Evaluation of mechanical characteristics by deflection measurement on rigid or composite pavement.

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Synopsis

The utilisation of non-destructive tests done on site, in order to evaluation the mechanical characteristics of the pavement layers, is now essential for a correct maintenance of the roads. A particularly suitable and widely used instrument is the falling weight deflectometer – FWD.
The aim of this paper is to illustrate a method for interpreting deflection basin measured by tests on rigid or composite (Asphalt Concrete/Portland Cement Concrete) pavements. The proposed method is based on correlations obtained through numerical simulations by the use of two different theoretical approaches (slab on elastic solid and elastic multilayer).
This methodology is practically important because, in case of composite pavement, it is able to get the mechanical characteristics of all the layers by the deflectometer measurements only; besides this methodology don't require to determine mix composition and bitumen properties. As a result, we can eliminate for the evaluation of asphalt concrete layer modulus the present use – AASHTO GUIDE – of a relationship with temperature layer and mix composition and bitumen properties. Therefore, this method consists in a procedure that allows us to obtain the mechanical characteristics of all the pavement layers by the use of parameters got by means of different deflectometer measurements and by the application of some simple specific equations.
In the end, the results obtained by the methodology application on a concrete case and the validity limits of this approach are illustrated.

Evaluation of mechanical characteristics by deflection measurement on rigid or composite pavement.

The purpose of this study is to develop a method to determine the mechanical properties of both composite and rigid pavements by interpreting the deflection measurements obtained by means of a falling weight deflectometer. These characteristics can be obtained through backcalculation techniques. There are two different approaches: the best-fit method and the definition of precise analytical relations between the directly measured quantities and the mechanical properties to be determined. This second approach is put forward by the AASHTO Guide [AASHTO,1993] where relations are established to this aim linking the deflections measurements to the various mechanical properties of the pavement layers. In case of composite pavements however the Guide suggests a procedure whereby pre-established relations are used to estimate the asphalt concrete modulus, linking the latter to the characteristics of the mix design and of the binder and to the layer temperatures. This implies that the values of the mechanical properties of the asphalt concrete layer do not take the in-situ conditions into consideration but rather exclude them.
The method proposed here takes the AASHTO Guide approach as its starting point but aims at obtaining all the mechanical properties of the pavement layers (asphalt concrete characteristics included) by means of deflection measurements only.

PAVEMENT TYPES AND STRUCTURAL MODELS

This study is centered on two special types of pavement: the Portland cement concrete rigid pavement (PCC) and the composite pavement formed by an asphalt concrete layer on top of a Portland cement concrete layer (AC/PCC). Both types of pavements show a high flexional stiffness and therefore the deflections that might develop are rather small.
Rigid pavements are assumed to behave like a slab. The schematization here adopted is therefore that of a slab on a dense liquid foundation, like a Winkler foundation.
The second type of pavements, composite pavements, behaves differently, as there is a flexible layer on top of a rigid layer: the schematization used in this case implies the superposition of two effects. This approach is therefore valid by assuming that all the materials that form the pavement have an elastic behaviour. The proposed scheme originates from observations made on these pavements which prove that there is a reduction in the thickness of the flexible layer only in the area adjacent to the load area, while from a certain point onwards its behaviour is similar to that of a slab, that is only deflections take place. As the Portland cement concrete layer is extremely rigid, it basically does not undergo any reduction in thickness, but only deflections. Therefore the full compression that the pavement undergoes is ascribable to the asphalt concrete layer. This behaviour is illustrated in the figures 1,2,3, and can be explained by assuming the superposition of two effects.

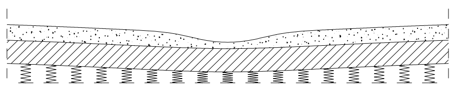

Figure 1: Overall deformation of the structure under load

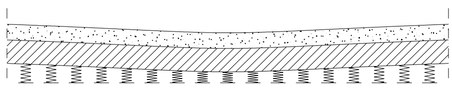

Figure 2: Deformation of a pavement considered incompressible

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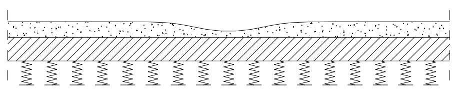


Figure 3: Deformation of a first layer considered compressible

The scheme above divides the deformation analysis into two phases: the final result is the superposition of two effects. The model used in the first scheme, that is if the entire pavement is considered incompressible, is of the Dense Liquid type [Khazanovich, 2001]. In case of composite pavements, the stiffness is the total stiffness of the two layers. The second scheme, which takes the compression of the surface layer into consideration, is obtained by assuming a elastic multilayer behaviour: here however the only compressed layer is the asphalt concrete layer, as for other layers a high stiffness value is considered which makes their incompressible.

METHOD APPLICABILITY LIMITS

Portland cement concrete pavements are generally not continous but rather interrupted by a certain number of joints. The assumption on which this method is based is that the load is applied in the centre of the Portland cement concrete slab and as far as possible from joints. A further assumption is that there are no crackings in the various layers which might induce a behaviour similar to that of joints.
Despite this being a dynamic test as an impulse load is applied, according to this method the values used to determine the elastic moduli do not consider the whole history of load and deflections but only peak values. In this way, the analysis is static even though values are obtained from dynamic moduli.
Several studies have proved that the presence of bedrock at a low depth causes alterations in the deflection measurements [Uzan, 1994 - Chang 1992a]. According to these studies, these alterations are due to the dynamic effects resulting from the reflection of the compression wave produced by the FWD on bedrock. Therefore, the results obtained by applying this methodology are only valid if there is no bedrock at a low depth.
A further assumption concerns the linear behaviour of elastic material. The use of a linear elastic behaviour also for the soil support is justified when load values are low [Uzan, 1994]. The cases examined satisfy this condition as the analyzed pavements, besides being extremely rigid, are also considerably thick. Thanks to these features, the stress transmitted to the soil support is far lower than the stress produced on the surface layer by the FWD, thus reaching such a level that a linear elastic behaviour can be assumed.
The results obtained with this method depend on the assumptions just made. Moreover, as far as the mechanical properties of the soil support are concerned, the results obtained are for the whole foundation under the slab. In other words, if there is a cement treated subbase and granular unbonded layer under it and then the soil support, results are interpreted with a single parameter representative of the behaviour of all layers (subbase, granular layer and soil support).
Finally, special attention has to be paid to the collection of deflectometer data, avoiding the curling effect [Ullidz, 1987] when taking measurements. This effect is mainly found in rigid pavements as the Portland cement concrete layer can rise up from its foundation in the central part of the slab in the hottest moments of the day. In composite pavements instead, the asphalt concrete surface layer acts as a “shield” for the Portland cement concrete layer so that the latter is less exposed to temperature differences which might induce the above-mentioned effect.

