STRESSES ANALYSIS OF CEMENTED BASES ON CONCRETE PAVEMENT

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SUMMARY

Traditional methods for road concrete pavements design do not take into account the structural contribuition of cemented bases and its fatigue consumption under the traffic loads. Sections designed without major care about the structural reponses of those bases can develop early cracks, decreasing the structural capacity of the pavement. This paper presents a closed numerical solution for computing the maximum flexural stress on cemented bases when the concrete slab is loaded by a dual tire single axle of 100 kN; wheel loads had been considered near the transversal joint for plain concrete pavements. No bond and full contact between slab and base are supposed. On the basis of experimental relation for fatigue of a typpical cement treated crushed stone it was allowed to define consistent thicknesses for bases as function of the forecasted number of load repetitions.

RESUMO

Métodos tradicionais de projeto de pavimentos rodoviários de concreto não levam em consideração a capacidade estrutural de bases cimentadas e seu comportamento à fadiga. Pavimentos assim dimensionados poderão desenvolver fissuras de maneira precoce, resultando em perda de sua qualidade estrutural. Neste artigo é apresentada uma solução baseada em modelo numérico para o cômputo de tensões de flexão em bases cimentadas quando o pavimento está sujeito a eixos de rodas duplas de 100 kN; para seu desenvolvimento, as rodas do eixo foram tomadas próximas à junta transversal do pavimento de concreto simples. A placa de concreto é suposta não aderida à base porém em pleno contato. Tendo por base um modelo experimental de fadiga para britas tratadas com cimento foi possível a definição de espessuras consistentes para a base cimentada em função do número de repetições de cargas previsto em projeto.

1. INTRODUCTION

Two design methods for road plain concrete pavements have been extensively employed by several road agencies around the World: the Portland Cement Association [1] and the AASTHO [2] criteria. Both methods, as it is well known, propose basically the improvement of the k-value of the foundation due the presence of a cemented base above the slabs.

As a matter of fact, a cemented base takes important rules for pavement behaviour on improving bearing capacity and homogenety for the supporting foundation. Despite these facts, the cemented base, also working as slabs, are subjected to flexural solicitations with minor or major regards to its fatigue process. A preliminary analysis of fatigue process consequences on cemented bases on concrete pavements was presented by Balbo [3], although that ocasion, no guidelines for the design question had been proposed yet.

By the employment of recently modified version of the FEACONS IV computational program developed by Tia *et al* [4], namely FEACONS 4.1 SI, it was possible to develop numerical analisys of stresses concerning plain concrete pavement containing a cemented base. As a result of these studies, it was allowed to develop numerical models for the computation of flexural stresses on both layers: concrete slab and cemented base.

Linking the numerical models with an experimental model for the fatigue consumption of a cement treated crushed stone (similar to low cement content roller compacted concrete), an analisys of consistent thickness for the cemented base, regarding the design load of 100 kN, is presented.

2. MODELS DEVELOPMENT

The choice of pavement characteristics for the factorial study was done on the basis of typical thicknesses and parameters employed in road design and construction of concrete pavements in Brazil.

The k-value ranged from 10 to 90 MPa/m, considering possibilities of soils with poor bearing capacity up to high bearing capacity of typpical tropical lateritic soils often employed as subgrade top layer in road construction.

Concerning the elasticity modulus of cemented bases, a large spectrum from 10.000 to 25.000 MPa was taken in order to allow the employment of the developed models for several possibilities of materials.

As mentioned, the study considered a dual tire axle load of 100 kN, and the pressures for the wheels of 0,64 MPa. On Table 1 are presented the parameters adopted for the analisys: thicknesses (t), elasticity modulus (E), k-values and Poisson's ratio (ν).

Table 1 Range of variation for the parameters

Layer	t (m)	E (MPa)	k-value (MPa/m)	ν
slab	0,15 0,18 0,21 0,24	28.000		0,15
base	0,15 0,20 0,25 0,30	10.000 15.000 20.000 25.000		0,15
subgrade			10 50 90	

The load position was located near the transversal joint, considered as critical position for non-dowlled slabs, as assumed by the PCA method of design, condition also verified by Ramsamooj [5] and Huang *et al* [6]. The axle was simmetrically placed regarding the midline of the slab, as shows Figure 1. The slab dimension was 5,0 by 3,6 m.

