FATIGUE VERIFICATION CRITERIA FOR SEMI-RIGID PAVEMENTS

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SUMMARY

The aim of this paper is to discuss some ideas about classification of semi-rigid pavements as well as to present some new models for verifying the fatigue process on pavements composed by asphaltic mixture coating and cement treated bases.

The more relevant diference, under the point of view of pressures transmited over the subgrades, between flexible and rigid pavement, is discussed. A revision of the fatigue concept for cemented materials is also done, and a recent experimental study concerning the fatigue behaviour of a cement treated crushed stone is presented.

Based on the layered theory, equations for computing the flexural stresses on the lower fiber of cement treated bases are presented. Linking these theoretical models with experimental models for the fatigue process, a criteria for verifying the design of semi-rigid pavements was proposed.

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INTRODUCTION

Despite the several options for the design of road pavements, based on empirical tools derived from field experiments, the use of mechanistic approach for verifying pavement structures has become now-a-days a non-dispensable analysis criteria for designers . These approaches are reasonable on considering that we can not generalize the existing empirical formulations for all types of asphalt coated structures, specially when a cement treated base or subbase layer is to be present on the pavement.

When using the AASHTO'86 criteria for the design of pavements, for instance, we need to take into account that the equation for flexible pavements was developed considering the functional responses of pavements tippically flexible, including only a few number of semi-rigid pavement sections during the road test.

By another way, we need to have in mind that, for semi-rigid pavements, specially during the non-damaged phase of the cement-treated layer, the behaviour of the structure under the point of view of serviciability could be neglected; on the other hand, the expected fatigue phenomena of the material become more important, due to the primary consequences from this process, in terms of reflective cracking for the asphaltic layer and changes on the pavement behaviour.

This paper deals with some basic ideas concerning the behaviour of semi-rigid pavements, and, considering the layered theory, presents some equations for computing the flexural stresses on the lower fiber of the cement treated layer on semi-rigid pavements, when this layer is considered on the base of the pavement. A sequence for verifying semi-rigid pavements designed *a priori* is also presented.

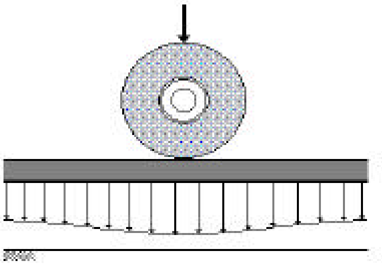
SEMI-RIGID PAVEMENTS

On looking for an way to define semi-rigid pavements, like any other effort to define or classify in engineering, we actually find some difficulties. Classical books or references normally presents the terms rigid or flexible to separate diferent possibilities of pavement structures. So, the term rigid refers to pavements with the top layer on cement concrete material; the term flexible is associated to pavements with asphalt mixtures carpets.

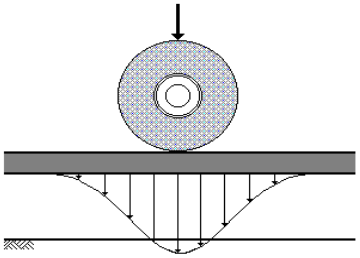
Despite these classical modes to define the type of a pavement, we can state that the more important difference between that types of pavements is the way that each structure distributes the vertical pressures over the subgrade (Figure 1).

Figure 1 - Pressure spreads over subgrades

RIGID PAVEMENT



FLEXIBLE PAVEMENT



While the rigid pavement tends to cause a dispersed spread of pressures over the lower layers, the response to loads on a flexible structure are more concentred near the loaded area; so, pressures over subgrades are less significatives for the rigid pavement case.
Considering the presence of a cement treated layer on the base or subbase of a pavement with an asphaltic surface coating, we can imagine that, due to the rigidity of such layer, the pressure spread over the subgrade tends to become more difuse compared to the flexible pavement case. Then the idea of using the term *semi* to define something not well classified on the extrems seems to be more adequate, although some considerations need to be stated obligatory yet.