MEASUREMENTS INTERPRETATION

The method hereunder described takes the methodology put forward by AASHTO as its starting point and shares some of its ideas but deals with the research on mechanical properties in a different way [AASHTO, 1993].
This method intends to find the values of the layers elastic moduli on the basis of deflection measurements obtained by means of a FWD or rather a HWD and the knowledge of the precise thickness of the pavement components. As far as the Poisson’s ratio values are concerned, these are assumed a priori on the basis of considerations and personal experience. The determination for a composite pavement of all elastic constants from deflection values only is a fundamental difference compared with the method devised by AASHTO which determines the values of the asphalt concrete modulus on the basis of temperature and mix design features, without considering deflection measurements. Moreover, the proposed method extends the field of application also to higher load values compared with those envisaged by the AASHTO Guide.
Similarly to the AASHTO method, some correlations have been defined to obtain the mechanical properties of layers directly from the deflections measured. The behaviour of a high number of pavements has been simulated by applying the structural models described above, in order to obtain these relations.
Table 1 shows the range of values used in the simulation for the elastic constants.

Tab 1: Elastic constant

		symbol	M.U.	interval
foundation	modulus of subgrade reaction	k	kPa/mm	15 - 200
PCC	elastic modulus	E_{PCC}	MPa	25000 - 50000
	Poisson’s ratio	ν_{PCC}	-	0,15
	Thickness	s_{PCC}	cm	15 - 30
AC	elastic modulus	E_{AC}	MPa	1000 - 10000
	Poisson’s ratio	ν_{AC}	-	0,30 – 0,35
	thickness	s_{AC}	cm	10 - 35

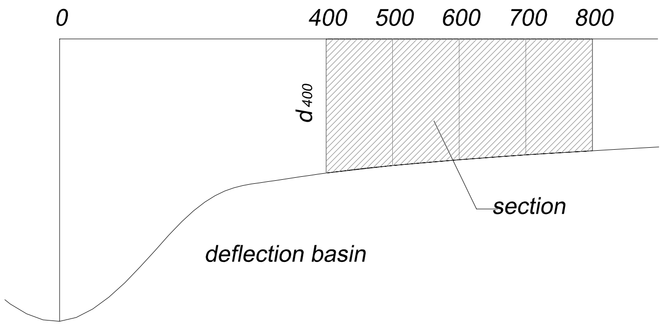
To evaluate the pavement elastic constants five geophones are positioned at a distance of 400, 500, 600, 700 and 800 mm from the load centre, besides considering the deflections which the load centre undergoes.

A new parameter, called *basin*, function of deflection measurements, is introduced (similarly to what AASHTO proposed) and is defined as follows:

$$\text{basin} = \frac{50}{d_{400}} \cdot \left(d_{400} + 2 \cdot d_{500} + 2 \cdot d_{600} + 2 \cdot d_{700} + d_{800}\right) \qquad [1]$$

It can be represented as follows:

Figure 4: Basin parameters



where:

$$\text{basin} = \frac{\text{section}}{d_{400}}$$

Another parameter is introduced too, called *normalized maximum deflection*, which is defined as follows:

$$d_{400N} = \frac{d_{400}}{F} \qquad [3]$$

where:
d_{400} = deflection at a distance of 400 mm [μm]
F = force applied by the FWD [kN]

