase comprised of the calculation of reference modulus. Construction quality data was used in the Shell's stiffness modulus prevision model and then evolution was calculated.

In order to better analyse the influence of construction quality data variability on pavement's evolution, in the last step reference modulus was recalculated using the properties obtained in the laboratory and the corresponding evolution was compared with the one previously calculated.

3. CONSTRUCTION QUALITY DATA ANALYSIS

Considering the present stage of road construction, all construction companies follow a quality control procedure supervised by the road owner or an independent entity. Despite this, often data obtained this way cannot be used, for example in maintenance activities such as predicting the evolution or modelling, due to the lack of accuracy or high variability.

Data originated from quality control have five main sources of variability: materials inherent variability; sampling and testing variability; within-batch variability; batch-to-batch variability; overall variability [1]. Overall variability includes all referred sources and it is the most important when dealing with previsions. For this reason and because control quality plans do not account for possible assessments of data variability, the analysis performed includes only overall variability. The analysis is based on a statistical procedure, comprising of seven steps.

1. Preparation of data, defining sets by stretch, layer and property or parameter.

2. Calculation of data normality for each set using the Kolmorogov-Smirnov statistical test, in this case for a significance level of 5%. Due to random behaviour of data, with little exceptions, each data set should have a normal distribution.

3. Calculation of variance and standard deviation, which define dispersion around the average, for each set. These parameters have been selected to define variability.

4. Calculation of variance homogeneity (VH) using Levene statistical test. With this step is possible to verify if data variability is similar between sets.

5. Calculation and comparison between sets of the median using the Mann-Whitney statistical test, for a significance level of 5%. The median is a localization parameter and represents more effectively the data than average since it is not influenced by extreme values. In addition, its comparison between sets allows for identifications which are not similar, namely in cases where the variance is not homogeneous.

6. Analysis of data agreement with specifications by comparing measured values with specified values.

7. To normal data sets, calculation of the population probability to be in agreement with specifications, to be under the lower value and to be above the upper value.

This procedure is wider than the scope of the paper. For this reason only some results regarding one stretch (7 km) are presented to illustrate it. In addition, data regarding the chosen stretch is used hereafter. Despite this, the procedure has been applied to the total extension of the road (40 km).

In Table 1 are depicted the results of normality and variance homogeneity tests. It has been found that a significant number of parameters do not have a normal distribution, as expected, which exclude their use where data accuracy is required. Furthermore, variance is frequently not homogeneous and medians are not similar. This is indicative of changes in total variability from stretch to stretch, which might occur from isolated variability sources, such as poor testing and reproducibility and changes in materials' properties. By identifying the anomalous stretches or parameters the origin of the problem may be more easily identified.

Table 1. Normality and variance homogeneity results (y –yes; n – no)

layer	statistical parameter	bc (%)	grading				ρ g/cm3	e (%)	stability (Kgf)	deflection (mm)
			# 19,00	# 4,76	# 0,300	# 0,074				
wearing coarse	normality	y	-	-	-	-	n	n	y	y
	VH (5%)	n	n	n	y	y	y	n	n	n
labeling coarse	normality	y	y	y	y	y	n	n	y	y
	VH (5%)	n	n	y	n	y	n	n	n	n
base coarse	normality	y	y	y	y	n	n	n	y	y
	VH (5%)	n	y	y	y	y	y	y	n	n

(bc – binder content; # - sieve; ρ - density; e – void content)

In Table 2 are depicted the statistical parameters utilized to calculate the probabilities of agreement with specifications for the control quality parameters that follow a normal distribution in one stretch of the road.

Regarding the total extension, it has been found that either the probability of surpassing the superior limit tolerance ($\%NC_{sup}$) or the inferior limit tolerance ($\%NC_{inf}$) is very high. After a detailed analysis of the results, a general idea of the future behaviour of the pavement may be formulated.

