PRACTICAL CONSIDERATIONS FOR CONCRETE PAVEMENT DESIGN BASED ON NUMERICAL MODEL

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1. INTRODUCTION

During the design process of concrete pavements, designers may confront with several doubts concerning materials properties and the relative significance of parameters which takes part of the design, and generally the problems are related to the definition of the modulus of reaction of the subgrade or of the base, slab/base interface problems due to shear stresses, variability of subgrade and base mechanical properties, fatigue of cemented bases, and others.

It must be clear, first of all that, as a matter of fact, the traditional criteria for the design of road concrete pavements does not take into account some factors that can induce, at least on a medium-term analysis, the rupture of cemented bases due to fatigue and its implications for the future concrete slabs.

In order to clarify such aspects in this paper several cases of concrete pavements, designed according to the PCA (1966) criteria, have been evaluated under the point of view of flexural stresses using the Finite Element Method (FEM). The flexural tensile stresses of concrete slabs and cemented sub-bases have been computed when loaded by dual-wheel single axles. The effects of the modulus of subgrade reaction, slabs and sub-bases thickness and the modulus of elasticity of sub-bases have been considered. The great structural contribuition of cemented bases been focused, to point out the necessity of considering the fatigue criteria for these kinds of bases.

The potentiality of the Finite Element Method (FEM) as a tool for the structural analysis of slabs on grade, and its accuracy, is a subject very well reported by several authors in the late thirty years. Currently, the main idea of developing a numerical model was to get a simplified tool able to analyse non-dowelled concrete slabs, but with sufficient resources to verify the effective structural contribution of cemented sub-base layers.

The model development was a short step to understand the tensional behaviour of concrete pavements, and the more significative implications for its design are discussed bellow. The received results from the analysis can aid engineers and designers to decide when it is necessary to up-grade the traditional design criteria by means of numerical models.

2. DEVELOPMENT OF THE NUMERICAL TOOL FOR CONCRETE SLABS

For the development of the numerical model some basic concepts were fixed, on the basis of the classical theory for isotropic plates in plane-stress state ($\varepsilon_z = 0$). So, the slab is considered as made from a homogeneous and isotropic material and the linear elasticity is assumed, in order to make it possible to apply the generalized Hooke’s law to the slab.
The current version of the model uses a two-crossed beams finite element for the simulation of the elementary slabs, and permits the analysis of concrete pavements with maximum three layers. Non-

treated sub-bases and subgrades are considered following the Winkler hypothesis. When necessary, the cement-treated bases are assumed as finite dimension structural elements exactly equal to the slab elements, and also as an homogeneous and isotropic media. The subgrade is for any case assumed like a Winkler fondation.

Shear stresses are not admitted in the interface slab/sub-base. Physical and geometric linearity is applied for all the structural elements. Considering both the slab geometry and the configuration and relative position of the load axle, it comes possible to discretize of the slab in a x-y linear mesh.

The shape function for the elements, the interpolation function for displacements and the stiffness matrix adopted by the numerical model was studied by Gallagher (1975), and the slab element is assumed like a two-crossed beams. Discussions about the convergence and the accuracy of this kind of element for the solution of the Lagrange differential equation governing the slab displacements can be found in Walz et al. (1968).

The displacements interpolation function is given by the expression:

$$W = [N] \cdot \{\Delta\} = [\, [N_{\omega}]\ [N_{\theta x}]\ [N_{\theta y}]\,] \cdot \begin{matrix} \{\omega\} \\ \{\theta_x\} \\ \{\theta_y\} \end{matrix}$$

where [N] is defined as the displacement field and {Δ} is defined as de displacement vector related to the freedom degresses of the slab element. In each node of the elements three displacements must be considered: the vertical displacement ω, and the rotational displacements θ_x and θ_y.