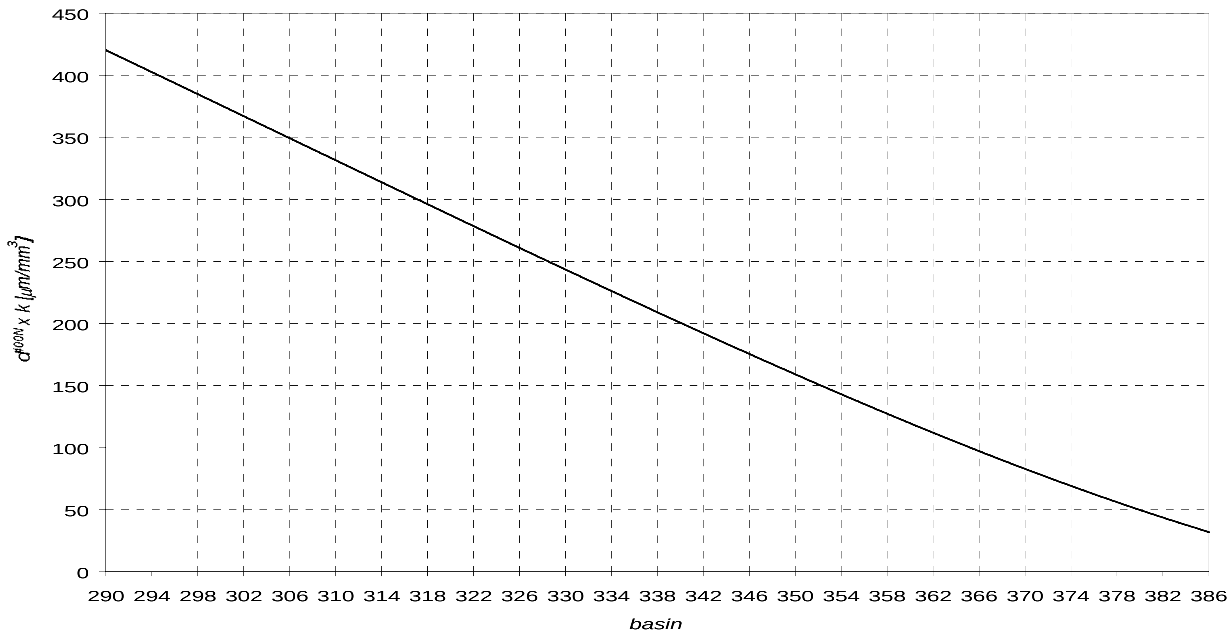
Determination of the k-value

By means of these two parameters a biunivocal relation has been found connecting the *basin* value to the $d_{400N} \cdot k$ value, where k is the value of the modulus of foundation reaction [Figure 5].
Therefore the k-value is calculated from the deflection values. This result is independent of the modulus of the asphalt concrete layer, of the bond between the two layers and of the type of pavement considered, rigid or composite.
The diagram developped to calculate the value of the modulus of foundation reaction can be expressed by means of the following equation
:

$$d_{400N} \cdot k = 0{,}00000043056 2 \cdot \text{basin}^4 - 0{,}000489568011 \cdot \text{basin}^3 + 0{,}207689418767 \cdot \text{basin}^2 + \\ - 43{,}36829267 \cdot \text{basin} + 4425{,}163 \qquad [4]$$

R^2=0.9999

Figure 5: Curve for determining the k-value



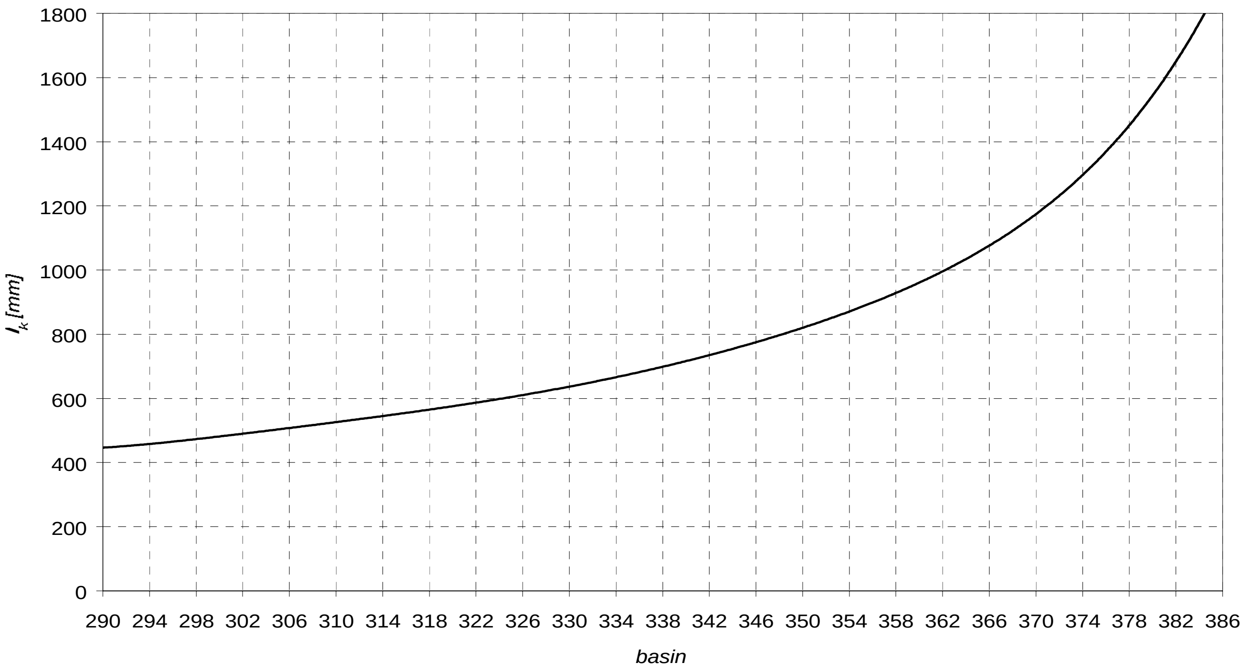
Determination of the relative stiffness radius

To determine the value of the relative stiffness radius, a relation has been established between the latter and the *basin* value [Figure 6]. It is therefore possible to determine the value of the relative stiffness radius by means of the proposed diagram, just by knowing the *basin*.
At this point, the diagram thus obtained is still independent of the type of pavement (composite or rigid). Moreover, the result is also independent of the applied load.
The diagram thus obtained can be expressed by the following relation:

$$l_k = 0{,}0000000126378 \cdot \text{basin}^6 - 0{,}000024775031 \cdot \text{basin}^5 + 0{,}020224275888 \cdot \text{basin}^4 + \\ - 8{,}798401054229 \cdot \text{basin}^3 + 2151{,}249066275 \cdot \text{basin}^2 - 280269{,}689 \cdot \text{basin} + 15199504{,}92 \qquad [5]$$

R^2=0.9999

Figure 6: Curve for determining radius of relative stiffness



Determination of the elastic moduli

The process that determines the value of the elastic moduli is different in case of rigid or composite pavements.
In case of rigid pavements, once the value of the relative stiffness radius is determined by means of the previous relation, recalling that it is defined as follows:

$$l_k = \sqrt[4]{\frac{E \cdot s^3}{12 \cdot (1 - \nu^2) \cdot k}} \qquad [6]$$

the problem of determining the elastic modulus of the slab is easily solved, as it is the only unknown.
In case of composite pavements, the method to be followed is different and requires the definition of additional parameters to determine the elastic moduli of the two layers. These are described hereunder.