The study have considered 192 cases based on the factorial experiment. For each simulation it was received the maximum flexural stress for the slab and also for the cemented base. The received values were treated by the use of conventional multi-linear regression, and it was allowed to define the following models for flexural stresses:

- Equation (A) for maximum flexural stress on concrete slab (r^2=0,91):

$$\sigma_{slab}=5{,}015035 . t_{slab}^{-0{,}491472} . t_{base}^{-1{,}286382} . E_{base}^{-0{,}440458} . k^{-0{,}038956}$$

- Equation (B) for maximum flexural stress on cemented base (r^2=0,89):

$$\sigma_{base}=0{,}000179 . t_{slab}^{-1{,}491913} . t_{base}^{-0{,}286708} . E_{base}^{0{,}55974} . k^{-0{,}038938}$$

For the above equations the following simbols and units were adopted:

σ_{slab} = maximum flexural stress on slab (MPa)

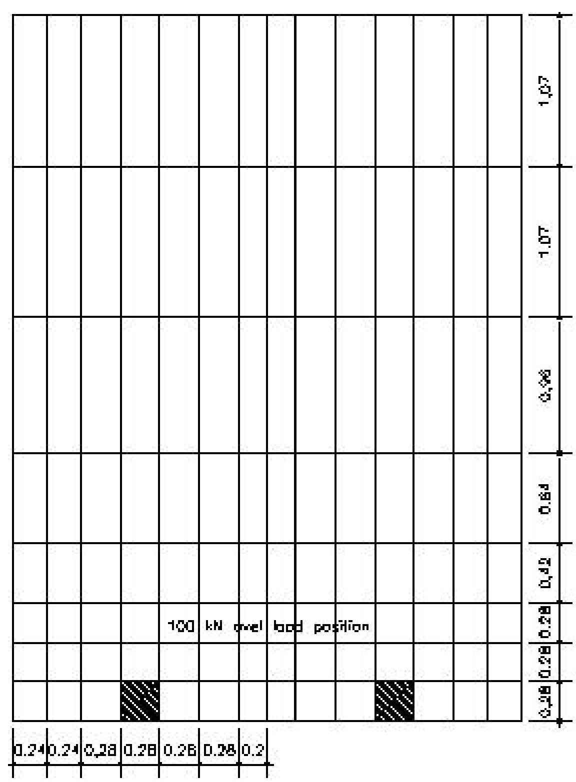
σ_{base} = maximum flexural stress on base (MPa)

t_{slab} , t_{base} = slab thickness , base thickness (m)

E_{base} = elasticity modulus of base (MPa)

k = modulus of subgrade reaction (MPa/m)

Figure 1 Finite element mesh for the slab (no scale)



From the equation for the slab it is inferred that the increase on elasticity modulus of the base will cause a decrease on the flexural stress on concrete slab, even considering the not bounded condition at the interface slab/base. On the other hand, as pressumed, the increase of the elasticity modulus of the base results in the increase of the corresponding flexural stress on the base itself.

On Figures 2 and 3 are presented a confrontation between the presented equations for stresses computation and the reciprocal results obtained from FEACONS 4.1 SI for the generation of both equations.

Figure 2 Flexural stresses from FEACONS 4.1SI and
equation A

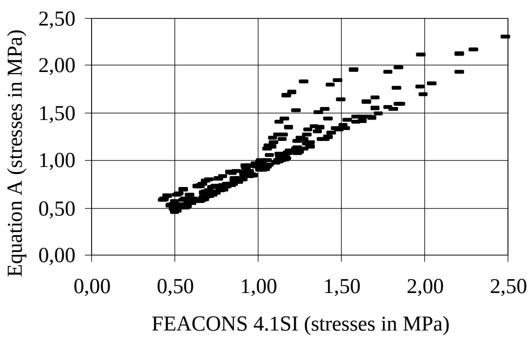
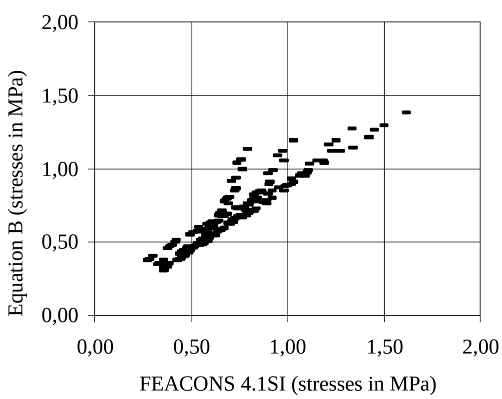


Figure 3 Flexural stresses from FEACONS 4.1SI and
equation B



3. APPLICATIONS OF THE MODELS

3.1 Fatigue Verification of Cemented Bases

These results might be employed for the structural verification of fatigue life of cemented bases when traditional design criteria are employed. For a short draw of this statement, it could be taken a practical example of design using the PCA method of design.