The interpolation function for the displacement field is based on a tweve terms polinomy and it is given by the following expressions:

$$N_{\omega} = [\, [N_1(x)\ N_1(y)]\ [N_2(x)\ N_1(y)]\ [N_2(x)\ N_2(y)]\ [N_1(x)\ N_2(y)]\,]$$

$$N_{\theta x} = [\, [(1-\xi)\ N_3(y)]\ [\xi\ N_3(y)]\ [-\xi\ N_4(y)]\ [-(1-\xi)\ N_4(y)]$$

$$N_{\theta y} = [\, [-(1-\eta)\ N_3(x)]\ [(1-\eta)\ N_4(x)]\ [\eta\ N_4(x)]\ [-\eta\ N_3(x)]$$

where

$$N_1(x) = (1+2\xi^3-3\xi^2)$$

$$N_2(x) = (3\xi^2-2\xi^3)$$

$$N_3(x) = -\ x\ (\xi-1)^2$$

$$N_4(x) = -\ x\ (\xi^2-\xi)$$

$$N_1(y) = (1+2\eta^3-3\eta^2)$$

$$N_2(y) = (3\eta^2-2\eta^3)$$

$N_3(y) = - y (\eta-1)^2$

$N_4(y) = - y (\eta^2-\eta)$

The simbols ξ and η represents the ratio between the position of a reference point assumed on the surface of one element and its side length, given by:

$\xi = x / x'$

$\eta = y / y'$

So, x' and y'are the side lengths related to the orientation axles of the slab, x and y, respectively. For all the presented analysis along this paper, the parameters are related to the center of the slab elements, resulting in $\xi = 0.5$ and $\eta = 0.5$ for all the cases.

The nodal loads are assumed on vertical direction; the general stiffness matrix for the system is then computed, generating the following system of linear equations:

$$[P] = \{ KG \} . [\Delta]$$

where [P] is the load vector (active forces minus reactive forces, let's say, reaction of the fondation system), { KG } is the global stiffness matrix and [Δ] is the displacement vector for the nodal points. The Cholesky method has been used to solve the system of linear equations. The element stiffness matrix is detailed in Gallagher (1975).

The general displacement function is defined by the development of the above given equations for the displacement field by substituition of all the given terms. After the determination of the displacement vector for all the nodes of the slab retangular mesh, it becomes possible to define the seconds derivates of the displacement field function for each element, according to the following equations:

$$\partial^2W / \partial x^2 = - (\theta_{y1}+\theta_{y2}+\theta_{y3}+\theta_{y4}) / (2.x')$$

$$\partial^2W / \partial y^2 = - (\theta_{x1}+\theta_{x2}+\theta_{x3}+\theta_{x4}) / (2.y')$$

$$\partial^2W / \partial x\, \partial y = 9 .(\omega_1-\omega_2 +\omega_3-\omega_4) / (4.x'y') + (\theta_{x1}-\theta_{x2}+\theta_{x3}-\theta_{x4}) / (4.x') + (\theta_{y1}-\theta_{y2}+\theta_{y3}-\theta_{y4}) / (4.y')$$

The tensile and shear stresses associated to the fexural and torcional moments in the x and y directions of each element is then achieved by applying the generalized Hooke's law to the slab elements, as follows:

$$\sigma_x = E . z . [(\partial^2W / \partial x^2)+\nu.(\partial^2W / \partial y^2)] / (1-\nu^2)$$
$$\sigma_y = E . z . [(\partial^2W / \partial y^2)+\nu.(\partial^2W / \partial x^2)] / (1-\nu^2)$$

$$\tau_{xy} = E . z . (\partial^2W / \partial x . \partial y) / (1-\nu)$$

where E is the deformability modulus of the slab, ν is the coefficient of Poisson of its material and z is the deep of the desidered point of analysis. To reach quickness on the process, the numerical model was developed using the FORTRAN 77 language and inserted on the CONVEX UNIX Primer main-frame.

3. DESIGN OF PAVEMENT THICKNESS AND NUMERICAL EVALUATION

The thicknesses of concrete pavement layers for the general proposal of this work was carried out according to the PCA(1966) criteria, and an *unlimited number of repetitions* has been considered for all cases (ratio between the flexural stress and the modulus of rupture of the concrete is 0.5). The choose of this procedure for the design is due to two main motivations. Firstly, the procedure implicitly considers the Westergaard solution for the calculation of stresses of slabs supported by a Winkler fondation; then, it become possible to compare the design stresses with the values received from the numerical model. By another hand, the PCA procedure has been used for several cases of design along the late third years.

The configuration of the design axle adopted for the design of the pavement structures is presented on Fig.1. The dimensions of the concrete slabs were fixed on 5.0 x 3.6 m, and the same dimensions were imposed to the cemented base when it became necessary. The modulus of elasticity and the Poisson's ratio of the concrete were assumed, respectively, 28,000 MPa and 0.2; for the cement-treated bases, values of 7,000 MPa and 0.25 were adopted for the same parameters. The value for the modulus of rupture of the concrete was 4.41 MPa (28 days).

