Contribution to the Design of Urban Pavement of Low Volume Traffic Using the Dynamic Cone Penetrometer

H.P. Jordão, A.E.F.L. Lucena, M.B. Chagas Filho, J.K.G. Rodrigues, D.A. Gama

Abstract. The characteristics of the subgrade soil, obtained from laboratory and in situ tests, are of fundamental importance to the design of pavements. The tests carried out in the field, such as CBR in situ, Bredboard and others, represent more significantly the conditions of the soil. The Dynamic Cone Penetrometer (DCP) is an equipment of easy use that has become an alternative to the pavement design. With that kind of equipment it is possible to determine the resistance profile to the penetration of the layers of the compacted soil or in its natural state from the correlations between this test and the CBR *in situ*. This work attemps to adequate a design method for urban pavements of low volume traffic, using the results of the penetration index obtained with the DCP. The results indicate that the DCP presents a high correlation with CBR *in situ* tests for A-2-4 soils, which can be used in pavement design of urban roads of low volume traffic.

Keywords: design of pavements, dynamic cone penetrometer, CBR *in situ*.

1. Introduction

The search for new methods of pavement design aims at greater savings or greater security when compared to traditional methods. Urban roads of low volume traffic must be designed for such request and not the same way as highways, which causes larger amount of pavements.

One of the very first design methods, established by the California Highway Department, in 1939, was based in the CBR (California Bearing Ratio) and until today keeps the same principles. The methods that use as parameters the CBR *in situ* ME-47 (PMSP, 1999) and/or the Plate load Test (ASTM D-1196, 2004), despite of favoring an analyses closer to reality, they become more costly and slower due to the high cost of the equipments and its execution.

An alternative of using a more simple method and of low cost is to use the Dynamic Cone Penetrometer (DCT), and then, its correlation with the CBR *in situ*, which could bring a great economy in the pavement of streets of low volume traffic.

2. Pavement Project

To elaborate a pavement design it is necessary to perform geotechnical studies in the place, which involve studies of the subgrade and of occurrence of materials for pavement that will suit as raw material in the execution of the layers that constitute the pavement.

The aim of studying the subgrade of the roads is the recognition of the soils and of its bearing capacity, for the characterization of its various layers for the effect of the pavement design.

2.1. Determination of the soil capacity *in situ*

Among the several existing methods for determining the soil capacity *in situ*, the Dynamic Cone Penetrometer (DCP) and CBR *in situ* are presented.

2.1.1. Dynamic Cone Penetrometer - DCP

The development of the DCP arouse from the necessity of evaluating, simple and quickly, the subgrade conditions of a certain pavement. The use of this equipment has gained more and more adepts in the last years in a national and international scale, and consequently, the necessity of having the analysis and results that generate more trusty correlations becomes ever increasing (Amaral, 2005).

According to Alves (2002), this test does not require great diggings or perforations, and consequently does not interfere in the traffic of vehicles. This can be characterized as a semi non-destructive test.

The Dynamic Cone Penetrometer (DCP) is an equipment which provides the rate of penetration carried out in non-deformed soils or compacted materials.

The DCP is performed with the help of two people. The length in millimeters that the rod penetrates in the soil, in relation to a determined number of hits, is measured. The results are noted in a pattern spreadsheet where it is indicated the depth versus the number of applied hits. The DCP was designed to penetrate to a middle depth of 800 mm or when rod extension is settled, it can reach a depth of 1.200 mm.

Hugo Pimentel Jordão, MSc, Universidade Federal de Campina Grande, Campina Grande, PB, Brazil, e-mail: hpjordao@yahoo.com.br.
Adriano Elísio de Figueiredo Lopes Lucena, DSc, Professor, Universidade Federal de Campina Grande, Campina Grande, PB, Brazil, e-mail: lucenafb@uol.com.br.
Milton Bezerra das Chagas Filho, DSc, Professor, Universidade Federal de Campina Grande, Campina Grande, PB, Brazil, e-mail: miltoncf@gmail.com.
John Kennedy Guedes Rodrigues, PhD, Professor, Universidade Federal de Campina Grande, Campina Grande, PB, Brazil, e-mail: jkennedy@dec.ufcg.edu.br.
Dennyele Alves Gama, Engenheira Civil, Universidade Federal de Campina Grande, Campina Grande, PB, Brazil, e-mail: dennyelealves@gmail.com.
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According to Herrick & Jones (2001, apud Guedes, 2008) the measurements of the penetrometer cone can be expressed as the number of hits by millimeter of penetration or as the agerage resistance of the soil by depth of the penetrated soil. This approach does not presume uniformity of the soil, simply generates an average resistance through the depth penetrated by the cone. These average numbers are more informative to soils, which are relatively uniform inside the advance in the depth penetrated in each hit.