Table 2. Population probabilities of agreement with specifications

layer	statistical parameter	bc (%)	grading # 19,00	grading # 4,76	grading # 0,300	grading # 0,074	ρ g/cm3	e (%)	stability (Kgf)	deflection (mm)
wearing course	$\bar{x}$	5.77	100.00	58.63	23.10	7.63	2.39	3.46	1567	4.44
	s	0.43	0.00	5.23	2.33	1.35	0.03	1.08	298	0.54
	lim sup	5.5	-	-	-	-	-	-	1200	4
	lim inf	4.9	100	-	-	-	-	-	800	-
	zsup	-0.6	-	-	-	-	-	-	-1.2	-0.8
	zinf	-2.0	-	-	-	-	-	-	-2.6	-
	$\%NC_{sup}$	74.2	-	-	-	-	-	-	89.44	80.23
	$\%NC_{inf}$	2.0	-	-	-	-	-	-	0.4	-
labeling course	$\bar{x}$	5.85	97.94	52.14	17.43	5.28	2.39	3.07	1782	3.86
	s	0.44	1.8	6.32	4.01	0.78	0.04	1.36	692	0.49
	lim sup	6.1	100	65	22.6	8	-	-	1200	4
	lim inf	5.5	80	47	13	0	-	-	800	-
	zsup	0.6	1.1	2.0	1.3	3.5	-	-	-0.8	0.3
	zinf	-0.8	-10.0	-0.8	-1.1	-6.8	-	-	-1.4	-
	$\%NC_{sup}$	25.78	12.51	2.02	8.85	0	-	-	80.23	36.32
	$\%NC_{inf}$	19.77	0	19.77	12.51	0	-	-	7.35	-
base course	$\bar{x}$	4.37	78.81	41.19	14.74	4.15	2.38	4.76	5.08	1641
	s	0.65	8.53	10.01	3.89	0.77	0.04	1.51	1.7	562
	lim sup	4.5	90	62	23	8	-	-	6	-
	lim inf	4.5	70	45	13	0	-	-	3	700
	zsup	0.2	1.3	2.1	2.1	-	-	-	0.5	-
	zinf	0.2	-1.0	0.4	-0.4	-	-	-	-1.2	-1.7
	$\%NC_{sup}$	40.13	8.85	1.58	1.58	-	-	-	29.12	-
	$\%NC_{inf}$	59.87	14.69	67.36	32.64	-	-	-	10.56	4.01

4. TEMPERATURE CORRECTION PROCEDURE

There are several methods of correcting the effect of temperature on stiffness modulus. The most popular consists of affecting the modulus to be corrected by a correction factor. Correction factors, such as those developed by Ullidtez [2] and by Lukanen et al. [3], are widely used however their application conditions are limited. The most important limitation is not considering material properties. Results achieved this way may be unreliable, namely when dealing with high temperatures. One reliable possibility to surpass these drawbacks is to establish for each pavement and for each layer a modulus-temperature law. Assuming that different testing principles do not influence the modulus behaviour with temperature, this task can be easily achieved using, for example, bending tests at several temperatures. Therefore, the correction may be done for each layer, calculating the product between the modulus to be corrected and a ratio that relates laboratory laws as follows:

$$M_i(T_r) = \frac{M_{iL}(T_r)}{M_{iL}(T)} \times M_i(T) \qquad (2)$$

with:

$M_i(T_r)$ = Layer i modulus at reference temperature (T_r);
$M_{iL}(T_r)$ = Layer i modulus at reference temperature, determined from laboratory testing;
$M_{iL}(T)$ = Layer i modulus at testing temperature (T), determined from laboratory testing;
$M_i(T)$ = Layer i modulus at testing temperature (ºC);
Tr = Reference temperature (ºC);
T = Testing temperature (ºC);
i = Layer: W – wearing course; L – labelling course; B – base course.

Four point bending tests were performed to measure the stiffness modulus on materials extracted from the pavement. Three cores from each layer were submitted to a sinusoidal loading corresponding to a maximum strain in their base of 100 μdef at 10 Hz in the following decreasing order of temperature: 30ºC, 25ºC, 20ºC, 15ºC, 10ºC, 5ºC 0ºC and -5ºC. The laws were established by curve-fitting the data obtained this way (Equations 3, 4 and 5).

$$M_W(T) = 0.1014T^3 - 3.4111T^2 - 253.28T + 11532 \quad (3)$$
$$M_L(T) = 0.1061T^3 - 5.1638T^2 - 249.09T + 12428 \quad (4)$$
$$M_B(T) = 0.1549T^3 - 8.0785T^2 - 202.20T + 13062 \quad (5)$$

with:

$M_W(T)$ = Wearing course stiffness modulus (MPa);
$M_L(T)$ = Labelling course stiffness modulus (MPa);
$M_B(T)$ = Base course stiffness modulus (MPa);
T = Temperature (ºC), ranging from -5ºC to 30ºC.