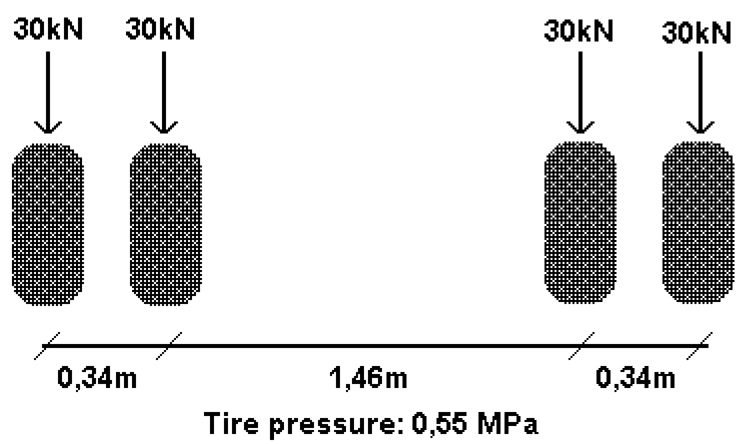

Fig. 1 Configuration of the dual-wheel single axle

STRESSES FOR SLABS-ON-GRADE

On Table 1 are presented three design cases for slabs supported exclusively by the subgrade. For this situation three different conditions of subgrade bearing capacity were considered, from lower to high capacity, by taking the California Bearing Ratio (CBR) as input for the design. The respectives values for the modulus of subgrade reaction (k-value) were found through the PCA correlation.

Table 1 Design cases for slabs-on-grade

Design	CBR (%)	k (Mpa/m)	t_{slab} (cm)
A	3	27.5	21.0
B	10	53.0	18.9
C	17	64.7	18.5

From Table 1 is possible infer that a variation of about 12% on the slab thickness is received if it is supported by a subgrade with good bearing capacity in comparison with the worst case. Anyway it must be clear that, for each case, the design stress is equivalent to 2,205, according to the design criteria for an unlimited number of load repetitions of the above axle.

Taking the referred slabs dimensions and the axle configuration, after the discretization of the slabs in a retangular mesh of finite elements, taking the loads position closed to the transversal joint of the slab, it was possible to apply the numerical model to verify the maximal stresses conditions on the concrete. The results of such simulations are presented on Table 2.

Table 2 Stresses on the concrete associated to design cases of table 1

Design	k (Mpa/m)	t_{slab} (cm)	σ_x (MPa)	σ_y (MPa)	τ_{xy} (MPa)	σ_{max} (MPa)
A	27.5	21.0	0.78	0.15	0.88	1.51
B	53.0	18.9	0.97	0.18	1.09	1.87
C	64.7	18.5	1.01	0.19	1.13	1.95

From the last colum on Table 2 is verified that in no one case a flexural stress greater than the design stress has occurred. Then, the hypothesis of a unlimited number of load repetitions is preserved, specially for the case A with a slab thickness greater than 20 cm. This results agree very weel with those obtained by Huang & Wang (1973). These authors using a FEM analysis for a 4.57 m per 3.66 m surface, 17.8 thicker, supported by a subgrade with a k-value of 27.7 Mpa/m and loaded by a single axle of 80 kN, and considering a concrete with deformability modulus of 28,123 Mpa and coefficient of Poisson of 0.15, received a maximal flexural stress of 1.55 Mpa against 2.00 Mpa forecasted by the influence charts. At first glance it could be said that the PCA criteria, based on the influence charts for the Westergaard solution, results in conservative thicknesses for the slabs.

Although, this statement could not be done here due to the fact that stresses are results not only from loads action but also from termal gradients between surface and bottom of the concrete and from loss of subgrade support. May be, considering all these extreme factors, the slab thickness as a result of the PCA criteria for design could be adequate. By another hand, from the point of view of stresses due to loads, the present results agree with older one's using the FEM, receiving lower flexural stresses.

k-VALUE CONSIDERATION

The following step is to verify for fair subgrade support condition the consequences of variations on its k-value. The simulations concerning these possibilities are presented on Table 3. As can be observed from the bellow results, the k-value seems to be of less significance for the flexural stresses than the behaviour of a high stiff concrete slab itself. This remark has been done by Yoder & Witczak (1975) for concrete roads with typpical trucks loads when they stated that "the thickness of highway concrete pavements is relatively insensitive to this modulus and the use of average values appears warranted".