Determination of the theoretical deflection at the centre of the loading plate

The following parameter, called normalized theoretical deflection at the centre of the load (plate centre), is introduced:

$$w_{0N} = \frac{w_0}{F} \qquad [7]$$

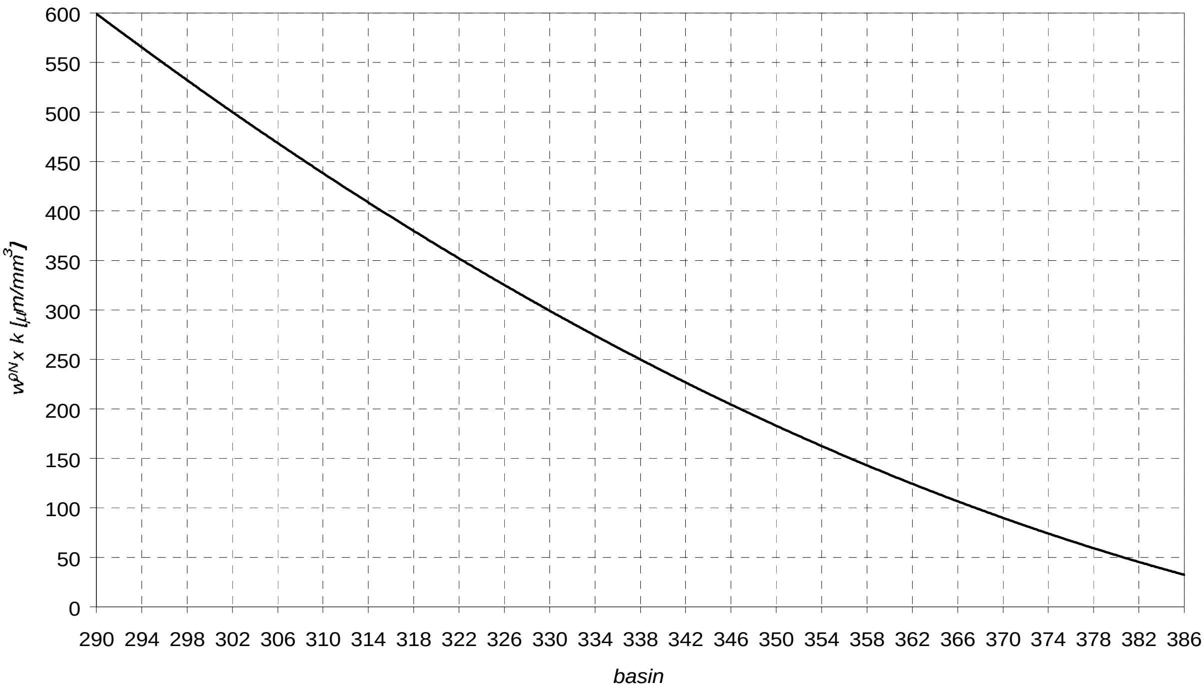
where:
w_0 = theoretical deflection at the centre of the load [μm]
F = force applied by the FWD [kN]
This parameter represents the normalized deflection at the centre of load if the behavior of the both layers were supposed incompressible. A relation has been established between, w_{0N}, and the *basin* value. To obtain this relation a high number of pavements has been simulated, assuming the behaviour of both layers of the pavement as a slab. To calculate the theoretical normalized deflection it was necessary to consider the bond state at the interface of the two layers (bonded or unbonded). But in any case the founded relation is independent of the bond state. Using the following equation [Figure 7] it is possible to find the normalized theoretical deflection at the plate centre if the parameter "basin" is know:

$$w_{0N} \cdot k = 0{,}0000087701 \cdot \text{basin}^3 + 0{,}0197117551 \cdot \text{basin}^2 - 22{,}2575024765 \cdot \text{basin} + 5182{,}38 \qquad [8]$$

R^2=0.9999

Therefore, by knowing the *k*- value it is possible to determine the value, w_{0N}, and the value w_0.

Figure 7: Curve for determination of the theoretical deflection at the centre of the plate



Determination of the elastic modulus of the AC layer

At this point, the compressibility which the asphalt concrete layer undergoes needs to be determined and therefore a model needs to be adopted to this end. The behaviour of an elastic multilayer has been examined in detail. In this case, however, the only layer which is considered compressible is the asphalt concrete, therefore an extremely high value of the elastic modulus is assigned to the other layers so that their “compressibility” is negiglible. The analysis of numerous pavements resulted in the determination of a relation connecting thickness and elastic modulus of the layer to the compression it undergoes.

Before examining the calculation of the elastic modulus, a new parameter (c_0) needs to be introduced. This is obtained by calculating the difference between the deflection measurement in the load centre and the, w_0 value.

The definition is therefore:

$$c_0 = d_0 - w_0 \quad [9]$$

Such value, like the others, is normalized to the load, by defining:

$$c_{0N} = \frac{c_0}{F} = \frac{d_0 - w_0}{F} = d_{0N} - w_{0N} \quad [10]$$

Finally, the following new parameter is defined:

$$M = E_{ac}^{1,04} \cdot s_{ac}^{3} \cdot c_{0N} . 10^{-10} \quad [11]$$

where:

E_{ac} = the modulus of elasticity of the asphalt concrete layer [kPa]

s_{ac} = thickness of the asphalt concrete layer [mm]

The analysis of numerous pavements by applying the above described hypotheses resulted in two biunivocal correlations which depend on the bond between the layers.