To conclude the correction procedure, temperature inside the pavement must be known. Measuring the temperature of each layer at a certain depth whenever a deflection test is performed by drilling the road is not a viable way of ascertaining it. COST Action 336 [4] proposes a procedure based on drilling which is unlikely to be suitable to be applied in areas with an irregular topography, such as mountain. Another way of doing it is using BELLS model, which has the inconvenient of requiring the temperature history. Nevertheless, temperature inside the pavement can still be calculated using a mathematical model.

Picado-Santos [5] developed a mathematical model to calculate temperature distribution inside a pavement, as a function of local climatic data and from its thermal characteristics. The model takes into account that heat transfer inside a pavement is a conduction problem in one dimension in a transitory regime. In its formulation and calculation are used numerical methods such as the finite differences method and a direct method to solve a linear system of equations. At the boundary surface/air heat transfer by convection, reflection and radiation is considered. This model has been modified by replacing surface boundary heat transfer phenomena by the corresponding measured temperature (Figure 1).

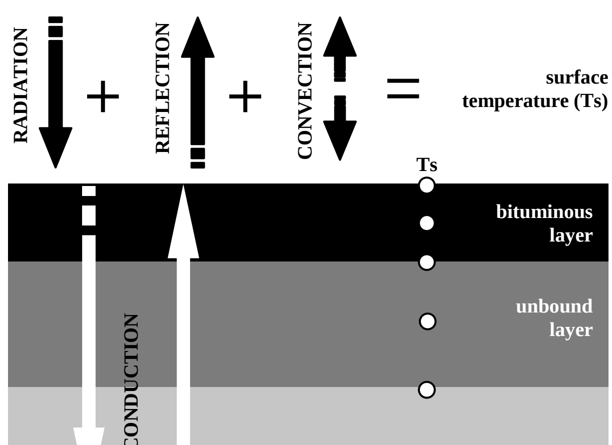

Figure 1. Illustration of temperature flux mathematical model

Based on this formulation, a computer program called TIP (Temperature Inside the Pavement) has been developed to calculate temperature inside the pavement at different points in an increasing time sequence [6], requiring the following data:

a) layer’s thickness;
b) layer’s thermal characteristics (current values are tabulated);
c) temperature at the surface (recommended at 0.5 cm from surface);
d) hour or time between measurements;
d) departure temperature spectrum (due to the numerical methods applied).

The departure spectrum may be easily measured by drilling the pavement at least at three depths at once. Often this is not possible due to several reasons, which was the case in this work. In this case one must arbitrarily attribute a spectrum and then recalculate it using a temperature measured at the surface several times in a point until it achieves the real temperature. In order to arrive at a reliable departure spectrum it is necessary to measure the temperature at the surface at least three times in a minimum amount of time of one hour. With the TIP program it is possible to calculate the temperature inside the pavement using both ways.

The application results of TIP to the road under study are depicted in Table 3. The calculated spectrum is used in the next sections to correct the effect of temperature on stiffness to a reference temperature.

Table 3. Application data and results of TIP

homogeneous section	testing point	time	time range	temperature (ºC)						
				surface	departure spectrum			calculated spectrum		
			(min)	0 cm	3 cm	10 cm	20 cm	3 cm	10 cm	20 cm
-	13	13:21	-	19.2	18.5	14.0	15.5	-	-	-
1	27	14:04	43	21.8				18.8	16.7	15.3
2	42	14:50	46	23.4				21.5	17.1	15.8
-	48	15:03	13	22.8				21.3	18.0	16.0
3	60	15:36	33	25.5				22.5	18.6	16.5
-	98	09:51	-	16.8	16.5	16.0	15.5	-	-	-
-	107	10:32	41	20.0				18.0	16.3	16.0
4	112	10:52	20	22.1				19.4	16.7	16.0
5	126	13:49	-	28.6	27.0	21.0	20.0	-	-	-
-	135	14:15	26	29.7				26.8	23.1	20.1
6	141	14:40	25	30.4				28.0	23.2	20.3
-	152	15:29	49	27.5				27.2	24.6	20.9
7	167	16:17	48	27.1				26.3	24.4	21.4
-	187	09:44	-	23.4	22.4	21.4	20.4	-	-	-
8	201	10:28	54	23.2				22.9	21.7	20.6
-	206	10:51	23	27.2				24.0	21.9	20.5
9	211	11:23	32	24.3				24.8	22.4	20.7

4. STIFFNESS MODULUS

The parameter EV relates to the stiffness modulus at different ages of the road, at a reference temperature, as stated before. The modulus which is going to be compared (characteristic modulus) with a reference modulus pertains to road's current age (8 years old). The reference modulus regards a moment in time of a pavement's life appropriate to reflect all the changes that might occur, which is the time immediately after construction. In the next sections the procedure to obtain both reference and characteristic modulus is presented in detail.