Table 3 Sensitivity analysis of the k-value

t_{slab} (cm)	k (Mpa/m)	σ_x (MPa)	σ_y (MPa)	τ_{xy} (MPa)	σ_{max} (MPa)
18.5	27.5	1.01	0.19	1.13	1.95
18.5	64.7	1.01	0.19	1.13	1.95
18.5	98.1	1.01	0.19	1.14	1.96

Another remark to be taken into account was done by Huang & Wang (1973) pointing out that "under a given load the subgrade k-value should increase with the increase in slab thickness", due to the fact that the lower is the vertical pressure over the subgrade the more stiffer the subgrade, considering its non-linear behaviour. Last, one of the results from the *3rd Workshop on Theoretical Design and Evaluation of Concrete Pavements*, held at Krumbach in 1994, pointed out the difficulties to model the supporting capacity of the fondations for concrete pavements by means of one single k-value, despite the fact that now-a-days numerical models better than the "old good Westergaard solutions" are on disposal for designers.

In anycase, it seems to be possible to state that for aircrafts pavements the k-value is much more important than for the highway case, considering the pavements thicknesses and the non-linear behaviour of the soils. It is also of paramount importance to remind that in the highway case important variantions of the subgrade support are find along the geometric alignment, justifying in this way to consider an average value the k-value. It must be remarked that during these discussions we are dealing with fair soils, excluded atyppical situations like soft clays, very expansive soils, etc.

EFFECTS OF SLAB THICKNESS, SLAB LENGTH AND LOADS POSITION

From the above discussion, the influence of the slab thickness on the flexural stresses can be described taking the intermediate support contidion of the subgrade of 64,7 Mpa/m. The flexural stresses as a function of the slab thichnesses are grafically presented on Fig. 2 as a result from several simulations of the numerical model, from which is concluded that the slab thickness influences strongly the flexural stress, and consequently, the allowed number of load repetitions to fatigue of the concrete.

The results presented on Fig. 2 show that in order to warranty an unlimited number of repetitions of the design load the slab must be at least 17,5 cm thicker. Slabs of 12,5 cm thicker are subjected to rupture by the first loading action of the considered axle. As a matter of fact the use of thinner slabs by trucks could be possible only increasing the concrete strength. In any case these results are closed with the actual practice of concrete slabs thicker 18 cm at least for roads.

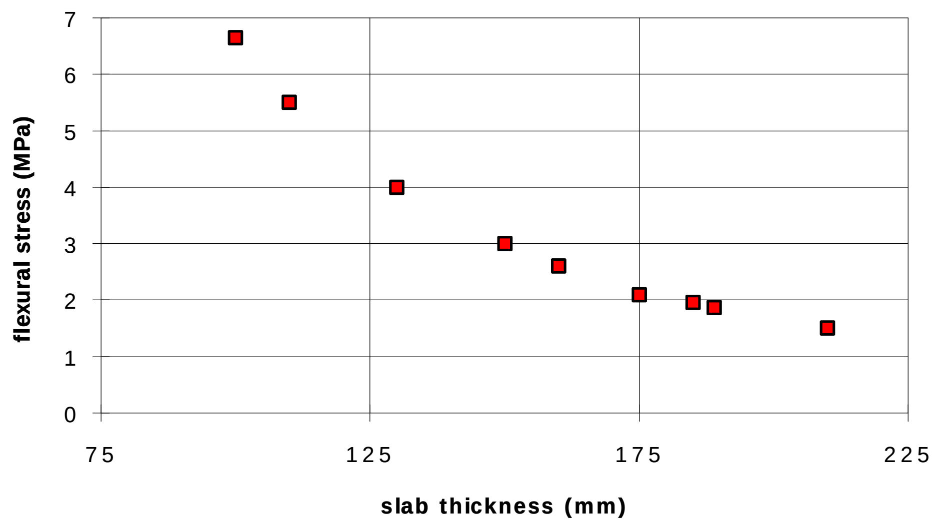

Fig. 2 Flexural stresses as a fuction of slab thickness

On Figure 3 is presented the changes on the slab flexural stress as a function of the slab length. For this simulations the case C from the table 1 has been taken and the length of the slab was changed on the range from 3.5 m to 7 m. The load position had still near the transversal joint.