It is showed in a graphic the values of the readings obtained from the penetration versus the number of hits. Generally the number of hits is plotted in graphic in the abscissas axis, while the penetration, in the ordered axis (Fig. 1). The DCP curve obtained represents the number of hits to reach a certain depth.

The soil resistance *in situ* is represented by the penetration indexexpressed by:

$$DCP = \frac{\text{Depth}}{\text{N. of Hits}} \quad (1)$$

Depending on the type of the material that constitutes the layer of the pavement or its conditions of water content and density, the inclination of the curve changes: when upright, it indicates materials with minor support capacity and when closer to the horizontal, the greater will be its resistance.

2.1.2. CBR in situ

The CBR *in situ* test provides the resistance of the soils, in field, when it is under a certain load. The test method was developed by the United States Army Corps of Engineers (USACE).

The equipment of the CBR *in situ* is composed by a piston of penetration with 4.96 cm of diameter, ring dynamometer with capacity to 4000 kg sensible to 2.5 kg duly calibrated, jack with capacity of 4 tons, capable of providing continuous addition of load, beam of reference with 1 meter of length, comparable watch with dispositive for its fixing in the penetration piston, steel curled discs for overload, divided diametrically in two parts, with 2.268 kg of total weight, with external diameter of 14.92 cm and inner diameter of 5.39 cm and a heavy vehicle or anchor system that provides an reaction equal or superior to 5 tons.

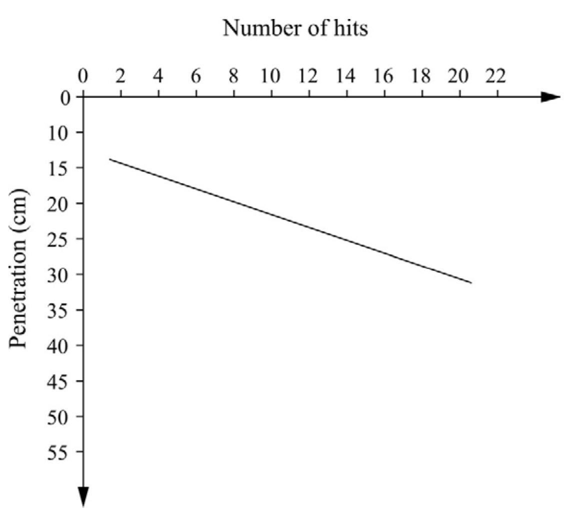

Figure 1 - Graphic of DCP.

According to Yoder (1959, apud Berti, 2005) the test is carried out by similar manner to the laboratory, where the piston of 19.63 cm^2 is forced to press the pavement and compare to the load on the piston with the penetration depth. According to Pattrol (2009), to a test *in situ*, the load reaction is provided by the weight of a loaded truck. The equipment is composed of a mechanic jack, adjusted to the back part of the mobile laboratory, a dynanometric ring, the piston and the connections.

The method of test ME-49/99 - Determination of the Support Index of the Subgrade *in situ*, adopted by the Secretary of Public Roads of the city of São Paulo, determines the support index *in situ* of the various layers of the pavement in its natural state.

According to the standard method, the equipment set (piston, ring and jack) is arranged over the leveled surface, in a way that it stays vertically below of the reaction point of the loaded vehicle. The reference beam is placed leaned by its extremities in two supports equally kept away from the test place, in such a way that the deflectometer rooted in the piston leans in the surface of the beam. Overload discs that are often used in laboratorial CBR loading are placed over the surface around the piston. The load application is initiated with the velocity of 1.27 mm/min, carrying out the readings, calculation of the pressures and graphic representation like the one carried out in the laboratorial test.