4.1 Characteristic modulus

With the aim of calculating the characteristic modulus by backanalysis, FWD testes were performed over the total length of the road. The backanalysis procedure fallowed the guidelines proposed in COST Action 336 [4]. Therefore, 9 homogenous sections were defined. A characteristic deflection basin had been defined for each of these sections, corresponding to the 85% percentile. Then, the modulus was backcalculated using a linear elastic analysis computer program and corrected to the reference temperature of 20ºC (Table 4), according to Equation (2).

4.2 Reference modulus

The reference modulus was calculated using the Shell's model, developed by Bonnaure et al. [7] and adapted to Portuguese conditions by Picado-Santos [8]. The Shell's model includes as mixture parameters the volumetric percentage of bitumen (bv) and the volumetric percentage of aggregate (av), as well as the bitumen stiffness calculated by the Ullidtz [9] model. The reference temperature is 20ºC.

Table 4. Asphalt layer backcalculated and corrected modulus to 20ºC (referred modulus)

homogeneous section	wearing + labeling course		base course		corrected modulus (MPa)		
	h (cm)	modulus (MPa)	h (cm)	modulus (MPa)	wearing course	labeling course	base course
1	12	4200	18	5000	3981	3573	4070
2	12	1800	18	4000	1929	1560	3321
3	12	4500	18	5000	5057	4189	4272
4	12	4400	18	5000	4283	3743	4185
5	12	5500	18	6000	7739	5805	6000
6	12	2500	18	3500	3703	2998	3517
7	12	2500	18	3000	3394	3234	3216
8	12	5500	18	4500	6302	6037	4634
9	12	5500	18	2200	6921	6287	2277

To better understand the influence of construction quality data variability and accuracy on pavements evolution the reference modulus was calculated with two data origins. Initially, it was calculated with the control quality data, to the total legth of the road (Table 5). Then, the reference modulus was recalculated using properties obtained in the laboratory (Table 6). These properties were obtained by performing tests over cores extracted from 8 points, concerning one stretch which includes homogeneous sections 5 and 6. Control quality data procedure previously presented pertains to the referred stretch.

Table 5. Control quality parameters used in Shell's model and reference modulus at 20ºC

layer	homoge-neous section	e (%)	bc (%)	bv (%)	av (%)	reference modulus (MPa)	homoge-neous section	e (%)	bc (%)	bv (%)	av (%)	reference modulus (MPa)
W		6.08	3.99	9	85	6220		3.46	5.77	13	83	4996
L	1	3.10	5.06	12	85	6100	6	3.07	5.85	14	83	5058
B		4.96	4.43	10	86	6711		4.76	4.37	10	86	6826
W		3.82	5.65	13	83	4993		4.55	5.53	13	83	4844
L	2	3.50	5.15	12	84	5773	7	4.60	5.17	12	83	5252
B		5.16	4.23	9	85	6597		4.19	5.21	10	86	7168
W		3.82	5.65	13	83	4993		4.55	5.53	13	83	4844
L	3	3.50	5.15	12	84	5773	8	4.60	5.17	12	83	5252
B		5.16	4.23	9	85	6597		4.19	5.21	10	86	7168
W		3.30	5.95	14	83	4853		2.38	5.88	14	84	5307
L	4	2.87	5.90	14	83	5080	9	3.88	5.09	12	84	5678
B		4.65	4.56	10	86	6891		4.83	4.44	10	86	6786
W		3.46	5.77	13	83	4996						
L	5	3.07	5.85	14	83	5058						
B		4.76	4.37	10	86	6826						

Table 6. Modulus determined with laboratory data for homogeneous sections 5 and 6

layer		void content (e) (%)	bitumen content (%)	bitumen volume (%)	aggregate volume (%)	reference modulus (MPa)
wearing course	S	5.48	6.41	14	80	3699
	I	1.19	6.44	15	84	5117
labeling course	S	5.94	5.64	13	81	4232
	I	1.10	7.34	17	82	4208
base course	S	7.52	5.61	9	83	5408
	I	1.44	6.25	10	89	9108

5. EVOLUTION ANALYSIS

The evolution was calculated according to Equation (1) using: a) the Shell's model with construction quality data (EV_{20}); b) the Shell's model with data obtained in laboratory considering the superior limit of void content (EV_S) and the inferior limit of void content (EV_I), and; c) design data (EV_D). Results are presented in Table 7 for homogeneous sections 5 and 6.