The first consideration regards to the fact that, the presence of a cement treated layer on the pavement concern this behaviour (*semi-rigid*) for the structure independent of its relative position. So, for instance, an existing flexible pavement which is reinforced by using two new layers, an intermediate layer of cement treated material and a new asphaltic surface coat, will present a new specific behaviour, and the reinforced pavement works as a semi-rigid pavement.

The second idea to have in mind is that, when a cement concrete layer is present on the pavement, we need to call by the rigid pavement case. It is valid also for the case of composite pavements. In this way, we believe that the term semi-rigid is suitable for all pavements containing asphalt surface courses and, at least, one cement treated layer on its structure, according to PIARC (1991) purpose.

The last consideration, and the more significative for this study, is that the semi-rigid pavement will have significative changes on its behaviour after a determined (but not well defined) number of repetitions of loads, due to the fatigue process concerning the cemented treated layer, afterwards the material will behave merely as a very good granular material (if produced originally with aggregates).

FATIGUE BEHAVIOUR

The fatigue phenomena induces the rupture of some paving materials after a number of solicitations, causing stresses values under the ultimate strength of the material, due to the slow development of micro-fissures on the internal structure of its component cristals. On cement treated paving materials, this slow fissuration will concentrate on the links developed between mortar and aggregates during the hidratation of cement.

There are several studies concerning the fatigue behaviour of cement treated materials on the literature, specially for the cement treated aggregate case. Although, the classical studies conducted by Larsen & Nussbaum (1967) and by Symons (1967) must be remembered, considering its important conclusions we could link to the behaviour of semi-rigid pavements.

On the first reference, the authors conducing tests at the laboratories of the Portland Cement Association, emphasized that the bearing characteristics of the roadbed (simulated during the fatigue tests on laboratory) have not significant influence on the fatigue behaviour of cement stabilized materials (including soils and aggregates).

The britanic author, during tests conducted at the Road Research Laboratory, concluded that variations on the cement content or on the load application frequence are less important for the fatigue behaviour of the cemented mixtures considering the dispersion he had find out from the fatigue tests itself.

Dac Chi (1981) noticed that for strain controlled tests of fatigue, the verified dispersions during the tests with cement treated aggregates are more important than the stress controled procedure. Moreover, he states that for constants applied stresses, the growing of fissures is more acelerated during the test when the modulus of elasticity decreases, and so, the rupture of the samples are determined in a more precise way.

The fatigue curves for cement treated aggregates are generally described by the use of SN equations (where SN is the relation between applied stress and ultimate strength) relating the logaritimic of the number of load applications, in a linear manner (SN = a + b log N). The dispersion tippically verified for this kind of relations is mainly due to the difficulty of defining with good precision the ultimate tensile or flexural strength of the cemented material.

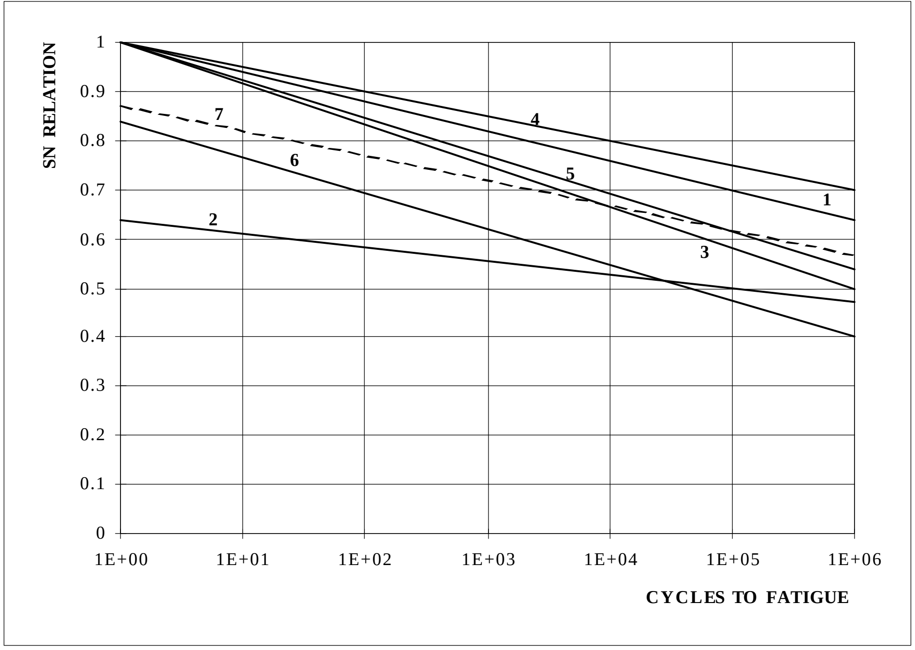
Based on a great number of samples, Dac Chi (1978) verified that for a million cycles of load, the SN relation ranges from 0.50 to 0.59, for cement treated aggregates. On Table 1 is possible to verify that on literature is found variations from 0.40 to 0.70 for the SN relation considering similar kinds of cemented materials. Figure 2 is related to Table 1.