2.2. Correlation of results of the CPD with the CBR

The correlations between the DCP and CBR are obtained by the regression analysis of the results. According to Karunaprema & Edirisinghe (2002), these patterns show that there is an inverse relation between the DCP and the CBR for the tested soils. The data can be analysed by linear, log, exponential or bi-log (log x log). The mathematical pattern that better describes the relation CBR X DCP is the one of log x log, with the CBR being the dependent variable and the DCP the independent variable, as given by:

$$\log(CBR) = a + b.\log(DCP) \quad (2)$$

where CBR = California Support Index (% in percentage), DCP = Penetration Index of the DCP (mm/hit); and *a* and *b* = constants that can vary according to the author of the research.

Table 1 presents some equations of correlation between DCP and CBR.

3. Materials and Methods

3.1. Choice of the test locations

Several locations of different districts of Campina Grande were chosen and studied, located in the state of Paraíba, Brazil, encoded as shown in Table 2.

Table 1 - Correlation DCP X CBR.

Correlations DCP X CBR		
Author	Region of the studied soil	Equation of correlation
Trichês & Cardoso (1999)	Duplication of the BR-101/SC	log(CBR) = 2.710-1.250.log(CPD) log(CBR) = 2.181-1.030.log(CPD)
Lima (2000)	Maringá/PR, Taubaté/SP, Palmas/To & São Carlos/SP	log(CBR) = 2.809-1.288.log(CPD)
	Estado do Paraná	log(CBR) = 2.647-1.300.log(CPD)
Silva Junior (2005)	Airport of Parnaiba/PI - BR	log(CBR) = 2.717-1.247.log(CPD)
Harison (1987)	Indonésia cohesive and graned	log(CBR) = 2.810-1.320.log(CPD) log(CBR) = 2.550-1.140.log(CPD)

Two inspection wells were dug in opposite sides to the axes of the streets, aiming this way, a more representative character to the procedure of data acquisition. The wells for physic and mechanic characteristics analysis of the subgrade soil were dug in a depth where it found the natural soil, therefore the depths of the inspection wells varied.

All tests *in situ* were carried out in the month of July of 2009. July is in the rainy period to this region, becoming the best period for the study of the behavior of the soils of the subgrade because it is more unfavorable for the pavement.

3.2. Procedures

The sequence of the works carried out during the experimental phase is illustrated in Fig. 2.

The tests carried out in laboratory and *in situ*, and its respective Standards (Table 3).