Table 7. Calculated evolution (EV)

homogeneous section	layer	EV20 (%)	EV_S (%)	EV_I (%)	EV_D (%)
5	wearing course	155	209	151	193
	labeling course	115	137	138	145
	base course	88	111	66	150
6	wearing course	74	100	72	92
	labeling course	59	71	71	75
	base course	52	65	39	88

It can be stated that results are not similar and evolutions superior to 100% may be reached. This may happen if the design method does not account for the mixture ageing. Important differences are found, superior to 50%, in particular for the wearing course and for the base course.

Comparison between EV_S and EV_I shows that differences may be very high when variability is considered, supporting the need to calculate the corresponding probabilities to surpass tolerance limits in order to define the more probable value. Despite this, uncertainties remain about the stiffness modulus effective evolution. Hereafter is proposed a methodology which intends to overcome this problem and to provide new analysis possibilities.

6. PROPOSED METHODOLOGY

If one more step is added to the methodology used in this work to study the influence of construction quality variability, a wide set of analysis opportunities is offered. This step is constituted of stiffness modulus backanalysis at the time of construction. Figure 2 shows the four possible levels of modulus knowledge, regarding a precise moment of a pavements life (design, construction and in service). The comparison of these moduli allows either for the assessment of design and construction quality or for the calculation of Evolution as follows:

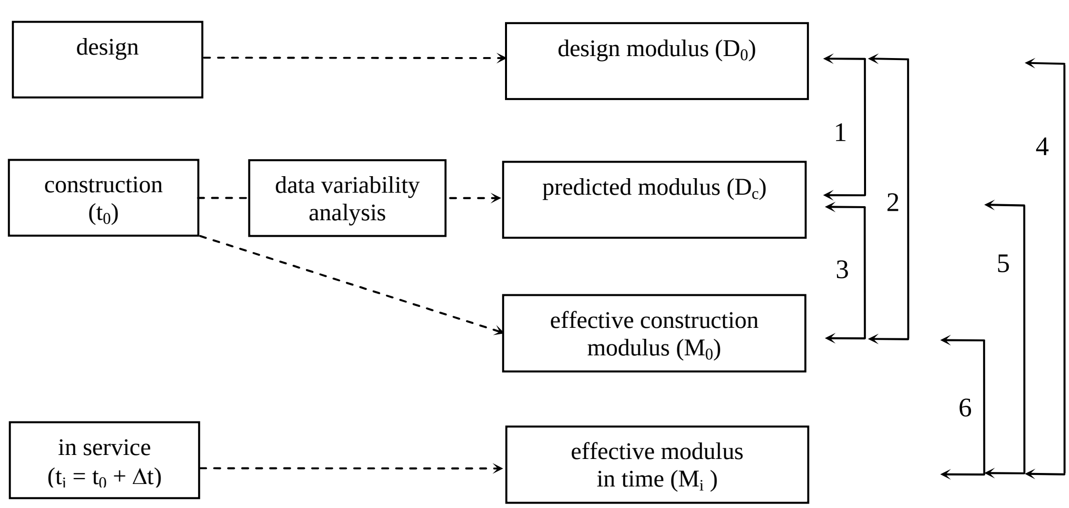

Figure 2. Procedure to assess design and construction quality

1. effect of construction quality variability on design;
2. effect of construction quality on design,
3. effect of design models;
4. evolution regarding design;
5. evolution regarding construction variability;
6. evolution regarding construction (effective evolution).

The effective evolution is eventually the most important parameter when dealing with maintenance. Its calculation may be improved if the procedure depicted on Figure 3 is adopted.