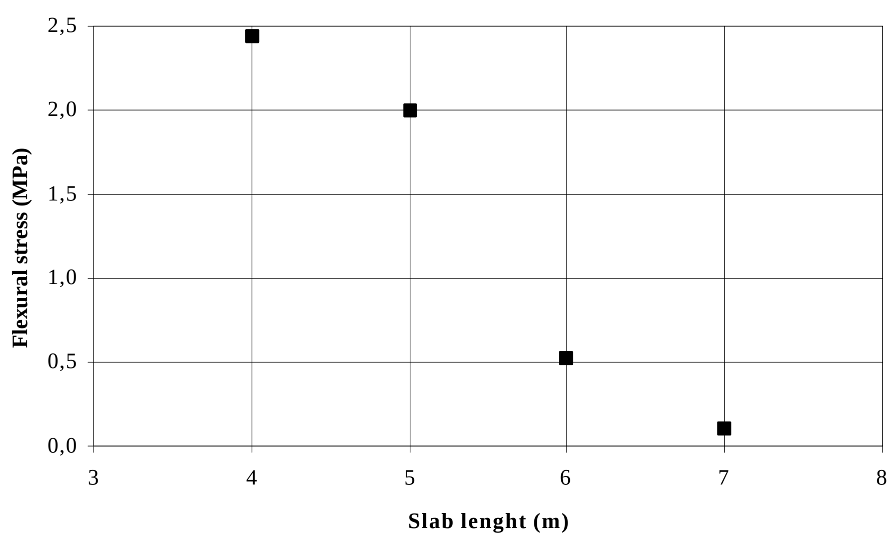

Fig. 3 Flexural stresses as a fuction of slab length

The PCA criteria takes as a criticals positions of loads for the design those near the transversal joints. Taking again the case C from Table 1 and posicioning the axle at the center, near the corner and centered near the tranversal joint of the slab, it was found the results presented on Table 4.

From these results is observed that the critical location would be near the transversal joints, as assumed on the PCA'66 criteria of design. This condition is also remarked by Ramsamooj (1994) for slabs thinner than 200 mm. Moreover, Huang & Wang (1973) had remarked that for non-dowelled slabs the critical flexural stress take place nearest the transversal joint, on the contrary for the case of dowelled slabs, when the critical flexural stress occurs more near to the center of the slab. Based on these considerations, the position assumed for the dual-wheel single axle was always near the transversal joint for the presented analysis on this paper.

Table 4 Influence of load position on flexural stresses

Position	σ_x (MPa)	σ_y (MPa)	τ_{xy} (MPa)	σ_{max} (MPa)
Center	0.70	0.14	0.98	1.11
Corner	0.55	0.12	1.12	1.45
Joint	1.01	0.19	1.13	1.95

THE CEMENT-BOUND BASE CASES

During one of the sessions on the *3rd Workshop on Theoretical Design and Evaluation of Concrete Pavements* (already mentioned) it was stressed that "specially in the case of bound base layers, these layers should be treated as individual layers represented by their specific modulus and strength values".

By an intuitive way engineers ask themselves what kind of rule a cemented paving material takes place when used as a base for concrete pavements. The difficulty of rationally solving this question consists many times on the fact that the design criteria does not takes into account this rule, or indicates only that this base shall improve the support capacity of the fondation for the slab, presenting how to consider it during the design through a modified k-value.

To gain a shortcoming in this knowledge, let us take another time the PCA criteria for the design of concrete pavements with cemented bases on its structure. On Table 5 are presentede nine design cases for three bases thicknesses taken *a priori*, and for the further subgrade conditions analysed on Table 1.

Table 5 Design cases with cemented crushed stone bases

Design	CBR (%)	k (Mpa/m)	t_{base} (cm)	t_{slab} (cm)
A.1	3	27.5	10	18.9
A.2	3	27.5	15	17.8
A.3	3	27.5	20	17.1
B.1	10	53.0	10	17.5
B.2	10	53.0	15	16.6
B.3	10	53.0	20	15.9
C.1	17	64.7	10	17.0
C.2	17	64.7	15	16.3
C.3	17	64.7	20	15.9

Regarding to Table 5, the first remark that must be done refers to the necessity of analysing the cost-effectiveness of one alternative for paving. For instance, it must be considered the final costs related to choose between alternative A.1 and A.3; if the alternatives are rationaly justified, what to prefer: a reduction of 2.1 cm on the concrete thickness consuption adopting a cemented base of 10 cm or a reduction of 3.9 cm on the concrete thickness with the increase of more 10 cm of base? It must be a decision balanced on materials and construction costs, among others.