The two relations are represented by the following equations:

- Bonded layers

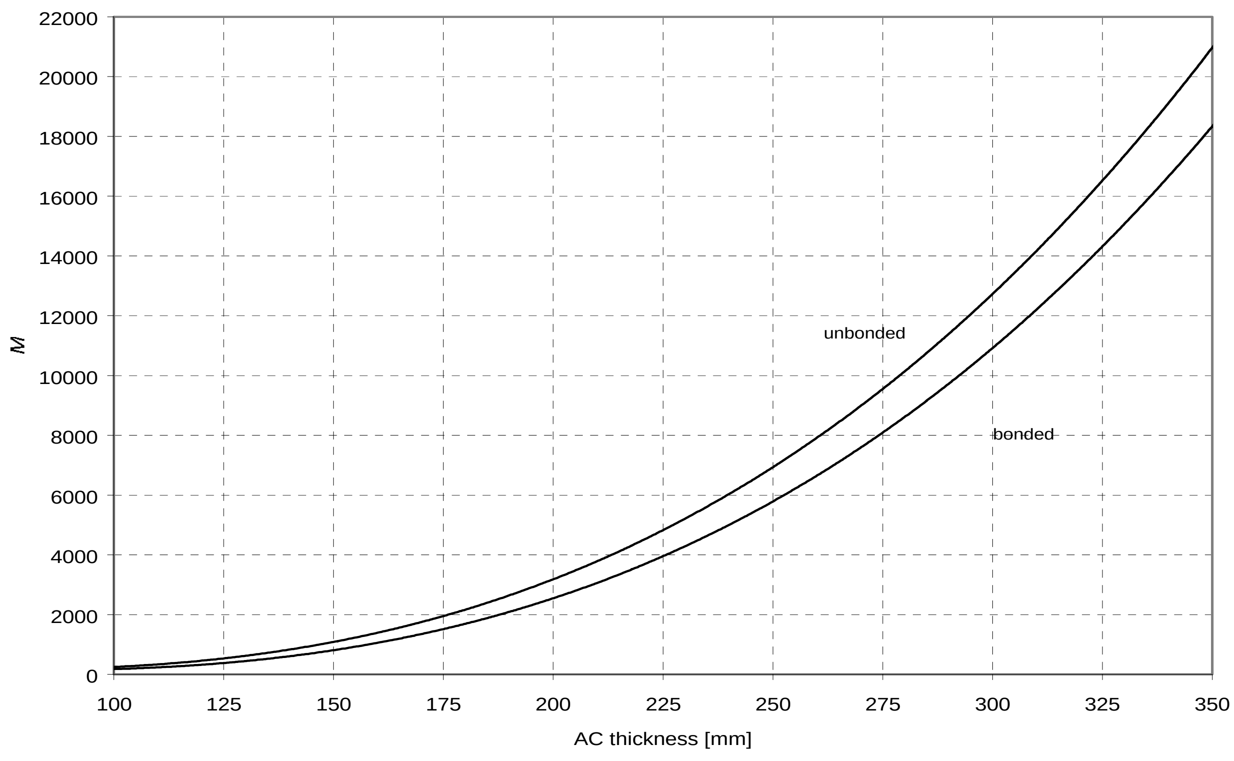
$$M = 0{,}0005259176 \cdot s_{ac}^{3} - 0{,}0155523104 \cdot s_{ac}^{2} - 8{,}4530906323 \cdot s_{ac} + 653{,}409 \quad [12]$$

- Unbonded layers

$$M = 0{,}0005268880 \cdot s_{ac}^{3} + 0{,}0145913251 \cdot s_{ac}^{2} - 11{,}9342374212 \cdot s_{ac} + 770{,}719 \quad [13]$$

It is thus possible to obtain the asphalt concrete modulus by knowing its thickness.

Figure 8: Curve for determination the AC moduls



Determination of the elastic modulus of the PCC layer

The final step is to determine the elastic modulus of the Portland cement concrete layer. Here too, two cases have to be discussed according to whether the two layers (asphalt concrete and cement concrete slab) are bonded or unbonded. The simplest problem, that is when the two layers are unbonded, is solved first.

In this case, the value of the overall pavement stiffness is given by the sum of the stiffness of each of the two layers, as the two behave separately in flectional terms. The flectional stiffness of a layer can be defined as follows:

$$D = \frac{E \cdot s^3}{(1-\nu^2)\cdot 12} \qquad [14]$$

Therefore the total stiffness for unbonded layers is:

$$D_{TOT} = \frac{E_{ac} \cdot s_{ac}^3}{12\cdot(1-\nu_{ac}^2)} + \frac{E_{pcc} \cdot s_{pcc}^3}{12\cdot(1-\nu_{pcc}^2)} \qquad [15]$$

and as a consequence the relative stiffness radius is the following:

$$l_k = \sqrt[4]{\left(\frac{E_{ac} \cdot s_{ac}^3}{12\cdot(1-\nu_{ac}^2)} + \frac{E_{pcc} \cdot s_{pcc}^3}{12\cdot(1-\nu_{pcc}^2)}\right)\cdot\frac{1}{k}} \qquad [16]$$

Therefore, if the value l_k which was previously calculated with the correlation 5, the value E_{ac} calculated with the equation [13] and value k calculated with the equation [8] are known, the value, E_{pcc}, is easily obtained. As far as the Poisson's ratio of Portland cement concrete is concerned, it is assumed to be 0.15. This is generally valid for all types of Portland cement concrete and does not undergo substantial changes. As far as the Poisson's ratio value of the asphalt concrete layer is concerned, if more reliable data are not available, it is possible to assume a value which changes according to the value of the elastic modulus and therefore to say that $\nu = \nu(E)$. More precisely, it is possible to assume a linear law which is valid in the range of values used for this study, like the following:

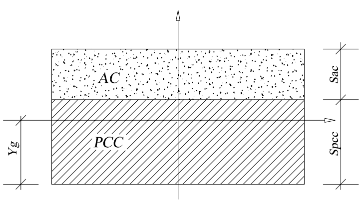
E_{ac}	1000 [Mpa]	$\longrightarrow$	10000[Mpa]
ν	0,35	$\longrightarrow$	0,25

As an alternative, it is possible to assume an average value of 0.30.

Now all the necessary data are available and thus all the elastic constants of a pavement can be obtained by applying this method.

If the two layers are bonded, their flectional behaviour is not independent but there is interaction between the two. As the two layers behave as a single layer from a flectional point of view, the new centre of gravity of the section has to be calculated and consequently the moment of total inertia has to be calculated, then the stiffness and finally the relative stiffness radius.