Let us take, for instance, a design situation when the following conditions are presented: subgrade with k-value of 30 MPa/m; cement treated crushed stone to be employed as base, with an elasticity modulus of 15.000 MPa and ultimate flexural strength of 1,0 MPa; concrete for slab with 5,0 MPa ultimate flexural strength.
Taking the 100 kN axle as design load and as design criteria that the pavement must be designed by an unlimited number of load repetitions, according to PCA criteria of fatigue for the concrete, the maximum flexural stress allowed for the designed axle will be 50% of the concrete strength (2,5 MPa).

Once the design method takes the presence of a cemented base as able to increase the foundation modulus of reaction, the new k-value for the support of the slab will be increased to 85 MPa/m for a base thickness of 0,15 m.

Taking the axle load (100 kN), the k-value (85 MPa/m) and the stated flexural stress (2,5 MPa), through the PCA diagram for single axles a thickness of 0,15 m is received for the slab, considering the *unlimited number of load repetitions* above mentioned.

Applying the equation for flexural stress on concrete it is received, for the described design situation, a maximum load stress of 1,85 MPa for the concrete slab, adequated for the design condition (the concrete is able to receive an unlimited number of loads repetition). Note that for this calculation the k-value of 30 MPa/m is employed in agreement with the developed model (the k-value is taken for the conditions of the foundation excluding the base).

Although, by applicating the equation for stress on cemented bases, for the same described situation, a maximum load stress of 1,0 MPa for the cement treated crushed stone is received. This value draws a situation where, within a very short-term, the cemented base will be in advanced process of rupture. Note that the flexural stress approaches the flexural strength of the material.

As consequence of the structural capacity loss for the pavement, no longer the cemented base will contribute for the control of flexural stresses, acting then as a merely good granular material base, causing a new k-value of 40 MPa/m for the system base/subgrade. In this context, the concrete will be stressed in flexion by 2,9 MPa, giving a stress ratio of 0,56 which allows near 57.000 repetitions of loads (PCA fatigue criteria for the concrete), a little number for the design of heavy traffic highways.

The solution for the design, theoretically, will be to consider, for the period of design, the amount of axle loads and the fatigue process for the cemented base. The definition of an ideal thickness of cemented base could be done, in that case, by the use of the following fatigue model for the cement treated crushed stone [7]:

$$SR = 0{,}973 - 0{,}026 \log N$$

where SR is the stress ratio between the flexural stress on the cemented base and its flexural strength, and N is the allowed number of load repetitions.

Supposing a value for N of 10^8 load repetitions, then the maximum flexural stress for the cemented base would be 0,76 MPa. By imposition of this stress value on equation B (for cemented base layer), the minimum thickness for the base would be 0,39 m. Obviously, for this thickness of base, a decrease for the stress on slab would be gotten (0,54 MPa would be the new value of this stress).

3.2 Development of Design Charts

Regarding to the PCA criteria it is remembered that the design method consists on linking flexural stresses charts derived from Westergaard solutions with an experimental model for fatigue behaviour of the plain concrete. For sure, as a complete method, which requires a field-based verification of performance for the adjustment of theoretical and laboratorial relations, such method can not be taken. Nevertheless, semi-theroretical methods can be focussed as first steps for the development of more consistent criterium, due to the fact to have rational basis.

Through the fatigue model presented on 3.1, it can be estimated the maximum flexural stress that can occur on a cemented base that is required for the desired pavement lifetime. Having this result, and making use of the equation B, the cemented base thickness which ensure the predeterminated lifetime can be calculated.

Charts below shows the steps described on the paragraph above: Chart 1 presents the required cemented base thickness as function of the number of a 100 kN axel load for a k-value of 10 MPa/m, while Chart 2 is designed for a k-value of 50 MPa/m and Chart 3 is for a k-value of 90 MPa/m.

From the design charts above, it can be inferred the low capacity foundations for bases and slabs require more thicknesses for the cemented base. As the k-value gets higher, its influence on stresses becomes less significant.

The charts show another important result, if it is taken as principle the minimum thickness for the cemented base of 0,10 m. Based on the seed equations for the charts, slabs thicker than 0,20 m requires very thin layers of the cemented base, which deserves a limitation for this minimum appliable value of thickness.