On the technical point of view it must be reminded that there are limitations on the concrete thickness reduction taking the design procedure itself. As can be inferred from Fig. 4 the thickness reduction of the slab for bases thicknesses from 15 cm to 20 cm has no significance in practical terms. It must be clear also that thicknesses bellow 15 cm are not common for cemented bases, bringing more support to the last statement.

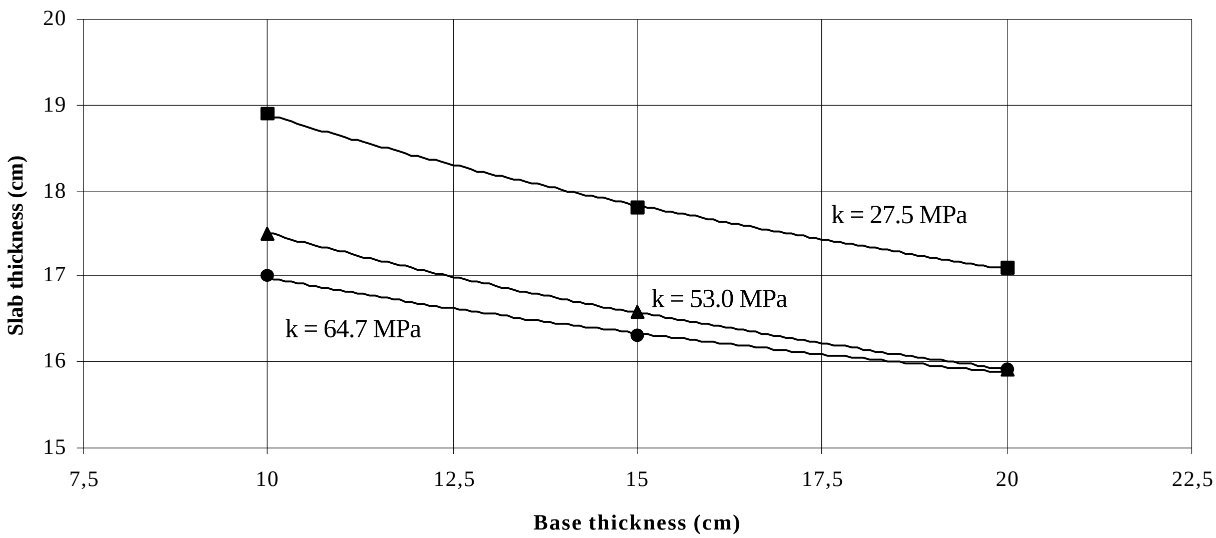

Fig. 5 Influence of base thickness on the slab thickness

Looking for a more accurate analysis of the pavements presented on Table 5, the numerical model was applied to some of those cases in order to define critical stresses on both slabs and cemented bases. The received results are presented on Table 6.

Table 6 Stresses on cemented bases and slabs presented on table 5

Design	**t_{base} (cm)**	**t_{slab} (cm)**	**$\sigma_{max, base}$ (MPa)**	**$\sigma_{max, slab}$ (MPa)**
A.1	10	18.9	0.23	1.78
A.2	15	17.8	0.36	1.74
A.3	20	17.1	0.42	1.46
C.1	10	17.0	0.31	2.16
C.2	15	16.3	0.45	1.97
C.3	20	15.9	0.48	1.55

The stresses values for the slabs presented on table 6 are able to confirm again that the designed thicknesses of slabs allow an unlimited number of repetitions of the design axle (the ratio between stresses and modulus of rupture of the concrete is alaway lower than 0.5); so, the design hypotesis is preserved.

On comparing the case A.1 with the case B (on table 2) becomes clear that the cemented base works to the reduction of the stresses on the slabs, once the slabs thickness and other design conditions are the same. Although the reduction was in a little amount (about 5%), is interesting to verify that the base is subjected to flexural stresses, working like a slab.