Figure 9: Scheme for determining the centre of gravity



The centre of gravity of the overall section is calculated as follows:

$$y_g = \frac{E_{pcc}\cdot s_{pcc}^2 + E_{ac}\cdot s_{ac}^2 + 2\cdot E_{ac}\cdot s_{pcc}\cdot s_{ac}}{2\cdot\left(E_{pcc}\cdot s_{pcc} + E_{ac}\cdot s_{ac}\right)} \qquad [17]$$

Based hereupon the total stiffness is calculated. In this case, the sum of the moments of inertia has to be made considering the centre of gravity of the overall section. As a result:

$$D_{TOT} = \frac{E_{pcc}}{(1-\nu_{pcc}^2)}\cdot\left(\frac{s_{pcc}^3}{12} + s_{pcc}\cdot\left(y_g - \frac{s_{pcc}}{2}\right)^2\right) + \frac{E_{ac}}{(1-\nu_{ac}^2)}\cdot\left(\frac{s_{ac}^3}{12} + s_{ac}\cdot\left(s_{pcc} + \frac{s_{ac}}{2} - y_g\right)^2\right) \qquad [18]$$

Finally the value of the relative stiffness radius can be calculated as:

$$l_k = \sqrt[4]{\left(\frac{E_{pcc}}{(1-\nu_{pcc}^2)} \cdot \left(\frac{s_{pcc}^3}{12} + s_{pcc} \cdot \left(y_g - \frac{s_{pcc}}{2}\right)^2\right) + \frac{E_{ac}}{(1-\nu_{ac}^2)} \cdot \left(\frac{s_{ac}^3}{12} + s_{ac} \cdot \left(s_{pcc} + \frac{s_{ac}}{2} - y_g\right)^2\right)\right) \cdot \frac{1}{k}} \quad [19]$$

At this point, the considerations made on the values to be assigned to the Poisson's ratio of the two layers are still valid. It is therefore possible to obtain the value of the modulus of elasticity of the Portland cement concrete layer which is the last unknown quantity.

INFLUENCE OF MEASUREMENT ERRORS

A sensitiveness analysis has been carried out to check the reliability of the results obtained by applying this method. This analysis consisted in the introduction of a given error in the deflection measurements in order to observe the error produced in the results thus obtained.
As far as parameter *k* is concerned, this analysis has shown that an error of 18% can be reached when all the deflection measurements show an error of 1μm (reading error) and the pavement being examined has a very high overall stiffness, that is when the thickness of layers and elastic moduli is the highest reported in table 1.
As far as the elastic moduli of pavement layers are concerned, the situation is different and more complex. These moduli are connected by rather complex relations according to whether they are bonded or unbonded and these relations do not make it possible to obtain the variation which the values of moduli undergo in the presence of errors in the deflection measurements. Therefore, the method used in this case to check the errors made is fundamentally different. The first step was to simulate the behaviour of a high number of pavements having different elastic properties and thicknesses. Basically, the deflections at different distances from the load were obtained from this simulation by applying the hypotheses of the method proposed here. Subsequently an error of ±1μm was casually applied to the deflection measurements just obtained. The application of this method to the wrong measurements implied errors in the results. The conclusion drawn was that the error made in the results depends upon the pavement stiffness and the modulus of subgrade reaction. In particular, the higher the values of these two parameters, the bigger the error in the results produced. However the relation linking the error to these parameters is exponential.
Finally, the influence of the load applied by the FWD has to be considered. If the load applied doubles, the inaccuracy of the results obtained is halved. This is explained by the fact that by doubling the load which acts on the pavement also the values of the deflection measurements produced double. Therefore, with equal reading error it is evident that the values of deflections are higher and the errors made lower in percentage points.

ACCURACY OF PROPOSED METHOD AND COMPARISON WITH THE AASHTO METHODOLOGY

A certain number of pavements of known mechanical properties has been analyzed to check which errors are produced by the mere application of this method. The deflection basin was calculated for each such pavement by applying the hypotheses on which this method is based. Thereafter, this method was applied on the values thus obtained to find the mechanical properties and check to what extent the latter move away from the known ones.
The results of some pavements are reported in the table hereunder and refer to load levels equal to 234 kN.

Tab 2: Results

s_{ac}	s_{pcc}	k			E_{ac}			E_{pcc}		
		input	output	Var.	input	output	Var.	input	output	Var.
[mm]	[mm]	[kPa/mm]		[%]	[MPa]		[%]	[MPa]		[%]
26.4	27.9	136	136	0.2	9474	9445	-0.3	41684	41652	-0.1
15,5	17,8	27,2	27,1	-0,1	6545	6477	-1,0	34450	34395	-0,2
25.1	33.0	27	27	0.8	9439	9112	-3.6	41340	41421	0.2
19,3	22,9	27,2	27,2	0,0	7234	7485	3,4	41340	40799	-1,3
25.1	33.0	136	137	0.7	9439	9353	-0.9	41340	40770	-1.4
26.4	27.9	81	82	0.8	9474	9521	0.5	41684	41086	-1.5
25.1	33.0	190	190	0.0	9439	9320	-1.3	41340	41457	0.3
15.5	17.8	136	136	0.1	6545	6508	-0.6	34450	33947	-1.5

This table shows that the error never exceeds 4% in results.

A comparison between the results obtained with the suggested method and with the AASHTO Guide follows. This comparison is founded on deflectometer measurements obtained by a numerical simulation based on the hypotheses on which the suggested method relies. In other words, the deflection values obtained with a Dense Liquid method have been added to those obtained for the upper layer only with a multielastic layer. The adopted load level is 9000 pounds (40.05 kN) as the AASHTO method envisages such value as the only load level.
The table hereunder shows the results which can be obtained by interpreting the deflectometer measurements in case of rigid (PCC) and composite pavements (AC/PCC) with the proposed method and with the method suggested by the AASHTO Guide. In case of composite pavements, the AASHTO Guide calculate the value of the asphalt concrete modulus by means of a relation which takes temperature and mix design into account, therefore the values of this layer in the following comparison are considered equal to those with which the deflection basins were produced.