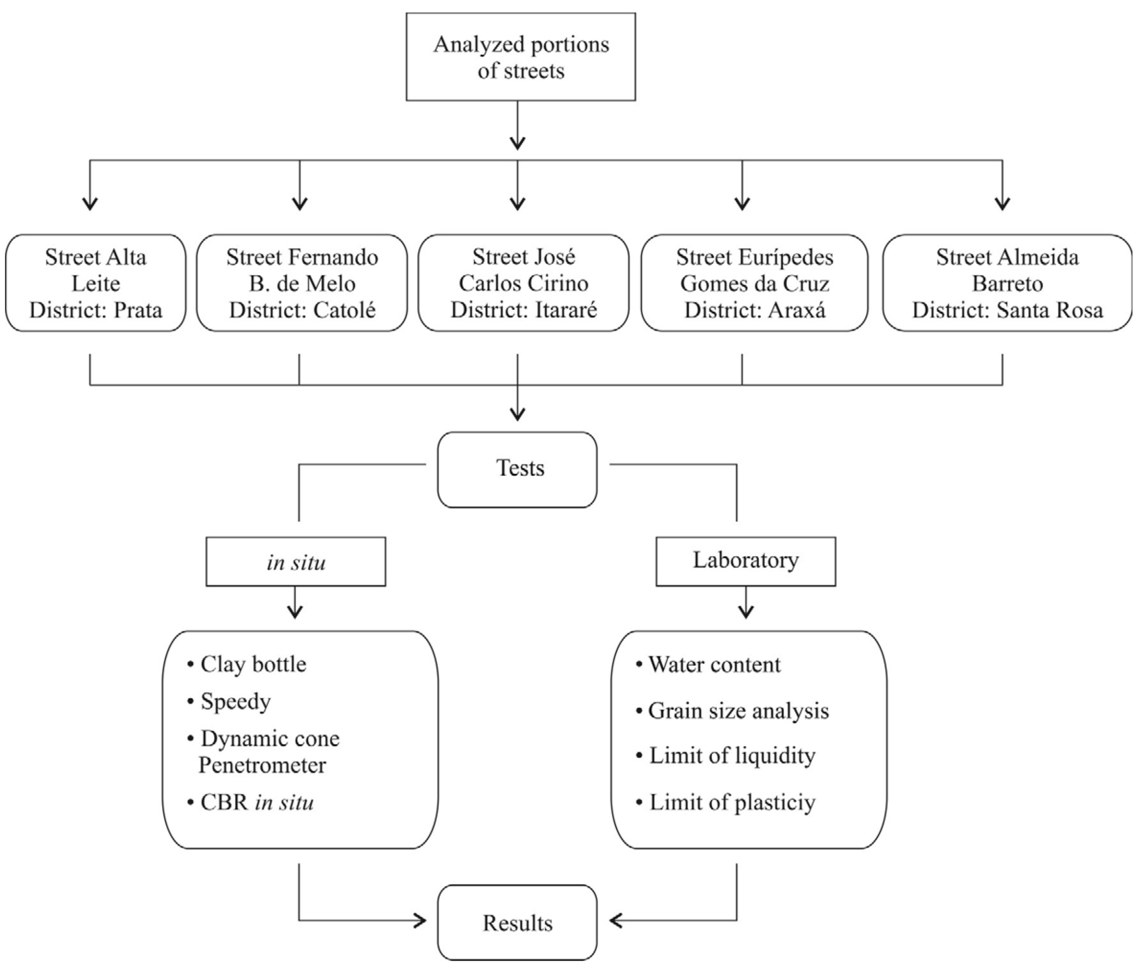

Figure 2 - Sequence of activities carried out during the experimental phase of the work.

Table 2 - Name of the streets and localization.

Inspection well	Street Name	District
AL- 01	Alta Leite - PI-01	Prata
AL- 02	Alta Leite - PI-02	Prata
FBM - 01	Fernando Barbosa de Melo - PI-01	Catolé
FBM - 02	Fernando Barbosa de Melo - PI-02	Catolé
JCC	José Carlos Cirino	Itararé
EGC - 01	Eurípedes Gomes da Cruz - PI-01	Araxá
EGC - 02	Eurípedes Gomes da Cruz - PI-02	Araxá
AB - 01	Almeida Barreto - PI-01	Santa Rosa
AB - 02	Almeida Barreto - PI-02	Santa Rosa

The tests carried out *in situ* and its respective Standards are shown in Tables 3 and 4.

4. Presentation and Results Analysis

4.1. Tests in laboratory

The classification and characterization tests of the collected samples were carried out for each inspection well.

The classifications of the samples obtained from the subgrade soils were made according to the methods HBR (Highway Research Board) and USCS (Unified System of Classification of Soil) since these systems are more commonly used. The results are found in Table 5.

The results of the carried out test indicates that the soils of the subgrade are predominantly a silty clay classified as A-2-4 and SM. The soil of the inspection well FBM-01 fits as A-6 and CL, which characterizes sandy soils, the soil of the well FBM-02 is A-4 and SC therefore a sandy clay and the well EGC-02 characterizes as A-1-b and SW that means gravel soil or well stuck clay.

Therefore, it is important to mention that the majority of the analysed soils are classified as of good quality to be used as subgrade in the pavement of streets, due to its behavior and for the possibility of stabilization with ligands.

4.2. Dynamic cone penetrometer

For each inspection well four penetrations were carried out with the DCP aiming to obtain a average index for each one of these wells. In the execution of the test it was considered the first hit of the hammer.

Table 3 - Laboratory tests.

Test	Standard
Preparation of the samples	NBR-6457 (ABNT, 1996)
Water content	ME-213 (DNER, 1994)
Grain size analysis	ME-080 (DNER, 1994)
Limit of liquidity	ME-122 (DNER, 1994)
Limit of plasticity	ME-082 (DNER, 1994)

Table 4 - *In situ* tests.

Test	Standard
Clay Bottle	ME-092 (DNER, 1994)
Speedy	ME-052 (DNER, 1994)
DCP	ASTM D 6951-03
CBR *in situ*	ME-47 (City Hall of Sao Paulo, 1999)

Table 6 presents the results of the average penetration index obtained from the tests of the Dynamic Cone Penetrometer (DCP).