Taking the cases A.3 and C.1 is verified that the more thicker the cemented base the higher are the stresses on this layer and the lower becomes the stresses on the concrete slab. To better clarify this point, other three hypotetical cases of concrete pavements with constant slab thickness and different bases thicknesses were numerically simulated, and the received results are presented on Table 7.

Table 7 Stresses on cemented bases and slabs (hypotetic cases)

Design	t_{base} (cm)	t_{slab} (cm)	$\sigma_{max, base}$ (MPa)	$\sigma_{max, slab}$ (MPa)
H.1	10	15	0.45	2.69
H.2	15	15	0.55	2.20
H.3	20	15	0.55	1.62

From the above results it can be said that the cement-treated materials present as a positive action a great capacity to absorb a part of the developed flexural stresses on the whole structure and consequently to decrease the corresponding stresses of the slab. In general, the level of stresses on the base is increased as its thickness is increased. By another hand, the results on Table 7 have pointed out that there will be a limitation for this capacity on absorbing stresses and the use of a cemented base layer thicker than 15 cm to 20 cm does not conduce to more significative increasing of stresses on it. Although, more thicker cemented bases still decreasing the stresses level on the slab.

Another actual situation can be studied with the help from the numerical model: the variability of the cemented base elastic behaviour along the construction. Such situation might be a consequence of low compactation of the material, localized excessive water content in the mixture, variations on the cement content, not well controled curing process, etc. These variabilities induce discontinuities on the mixture resulting in variability on strengths and elastic properties after curing, resulting on different behaviour of the structures when compared to the design hypotesis. For ilustration, on Table 8 are presented the resultant stresses for slabs and bases when the E-modulus of the cemented base ais subjected to changes.

Table 8 Stresses consequences due to changes on the base E-modulus

Design	t_{base} (cm)	t_{slab} (cm)	E-mod, $_{base}$ (MPa)	$\sigma_{max, base}$ (MPa)	$\sigma_{max, slab}$ (MPa)
C.3	20	15.9	7,000	0.48	1.55
C.3	20	15.9	5,000	0.39	1.76
C.3	20	15.9	3,000	0.27	2.03

From the above results it can be stated that the quality control exigence must be preserved all construction long because to lacks of quality of course influence the behaviour of the structure, which might not be able to receive the forecasted traffic and climate conditions.

In conclusion, the computation of stresses of cement-treated bases on concrete pavements is essential for a good design. This computation actually requires a numerical model as well as the knowledge of the elastic and strength properties of the choose material. But if we are dealing with a cemented material its fatigue behaviour is of paramount importance, in order to permit the prediction of its service life. To make it clear for the reader, let us present a fatigue analysis case related to some of the designs presented above, taking for instance a cement-treated crushed stone (CTCS) as a base material for the concrete pavements.

In literature the flexural strength of CTCS is given 1,1 MPa (for 4 % cement in weight) as can be found in Dac Chi (1977). Balbo (1993) has proposed the following fatigue model for this material:

$$\sigma_n / \sigma_o = 0.874 - 0.051 \log N$$

where σ_n is the maximum flexural stress verified on the layer, σ_o is the flexural strength of the material and N the number of load repetitions to fatigue. Taking some design cases already presented and applying the above fatigue model, it has been received the results presented on Table 9.

Table 9 Fatigue analysis for the cemented base and for the slab

Design	**t_{base} (cm)**	**t_{slab} (cm)**	**$\sigma_{max, base}$ (MPa)**	**$\sigma_{max, slab}$ (MPa)**	**N_{base}**	**N_{slab}**
C.1	10	17.0	0.31	2.16	4.1 E+11	unlimited
C.2	15	16.3	0.45	1.97	1.3 E+09	unlimited
C.3	20	15.9	0.48	1.55	3.8 E+08	unlimited

From Table 9 we can infer that, in principle, for the case C.1 the cemented base shall endure unlimited repetitions of the considered axle. Nevertheless, for the case C.3, we got a number of repetitions near 10^8, that could be considered to much restrictive, once this value is to much similar to short-term heavy traffic on high volume rural and urban roads.

The case C.3 draws a situation when in short-term the cement-treated base will be in a complete process of fatigue. Consequently, the sub-base in this condition, completely cracked, will not resist to flexural solicitations, working merely as a good quality granular material.