Tab 3: Comparision

Start value					Results with the suggested method						Results with the AASHTO method					
E_{ac} [MPa]	s_{ac} [cm]	E_{pcc} [MPa]	s_{pcc} [cm]	k [kPa/mm]	E_{ac} [MPa]	Var [%]	E_{pcc} [MPa]	Var [%]	k [kPa/mm]	Var [%]	E_{ac} [MPa]	Var [%]	E_{pcc} [MPa]	Var [%]	k [kPa/mm]	Var [%]
1378	12,7	34450	20,3	136	1641	19,1	32900	-4,5	135	-0,2	1378	-	29627	-14,0	190	40,0
8957	12,7	34450	20,3	136	9650	7,7	32300	-6,2	136	-0,1	8957	-	57187	66,0	163	20,0
1378	25,4	34450	20,3	136	1528	10,9	31500	-8,6	135	-0,2	1378	-	107484	212,0	109	-20,0
8957	25,4	34450	20,3	136	9189	2,6	32450	-5,8	136	-0,1	8957	-	192920	460,0	244	80,0
1378	12,7	48230	27,9	54	1646	19,5	47300	-1,9	54	-0,3	1378	-	24804	-48,6	81	50,0
8957	12,7	48230	27,9	54	9764	9,0	46300	-4,0	54	0,0	8957	-	41340	-14,3	68	25,0
1378	25,4	48230	27,9	54	1530	11,0	46600	-3,4	54	-0,4	1378	-	144690	200,0	33	-40,0
8957	25,4	48230	27,9	54	9041	0,9	49500	2,6	54	-0,8	8957	-	93015	92,9	81	50,0
1378	12,7	25493	15,2	81	1642	19,1	22800	-10,6	81	-0,1	1378	-	37895	48,6	95	16,7
8957	12,7	25493	15,2	81	9599	7,2	23500	-7,8	81	-0,2	8957	-	82680	224,3	95	16,7
1378	25,4	25493	15,2	81	1526	10,8	21000	-17,6	81	-0,2	1378	-	95771	275,7	73	10,0
8957	25,4	25493	15,2	81	9208	2,8	24300	-4,7	81	-0,3	8957	-	127465	400,0	109	33,3
1378	12,7	25493	15,2	190	1660	20,5	23000	-9,8	190	-0,2	1378	-	out	-	out	-
8957	12,7	25493	15,2	190	9754	8,9	22500	-11,7	190	-0,3	8957	-	79235	210.8	190	0,0
1378	25,4	25493	15,2	190	1529	10,9	20600	-19,2	190	-0,2	1378	-	64077	151.3	217	-10,0
8957	25,4	25493	15,2	190	9186	2,6	24600	-3,5	190	0,0	8957	-	254930	1000	271	-
-	-	34450	20,3	136	-	-	34150	-0,9	136	-0,1	-	-	46228	4,0	136	0,0
-	-	48230	27,9	54	-	-	47850	-0,8	54	-0,1	-	-	65786	5,7	54	0,0
-	-	25493	15,2	81	-	-	25550	0,2	81	-0,2	-	-	32893	0,0	81	0,0
-	-	25493	15,2	190	-	-	25350	-0,6	190	-0,2	-	-	33072	29,7	217	14,3

Some considerations can be made based hereupon. By using the proposed method, the values of the asphalt concrete modulus differ by 9% on average with a peak of 19.5%, while the values of the slab modulus differ by –5.5% on average with a peak of –17.6%; finally the modulus of foundation reaction does not practically undergo any changes. Far higher values are obtained by applying the method proposed by AASHTO, in which case values up to 460% above the starting values are obtained for the slab modulus, with an average of 160%. Both methods show very low variations in case of a rigid pavement.
These marked difference compared to the AASHTO results in case of composite pavements can be explained by the fact that it is not the overall pavement stiffness which is taken into account, but the whole stiffness is assigned to the Portland cement concrete slab only.

METHOD APPLICATION

The following measurements have been taken near Settebagni on the A1 highway branch north of Rome on a composite AC/PCC pavement with a 33cm asphalt concrete thickness and a 25 cm Portland cement concrete thickness. The instrumentation used is a Heavy Weight Deflectometer which was kindly provided by the Autostrade S.p.A.
The values collected during the testing period are reported hereunder. These values are divided into two groups which represent the two points where the measurements were taken. Tests have been carried out on each point with different load values by changing the height of the falling weight. Each time three drops have been made so that three deflection basins were obtained for each test.

Tab 4: Measurement

position number	drop	d_0 [μm]	d_{400} [μm]	d_{500} [μm]	d_{600} [μm]	d_{700} [μm]	d_{800} [μm]	pressure [kPa]	height of the falling weight
1	1	206	148	144	139	136	131	1651	II
	2	201	146	142	138	134	128	1636	
	3	199	144	140	136	132	127	1633	
	1	448	293	286	277	270	258	3445	IV
	2	444	295	288	279	272	261	3445	
	3	444	294	288	279	271	260	3444	
2	1	426	281	274	265	256	247	3433	IV
	2	428	283	277	268	259	249	3441	
	3	428	283	276	267	258	249	3429	
	1	440	284	277	268	260	250	3438	IV
	2	441	283	276	267	258	249	3434	
	3	437	284	277	267	260	250	3426	
	1	446	288	279	269	260	251	3442	IV
	2	436	285	278	269	260	251	3432	
	3	435	285	277	268	259	250	3426	
	1	205	143	139	134	130	125	1631	II
	2	202	142	140	133	129	124	1622	
	3	204	143	140	134	131	126	1623	
	1	206	143	140	134	131	125	1636	II
	2	204	142	139	132	130	124	1621	
	3	203	141	138	132	128	122	1618	
	1	209	143	139	135	129	127	1633	II
	2	206	142	140	135	129	125	1625	
	3	204	141	139	133	130	125	1624	

The values of the pavement elastic constants have been calculated for each single measurement. The results thus obtained show that the moduli in the same group of drops are not very stable. However, the results which are generally considered are not those of all drops but those referring to the third one only, as the instrumentation has the time to "adjust" in this way.
The results obtained by the application of the proposed method are reported in the table hereunder.