For the curve 7 on Table 1, the admixture presented by Balbo (1993) is reffered to a cement treated crushed granite stone, gradation 0/20 mm, with cement content of 4% and moisture content of 4.5%. The tensile strength of the material is 0.68 MPa and the flexural strength about 1.088 MPa (28 days); the typpical modulus of elasticity for this material is 15,000 MPa (secant modulus at 2/3 of the ultimate strength).

Table 1 - Fatigue relations for cement treated aggregates

Curve	**a**	**b**	**SN_6**	**Reference**
1	1	-0.060	0.64	PIARC, 1979
2	0.640	-0.028	0.47	Symons, 1967
3	1	-0.083	0.50	Dac Chi, 1978
4	1	-0.050	0.70	Marchionna, 1989
5	1	-0.077	0.54	Peyronne & Caroff, 1989
6	0.840	-0.074	0.40	Gschwendt et al, 1982
7	0.874	-0.051	0.57	Balbo, 1993

Figure 2 - Fatigue curves for cement treated aggregates (ref. to Table 1)



AASHTO CRITERIA RESPONSE ANALYSIS

In order to verify the necessity of considering the fatigue mode of rupture for semi-rigid pavements, is necessary to apply the fatigue estimative concept further mentioned to a factorial study of cases using the AASHTO'86 criteria for the design of pavement structures, which is presented in the following paragraphs.

On Table 2 is presented a summary of the studied cases by the authors for a semi-rigid pavement composed by an asphaltic surface course (AC), a cement treated crushed stone (CTCS) base and a granular crushed stone (CS) base supported by the subgrade. The resilient modulus of each layer and its corresponding structural coeficients are presented.

Table 2 - Parameters for the design with AASHTO'86 guide

Layer	**E-Modulus (MPa)**	**Structural coeficients**	**Reliability parameters**	**N_{18}**
Surface	2,945	0.43	R = 95 % Z_R = -1.645 S_o = 0.49 (for all cases)	5×10^5 10^6 5×10^6 10^7 5×10^7 10^8 (for all cases)
Base	15,000	0.30		
Subbase	100	0.10		
Subgrade	20, 40, 60, 80 and 100	-		

The values of N_{18} on Table 2 are reffered to the 18 kips single axle considered by the designer. Drainage coeficients values for the bases and subbases were taken as the unit. The final level of serviciability taken for such cases was 2.5.Considering the mentioned parameters for design, applying the AASHTO'86 equation it was received the thickness for each layer presented on Table 3.

From these results we are able to confirm that when the resilient modulus of subgrade decreases and the expected traffic is increased, more thicker layers of cement treated material is necessary for the design. Furthermore, let us confirm the adequacy of the received thickness of bases under the point of view of flexural stresses and fatigue behaviour.

For this purpose we carried out structural analysis for all the designed pavements adopting the ELSYM5 model. The single axle considered for this analysis had a total load of 80 kN, and tire pressures of 0.53 MPa. The distance between dual wheels is 0.34 m and between the centers of dual wheels is 1.81 m. On Table 4 are presented the received maximal flexural stresses for the base layer of the mentioned pavement cases.