If the structure reach this non-desired situation, supposing all the others conditions keept on the predicted ones during the design, it is needed to compute the flexural stresses of the slab supported by both a granular base and the subgrade. For this new situation the maximum computed flexural stress of the slab is about 2,60 MPa.

Taking the fatigue model for the concrete proposed by Bradbury, the stress as a percentage of the ultimate flexural strength would be about 0.59, that makes the number of repetitions to failure to be less than 50,000 for the slab, a number in disagreement with the initial unlimited number of repetitions supposed on the design.

Considering the case study described, it can be confirmed the great relevance of studying the fatigue condition also for the cemented base, once the design criteria are not completely able to predict this kind of behaviour. Therefore, the use of numerical methods to compute the stresses on concrete pavements might be a powerful tool for the designers in many similar situations.

4. CONCLUSIONS

Numerical methods for the structural analysis of concrete pavements were widely developed in the last two decade. Its greater contribution was to permit a better theoretical cognizance on the behaviour of concrete pavements and consequently have permitted the study of several parameters concerning to the slabs, as geometric shape, load configuration and position, and the study of other elements as bases and subgrades.The main conclusions allowed from the carried studies can be summarized in the following statements:

- The main factors influencing the design of concrete pavements are the properties of the concrete, specially its flexural strength. Due to its nature, the concrete slab works spreading low pressures over the subgrade and on this way, the pavement deflection is resultant mainly from the slab deflection itself, actually, for fair subgrade conditions.

- The behaviour of the slabs makes the subgrade modulus of reaction to become of less significance for the flexural stresses on the concrete, considered the dual-wheel single axle adopted in this study. For highway pavements, variations on the k-value are not the main conditionant for the design, making it possible to work with an appropriate average value for this parameter.

- When a cemented base layer is desired as part of the concrete pavement, numerical simulations of the stress-strain state of the base layer are helpful to the prediction of fatigue of the material, in order to adjust thickness of the slab and the base itself, as a way to warrant endurance of unlimited repetitions of loads for both layers. So, the simple consideration of an incremented k-value due to the presence of a cemented base layer is not adequate in terms of performance prediction for the pavement.

- For the case of non-dowelled slabs for roads, the critical stresses on concrete takes place when the load is near the transversal joint.

- Slab lengths little than 4.5 m must be avoided due to the possible increment of stresses on the concrete for short lengths.

As it was demonstrated, the use of numerical methods for computing stresses on concrete pavements is not a overstatement; on the contrary, with the current dissemination of the computational *media*, they become more and more efficient tools for application in complexes problems like layered systems. If, by one hand the numerical methods are able to up-grade the traditional criteria, defining more precisely the stress state of pavement structures, on the other hand these improvements shall not be effective for the engineers if efforts to define the materials behaviour and the to warrant the quality control of highway construction will not be done.

REFERENCES

Balbo, J.T. (1993) **Study of the mechanical properties of the cement-treated crushed stone and its application on semi-rigid pavements.** PhD Dissertation (in Portuguese). Polytechnical School, University of São Paulo, São Paulo.

Dac Chi, N. (1977) **Nouvelles méthodes d'éssais en laboratoire des graves traitées aux liants hydrauliques.** Bulletin de Liaison des Laboratoires des Ponts et Chaussées, n.91, sept.-oct.,pp.73-80.

Gallagher, R.H. (1975) **Finite element analysis - fundamentals.** Englewood Cliffs, Prentice Hall.

Huang, Y.H.; Wang, S.T. (1973) **Finite element analysis of concrete slabs and its implications for rigid pavement design.** Highway Research Board, HRR 466, pp.55-69, Washington, D.C.

Portland Cement Association (1966) **Thickness design for concrete pavements**, HB-35, Chicago.

Ramsamooj, D.V. (1994) **Prediction of fatigue cracking of rigid pavements**. Paper presented at the 3rd International Workshop on the Design and the Evaluation of Concrete Pavements, CROW, Krumbach.

Yoder, E.J.; Witczak, M.W. (1975) **Principles of pavement design.** John Wiley and Sons, 2nd. edition, New York.

Walz, J.E. et al. (1968) **Accuracy and convergence of finite element approximations.** Proc. of 2nd. Conf. on Matrix Methods in Structural Mechanics, AFFDL TR 68-150, pp.995-1027.