Tab 5: Calculated elastic constants

position number	drop	E_{ac} [MPa]	E_{pcc} [MPa]	k [kPa/mm]	temperature air/AC[°C]	falling height
1	1	5335	29123	45.8	27,5 / 29,9	II
	2	5599	27111	45.9		
	3	5574	28441	46.4		
	1	3998	62273	45.7	27,5 / 31,4	IV
	2	4163	60725	44.6		
	3	4109	67619	43.2		
2	1	4312	49823	51.6	27,5 / 30,1	IV
	2	4282	59471	47.9		
	3	4306	50137	50.7		
	1	3976	59595	49.5	27,5 / 29,7	IV
	2	4282	59471	47.9		
	3	4059	54739	50.3		
	1	4030	34547	58.1	27,5 / 29,9	IV
	2	4122	53197	49.9		
	3	4186	43727	53.3		
	1	4955	26133	51.7	27,5 / 32,0	II
	2	5046	31171	48.5		
	3	4934	34693	46.8		
	1	4816	35033	48.1	27,5 / 30,4	II
	2	4896	29267	50.3		
	3	4905	27121	52.0		
	1	4595	33797	49.9	27,5 / 31,3	II
	2	4624	48601	44.0		
	3	4655	56241	41.9		

These results are illustrated in figures 10, 11, 12. The graph hereunder clearly shows that the value of the modulus of foundation reaction is extremely constant also regardless of the applied load and is on average around 48kPa/mm.

Figure 10: Calculated k-values

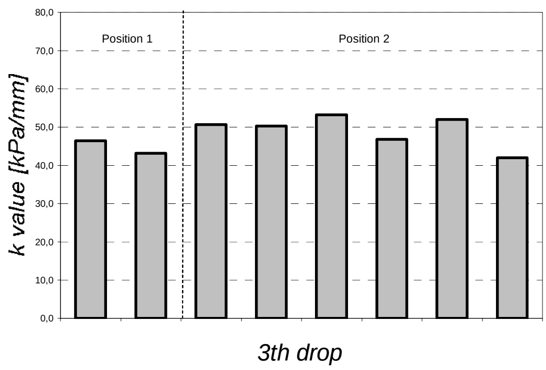
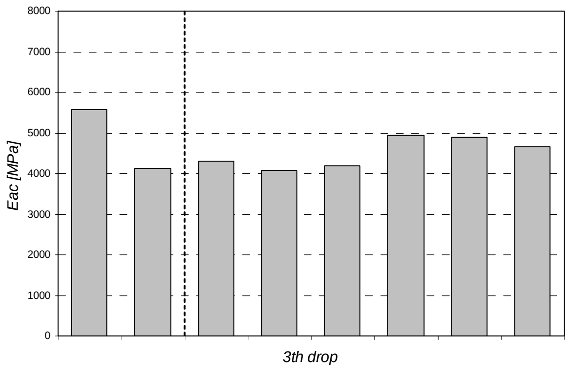


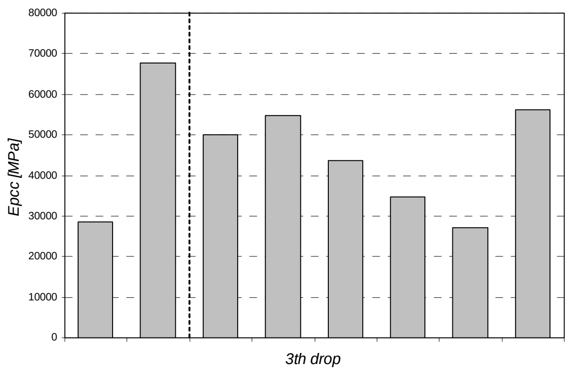
Figure 11 shows the situation as far as the modulus of elasticity of the asphalt concrete layer is concerned. Such value has to be put in relation with the temperature at which it was obtained.

Figure 11: Calculated AC moduli



In this case, the results of position 1 move 26% away while the values of position 2 move maximum 18% away. The values which present the maximum difference are the values of the elastic modulus of Portland cement concrete [figure 12].

Figure 12: Calculated PCC moduli



It is probably the inaccuracy of measurements, in particular at low load levels, which determines a remarkable difference in the results obtained. Such difference is more clearly visible when calculating the Portland cement concrete modulus as this is obtained indirectly starting from the values of the relative stiffness radius and the asphalt concrete modulus, and when, as in this tests, the relative stiffness radius proved to be fundamentally constant.

CONCLUSIONS

With a view to correct maintenance of road and airport infrastructures it is essential to know the pavement conditions. The assessment of the mechanical properties of such infrastructures by means of lab tests is expensive and produces moreover results which show little closeness to what are the in-situ characteristics. The falling weight deflectometer proved to be a valid alternative for the solution of these problems.

The accuracy of the instrumentation is of fundamental importance. Therefore an improvement of this instrumentation would be highly welcome so as to obtain more accurate results.

Some considerations have to be made on the comparison between the method proposed here and the method put forward by AASHTO for the same types of pavement. In the case of composite pavement, unlike the AASHTO method, this method determines the mechanical properties exclusively with the analysis of deflection values and therefore the asphalt concrete modulus is not estimated on the basis of formulas which require knowledge of the temperature and mix design. A further consideration concerns the accuracy of results which is higher than with the AASHTO method.

Finally the proposed method seems to produce good results. The measurements obtained with the falling weight deflectometer have to be analyzed however to check the absence of variations in the values. Moreover, it is advisable to use rather high load values for this type of pavements in order to limit the errors that can be made during the analysis.

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