The results of the penetration indexes indicate a higher resistance to the penetration of the tested soils in the FBM-02 and AB-01, which are classified as sandy clay and silty clay.

4.3. CBR *in situ*

The tests of CBR *in situ* were carried out in inspection wells until it reached the depth necessary to find the natural soil. The results are presented in Table 7.

It is possible to note that the higher values of CBR were obtained in the inspection wells EGC - 02 and AB - 01 which have soils SW and SM.

4.4. Analysis of the results: CPD *vs.* CBR *in situ*

The results of the Penetration Index (DN) obtained with the Dynamic Cone Penetrometer were correlated with the values of the CBR *in situ* for each inspection well. Table 8 presents the values of DCP and the respective CBRs *in situ*.

The CBR in situ values are outlier because the locations, type of soils and confinement conditions are different.

Table 5 - Results of soil classification.

Classification method	Inspection wells								
	AL-01	AL-02	FBM-01	FBM-02	JCC-01	EGC-01	EGC-02	AB-01	AB-02
HRB	A-2-4	A-2-4	A-6	A-4	A-2-4	A-2-4	A-1-b	A-2-4	A-2-4
SUCS	SM	SM	CL	SC	SM	SM	SW	SM	SM

Table 6 - Results of the tests of the Dynamic Cone de Penetrometer.

	Penetration index - DN - (mm/hit)								
Inspection well	AL- 01	AL- 02	FBM - 01	FBM - 02	JCC	EGC - 01	EGC - 02	AB-01	AB - 02
DCP	18.40	15.00	6.40	18.60	17.30	11.70	12.50	9.50	13.50

Table 7 - Results of the test of CBR *in situ*.

	CBR *in situ*								
Inspection well	AL- 01	AL- 02	FBM - 01	FBM - 02	JCC	EGC - 01	EGC - 02	AB - 01	AB - 02
CBR (%)	24.83	38.9	16.58	14.62	24.27	38.14	53.27	59.1	40.71

Table 8 - Results of the CPD to the respective CBR *in situ*.

Inspection well	DN (mm/hit)	CBR *in situ* (%)
AL- 1	18.40	24.83
AL- 2	15.00	38.90
FBM - 1	6.40	16.58
FBM - 2	18.60	14.62
EGC - 1	11.70	38.14
EGC - 2	12.50	53.27
AB - 1	9.50	59.10
AB - 2	13.50	40.71
JCC	17.30	24.27

As shown in Table 5, the found soils were in its majority, A-2-4 kind, because it is a silty clay. Therefore, the results of the DCP and CBR *in situ* were correlated to the soils A-2-4 kind.

Figure 3 shows the correlation graphic of the DCP x CBR *in situ* to the materials classified according to the HRB as A-2-4 that are silty clays.

The regression equation correlating the CBR *in situ* and DCP indexes, relating the curve of the graphic, from the adopted model will be (Eq. 3):

$$\log(\text{CBR}) = 2.98 - 1.257.\log(\text{DCP})$$

or

$$\text{CBR} = 950.55.\text{CPD}^{-1,257} \quad (3)$$

Table 9 presents, in a detailed form, the results of the CBR obtained by means of the equations determined by the correlations in function of the penetration indexes of the DCP to the soils A-2-4.

Analysing the values of the calculated CBRs by the proposed equation the values are quite closer to the ones found in field, except by the wells FBM - 01, FBM - 02 and EGC - 02 where it is found soils silty and gravel types.

It is also observed, that the founded equation is equivalent to the known values in the bibliography, presented in Table 1.

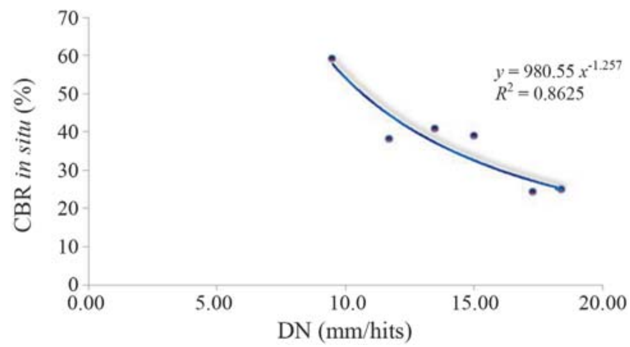

Figure 3 - Correlation between DCP x CBR *in situ*.