Table 3 - Thicknesses of layers (mm) according AASHTO'86 criteria

Subgrade Modulus (MPa)	Layer	**5 x 10^5**	**10^6**	**5 x 10^6**	**10^7**	**5 x 10^7**	**10^8**
20	CA	75	75	90	100	100	100
	CTCS	235	275	365	400	530	595
	CS	200	200	200	200	200	200
40	CA	75	75	90	100	100	100
	CTCS	145	180	260	285	400	455
	CS	200	200	200	200	200	200
60	CA	75	75	90	100	100	100
	CTCS	100	130	200	225	330	380
	CS	200	200	200	200	200	200
80	CA	75	75	90	100	100	100
	CTCS	70	100	170	185	285	330
	CS	200	200	200	200	200	200
100	CA	75	75	90	100	100	100
	CTCS	50	75	135	155	250	295
	CS	200	200	200	200	200	200

Table 4 - Flexural stresses on the cement treated base (MPa)

Subgrade Modulus (MPa)	**5 x 10^5**	**10^6**	**5 x 10^6**	**10^7**	**5 x 10^7**	**10^8**
20	0,820	0,680	0,470	0,415	0,292	0,250
40	1,403	1,118	0,698	0,613	0,415	0,355
60	1,952	1,570	0,940	0,799	0,518	0,440
80	2,452	1,952	1,118	0,981	0,613	0,518
100	2,815	2,364	1,403	1,177	0,710	0,589

It must be added that for all cases the received stresses in the lower fiber of the asphaltic concrete layer were in compression, showing the great capacity of the bases in absorving the flexural stresses. For the granular subbases the confining stresses ranged from -0.006 to -0.032 MPa, that means, the subbase is subjected to lower pressures, confirming the intuitive idea that the cemented base has great capacity to distribute the imposed loads on a large area.

Taking the fatigue model proposed by Balbo (1993) already presented on Table 1 and the flexural strength of the cement treated crushed stone of 1.088 MPa, it is possible to establish the SN relation for each pavement case and to verify the number of load repetitions to fatigue that the base is able to support. On Table 5, for each pavement case, are presented the following coments: *yes* or *no*, if the theoretical flexural stress *is* lower than the flexural strength or *not*, and, if positive, the number of repetitions allowed considering the fatigue criteria for the cemented base.

As a matter of fact the results show clearly that for several cases the thickness of the base would be unable to support the flexural stress due to the load of a single standard axle. By another hand, the number of repetitions allowed for the considered axle is significantly lower than the number of repetitions taken during the design, if we take into account the fatigue strength consumption for the cemented base. On both cases, we are dealing with a considerable possibility of under-design.

Table 5 - Backcalculation of the allowed number of repetitions (N_{18})

Subgrade Modulus (MPa)	**5 x 10^5**	**10^6**	**5 x 10^6**	**10^7**	**5 x 10^7**	**10^8**
20	**yes** 228	**yes** 7,7 x 10^4	**yes** 4,7 x 10^8	**yes** 4,6 x 10^9	**yes** 7,4 x 10^{11}	**yes** 4,3 x 10^{12}
40	**no**	**no**	**yes** 3,5 x 10^4	**yes** 1,2 x 10^6	**yes** 4,6 x 10^9	**yes** 5,5 x 10^{10}
60	**no**	**no**	**yes** 2	**yes** 557	**yes** 6,3 x 10^7	**yes** 1,6 x 10^9
80	**no**	**no**	**no**	**yes** 1	**yes** 1,2 x 10^6	**yes** 6,3 x 10^7
100	**no**	**no**	**no**	**no**	**yes** 2,2 x 10^4	**yes** 3,4 x 10^6

So, it must be considered that, for the design of semi-rigid pavements, fatigue analysis must be carried out in order to avoid early possibilities of damages on the cemented base. These kind of analysis is considered complementary to several design procedures which does not take into account, nor at least implicitly, the fatigue behaviour of the cemented layer.

FLEXURAL STRESSES MODELLING

With the aim of obtain single models to make possible the calculation of the maximal flexural stresses on the cemented base of a typpical semi-rigid pavement, it was proposed a factorial design considering the rule of some parameters such as thickness of layers, kind of axle and loads, resilient properties of the subgrade.