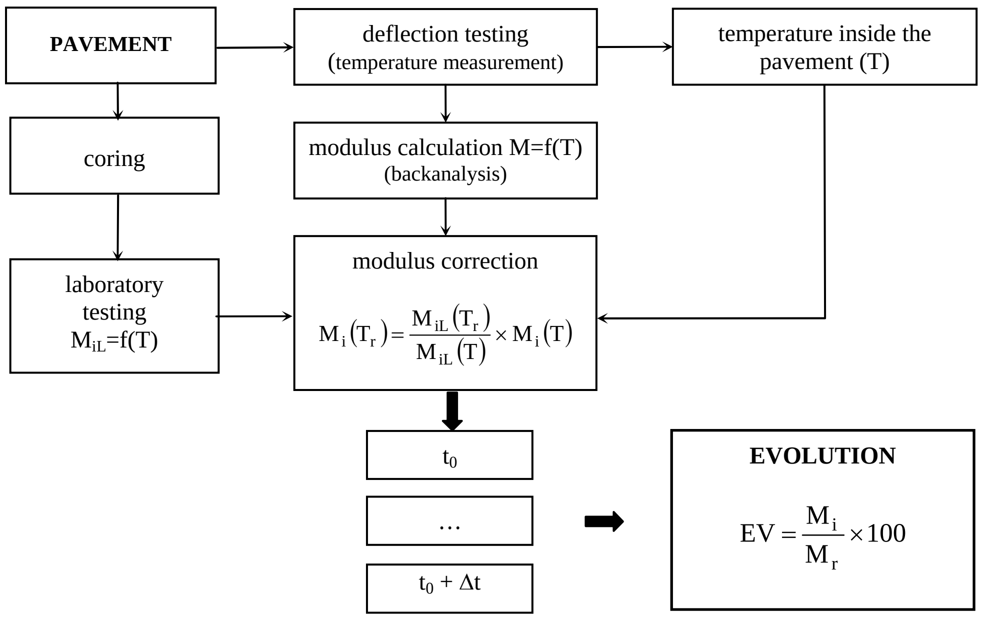

Figure 3. Evolution calculation methodology

The procedure must be applied several times along a pavement's life, starting at the time of construction as follows:

1. pavement coring and, for each asphalt layer, stiffness modulus testing at several adequate temperatures to establish the curve modulus-temperature (M_{iL} = f(T)).
2. deflection testing. This step must be accompanied by the measurement of the departure temperature spectrum and the surface temperature with the aim of supporting the calculation of the temperature inside the pavement.
3. backanalysis of the stiffness modulus. With this step, at the time of construction, the reference modulus at testing temperature (M_r=f(T_0)) is established. After construction, with this step the evolved modulus at testing temperature (M_i=f(T_i)) is established.
4. calculation of the temperature inside the pavement at desired depths, using the TIP programme from temperature measured at the surface (T).
5. correction of the reference stiffness modulus of each asphalt layer to the service temperature (M_i(T_r)), or other reference temperature, by means of Equation (2).

After applying at least twice the proposed procedure, calculation of the Evolution (EV) for a time span from construction to a certain age of the road (Δt) may be performed.

The main advantages of the use of this methodology are the improvement of data quality, by introducing a procedure to correct effect of the temperature on stiffness modulus based on the materials under analysis, and the possibility of analysing the effect of construction quality on a pavement's behaviour. It also allows for the assessment of the ageing effect on stiffness. The main disadvantages are its integration on control quality procedures and the need to establish modulus-temperature laws using bending tests rather than deflection tests.

7. CONCLUSIONS

The effect of construction quality data variability on pavement performance has been assessed in this paper based on a parameter defined as Evolution. The study methodology comprised of the development of several procedures, which proved to contribute to the improvement of data quality, namely a procedure to analyse construction quality data and a procedure to correct temperature effect on modulus.

The procedure of analysing control quality data not only allows for the improvement of previsions' reliability by identifying poor quality data, but also for the establishment of relationships between data sets and their probabilities of agreement with specifications. This procedure can be easily adapted if sources of variability other than total variability are intended to be studied.

The temperature correction procedure includes the establishment of modulus-temperature laws and the use of a program (TIP) to calculate temperature inside the pavement from measurements performed at the surface. Its application implies some adjustments to current practice procedures, fairly easy to implement.

The case study based on the referred methodology showed that modulus evolution is significantly affected by variability and a reference modulus must be carefully established. As a result of these findings, a methodology to calculate modulus Evolution has been proposed. With its implementation on control quality procedures, it will be possible to assess changes in modulus with increased accuracy, which occurs from reducing errors. Furthermore, the effect of construction quality variability, the effect of construction quality on design and the effect of design models may be assessed since design has been included in the proposed methodology.

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