Chart 1 Cemented Base thickness and Number of load repetition - k = 10 MPa/m

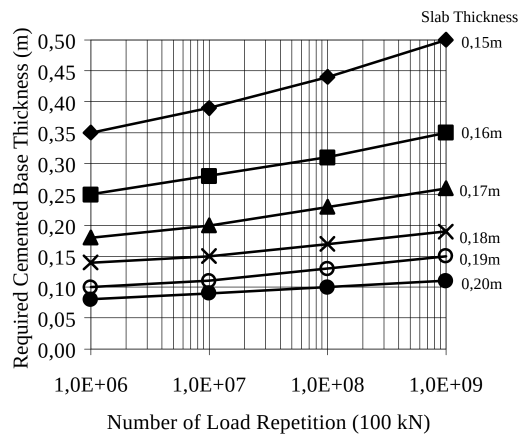


Chart 2 Cemented base thickness and number of load repetition - k = 50 MPa/m

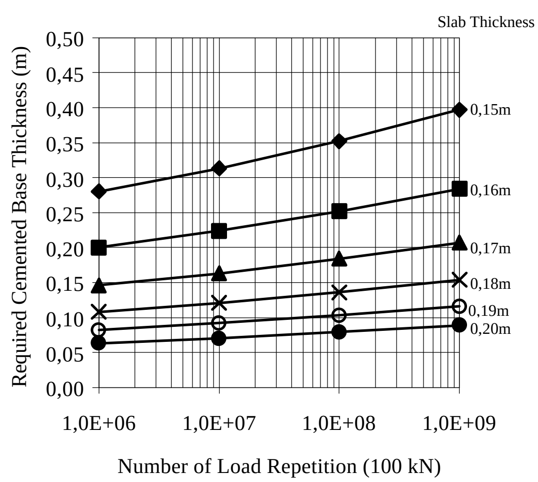
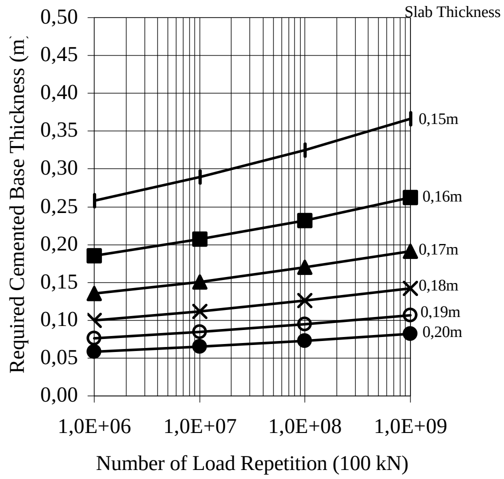


Chart 3 Cemented base thickness and number of load repetition - k = 90 MPa/m



On Table 2 is presented the received results for the flexural stresses on the slabs by fixing the minimum base thickness of 0,125 m. From those results, it's clear that, using such criteria, for conventional concretes, it would be allowed a long service life for the pavement (flexural stresses lower than 2,1 MPa).

Table 2 Maximum flexural stresses on slabs for a 0,125 thick cemented base

k-value (MPa/m)	slab thickness (m)	Maximum flexural stress on slab (MPa)
10	0,20	2,12
	0,21	2,07
	0,22	2,02
	0,23	1,98
	0,24	1,94
50	0,20	2,00
	0,21	1,95
	0,22	1,90
	0,23	1,86
	0,24	1,82
90	0,20	1,95
	0,21	1,90
	0,22	1,86
	0,23	1,82
	0,24	1,78

The last point to be stressed concerns that question: if the thickness of the cemented base is increased after the verification through the charts, which are the consequences for the slabs? The back-verification can be done through equation A by the imposition of the new cemented base thickness, in order to adjust slab thickness on the basis of an economic criteria.

The development of such kind of charts could be done for several kinds of cemented base since a fatigue-based criteria would be avaiable. Nevertheless, as a matter of fact, realistic design charts would be possible to assemble if realistic fatigue field performance are knew.

CONCLUSIONS

By the employment of a computer model for the calculation of stresses on calculation of stresses on concrete pavements it was allowed to verify that the traditional criteria for the design fails when permits the designer to define *a priori* the thickness of the cemented base. In such way, the fatigue damage of cemented bases is not taken into account during the design. As contribuition two new numerical models were developed by means of FEACONS 4.1 SI in order to allow the designer to compute the flexural stresses on slabs over cemented bases with no-bond condition. The employment mode of such models has been shown during the paper.

The application of such models joint to a fatigue experimental model for cemented crushed stone has shown that reasonable thicknesses are required (for the base) when it is used slab thickness little than 0,18 m. On the other hand, slab thicknesses greater than 0,20 m could be very effective for roads if employed with a minimum thickness of 0,125 m of such base.

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