4.5. Proposed urban pavements design method

The method suggests the design of urban pavements based in the following characteristics:

- with two tracks of traffic variation: very light and light traffic;
- in the structural characteristics of the subgrade, obtained in the field, in case of this research the acquired results with the test of the DCP, expressed in penetration index (mm/hit);
- in the thicknesses recommended by U.S. Corps of Engineers for urban pavements with low volume traffic;
- and in designed cross sections of urban pavements types suggested by the City Hall of São Paulo (PMSP), what allows a quick convergence to a determinate kind of pavement.

The presentation of the design method proposed obeys to the following sequence: subgrade, traffic and the layers of the pavement.

4.5.1. Subgrade

The subgrade soil will be presented by its capacity of support that is given from the results of the test with DCP considering, to the calculation of the penetration index with the first hit of the hammer.

This procedure is not applied to the calculation of the total thickness of the pavement in case of subgrades with

Table 9 - Values of CBR, obtained from the equation of correlation to the soils A-2-4, in function of the penetration indexes obtained with the CPD.

Well	DN (mm/hit) cons. o 1° hit	CBR (%)
AL- 01	18.40	24.44
AL- 02	15.00	32.69
FBM - 01	6.40	92.17
FBM - 02	18.60	24.11
EGC -01	11.70	43.19
EGC - 02	12.50	39.73
AB - 01	9.50	56.10
AB - 02	13.50	36.06
JCC	17.30	26.41

penetration indexes superior to 134.75 mm/hit, because, with these results it is obtained subgrades with low capacity of support (CBR ≤ 2%). In this case the subgrade soil must be substituted by soil with CBR ≥ 5% and expansion ≤ 2%.

4.5.2. Traffic

The traffic in the urban-road design was classified in two kinds to essentially residential streets:

- Very Light Traffic - essentially residential streets, with no forecast of bus traffic, and can occasionally exist, passages of trucks in a number not superior to three (03) per day, per traffic lane, characterized by a typical number N of 10000 (10^4) requests of the pattern simple axis to the life time of 10 years (Senço, 1997).
- Light Traffic - streets of essentially residential characteristics, forecasting the bus traffic, and can occasionally exist, passages of trucks or buses in number not superior to fifty per day, per traffic lane, characterized by a number N - operations equivalence, typical of 100000 (10^5) requests of the pattern simple axis (8.2 ton), to the life time of 10 years (Senço, 1997).

4.5.3. Pavements layers

The pavements layers are considered in function of the structural equivalence coefficient, which is a number that relates the thickness of the layer, constituted of pattern material, with the equivalent thickness of the material that will effectively compose this layer.

According to Senço (1997), the pavement layers have an effective thickness (ER) equal to the sum of the layer thicknesses and an equivalent thickness (Eq), calculated by the sum of the product of the effective thicknesses of the layers by the respective structural equivalence coefficients of the materials that compose them.

The proposed coefficients of structural equivalence (*k*) are based and exposed by the method of the DNIT (former DNER) and by the design method of the City Hall of São Paulo (PMSP). The values are presented in Table 10. It is recommended to adopt $k = 1$ to the sub-base or reinforcement of the subgrade, when necessary.

4.5.4. Pavements thicknes design

The value of the CBR is obtained from Eq. 3 of the correlation with the DCP.

$$\log(\text{CBR}) = 2.98 - 1.257\log(\text{DCP}) \rightarrow \text{DCP} = \left(\frac{\text{CBR}}{950.55}\right)^{-1/1.257} \quad (3)$$

With the established correlation, it is predicted the value of the DN correspondent to each CBR and then it is obtained the thicknesses to each penetration index.

The total thicknesses of the pavement to this method were obtained based in the abacus of the U.S. Corps of Engineers. By means of the proposed equation (Eq. 3), it is found the penetration index (mm/hit) of the DCP, in function to the values of CBR (%) and the values of the thicknesses to each traffic presented in Table 11 or in the abacus of Fig. 3.

With the total thickness necessary for the pavement (ETOTAL), according to the traffic (T), the option was made for one of the design alternatives, where it is obtained the thickness of the covering + base thickness (ERB or Eq). The thickness of the sub-base corresponds to the difference between the total thickness and the equivalent thickness (ESUB = ETOTAL - Eq). The equivalent thickness is the sum of the layers thicknesses multiplied by the

Table 10 - Structural equivalence coefficient (*k*) to various materials (Source: Silva Júnior, 2005).

Type of material	Symbol	Coefficient - *k*
Revestment of the asphaltic concrete	CA	2.0
Revestment of the thin concrete	CM	2.0
“Binder” or Pre-mixtured by heat	BI	1.8
Base of soil-cement	SC	1.7
Base or revestment pre-mixtured by cold, of dense graduation	PMF	1.4
Asphaltic revestment of penetration	PI	1.2
Articulate Pavement of concrete	PA	1.2
Base of bituminous macadame	MB	1.2
Granular Base	BG	1.0
Base of hydraulic macadame	MH	1.0
Revestment cobblestone type in pavement stone	P	1.0
Selected Running Gravel	BCS	0.9
Clay	A	1.0

Obs: Old pavements of pavement stone, when recovered with bitumen mixtures, the value of k can vary from 1.2 to 1.8 in function of the behavior, bulging and sealing of the pavement stones.

Table 11 - Total thicknesses of the pavement in function of the values of CBR, obtained based in the abacus of U.S. Corps of Engineers.

CBR (%)	DN (mm/ hit)	Total thickness of pavement (cm)	
		Traffic	
		Very light	Light
2	134.78	60	70
3	97.62	46	57
4	77.65	39	48
5	65.02	34	42
6	56.24	30	37
7	49.75	27	33
8	44.74	24	30
9	40.74	22	27
10	37.46	20	25
12	32.40	17	22
15	27.13	15	18
17	24.56	13	16
20	21.58	11	14
25	18.07	9	12
30	15.63	8	10
Comercials vehicles by day in a direction			
	Máx. 3	Máx. 50	

respective structural equivalence coefficients of the same type project.

It is important to mention that for the proposed abacus that all the materials of layers of the pavement have structural equivalence coefficient equal to one ($k = 1$).

Figure 4 presents the abacus for the design of the total thickness of the pavement.

With the value of the penetration index (axis X) obtained with the Dynamic Cone Penetrometer and in function of the kind of traffic (Very Light or Light), one finds the total thickness of the pavement in cm (axis Y).

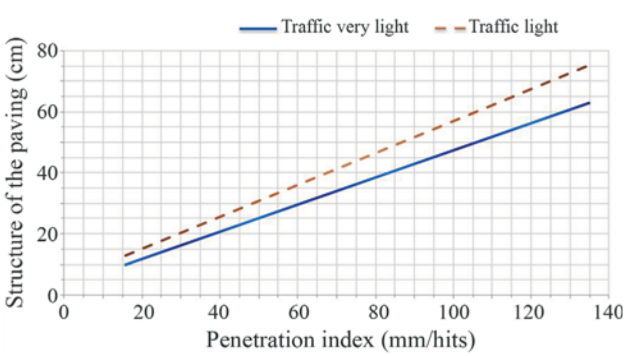

Figure 4 - Abacus of design of the total thickness of the structure of the pavement in function of the penetration index of the DCP, and of the traffic (T), to the proposed method Very Light Traffic.

By this proposed design method for urban pavements it becomes possible from the Dynamic Cone Penetrometer, as a tool to evaluate the support capacity of subgrade soils, to design streets pavements of low volume traffic.

5. Conclusions

The DCP, unlike the CBR *in situ*, is a practical test, quick and more economical due to its easy execution and semi-destructive nature, with no great movement of soil.

When the tests of DCP and CBR *in situ* correlate each other to all kind of soils found in the inspection wells, there is no practical correlation between them. This is due to the fact that the conditions found in field, to each kind of soil, are diverse enough because they present countless variables (variation of the water content, density, grain size, kind of soil, confinement state, etc.).

The correlations found in this work serve only to the penetration indexes obtained with the DCP and the values of CBR *in situ* to the soils A-2-4 and SM. Therefore, these correlations do not necessarily serve to other kind of soils.

The creation of an abacus in the urban pavement design method aims to simplify the design practice, leaving little margin to the variant studies, converging quickly to a project-type economically recommended.

The result of the proposed method suggests smaller thicknesses to the pavement when compared to the ones obtained by the DNIT method. This results in lower costs when talking about the execution.

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