For the generation of data the ELSYM5 program was used. The number of combinations for axles and loads was eighteen, comprising: single axle (four wheels) loaded from 59 to 118 kN; tandem axles (eight wheels) loaded from 109 to 206 kN, and trial axles (twelve wheels) loaded from 186 to 334 kN. The number of loads generated for each axle was of six, lineary distributed between the extremal above mentioned values, including these ones.

On Table 6 are presented the ranges for thickness, resilient modulus and Poisson coeficients considered for the factorial design. The generation of all the data together resulted on 4,050 combinations for the parameters.

Table 6 - Parameters for the semi-rigid pavements generation

Layer	Material	E (MPa)	υ	Thicknesses (mm)
Surface	AC	3.000	0,35	100 , 125 , 150
Base	CTCS	15.000	0,25	200, 250, 300, 350 ,400
Subbase	CS	100	0,35	100 , 150 , 200
Subgrade	soil	25, 50, 75, 100, 125	0,40	(semi-infinite)

After simulations, it was performed a search on linear regression to find equations defining the flexural stress on the pavement base (dependent variable) as a function of other parameters taken on the factorial design. The best results obtained are presented on the following paragraphs.

Single Axles

$$\sigma_f = 59{,}463847 \cdot t_r^{-0{,}323205} \cdot t_b^{-1{,}178098} \cdot t_s^{-0{,}007887} \cdot E_s^{-0{,}214274} \cdot L^{0{,}970153} \quad (1)$$

with r = 0,998 and standard deviation of 0,0084 MPa.

Tandem Axles

$$\sigma_f = 9{,}301950 \cdot t_r^{-0{,}267539} \cdot t_b^{-0{,}883009} \cdot t_s^{-0{,}008576} \cdot E_s^{-0{,}340332} \cdot L^{0{,}927047} \quad (2)$$

with r = 0,999 and standard deviation of 0,0073 MPa.

Trial Axles

$$\sigma_f = 2{,}288453 \cdot t_r^{-0{,}227463} \cdot t_b^{-0{,}705838} \cdot t_s^{-0{,}009278} \cdot Es^{-0{,}392020} \cdot L^{0{,}940948} \quad (3)$$

with r = 0,999 and standard deviation of 0,0063 MPa.

The dependent and independent variables described on the above equations represents:

σ_f = flexural stress on the base (MPa);

t_r = surface coarse thickness (mm);

t_b = base thickness(mm);

t_s = subbase thickness (mm);

E_s = subgrade resilient modulus (MPa);

L = total axle load (kN).

From the above models we can infer that the thickness of the granular subbase has little significance on the mechanical behaviour of the semi-rigid pavement. Nevertheless, the employment of such layer must become necessary due to the road drainage conditions.

Is also inferred from these equations that, *a priori*, variations on the base thickness has more significance for the single axle case and, by another hand, variations on the subgrade resilient modulus has more influence for the trial axle case.

It must to be taken into account that the theory and the software adopted for the generation of such models does not permit to consider some aspects as non-linearity of subgrade as well as the occurence of transversal cracks on the cemented subbase during its cure. In this last case, it become necessary to calculate the stresses on the vicinity of these cracks, which is allowed by finite element models.

Last, the validity of the proposed models is limited for the specified ranges of variation of the thickness, of the loads magnitudes and of the subgrade resilient modulus. The minimum value for surface coarse thickness was adopted considering the recomendations of AASHTO'86 guide for a number of repetitions over five millions. The minimum value of thickness adopted for the cemented base comes from the international experience on using the cement treated crushed stone.

FATIGUE VERIFICATION

Based on both fatigue experimental model and the cement treated crushed stone presented in this paper, and also on the models for computing flexural stresses on this material when adopted for the base of semi-rigid pavement, it becomes possible to propose a fatigue verification procedure for the pavement base, as presented bellow, taking a structure designed *a priori*.

The first step is to define the total expected number of repetitions of each axle, by separate values of total load. By this process is defined, for all the design period, the expected number of repetitions of each load (Ne,j).

As a second step, for each load must to be calculated the flexural stress on the cemented base, with aid of the correponding equation ((1), (2) or (3), over deduced, depending on the kind of axle). With the calculated stresses values, for each kind of load is determined the SN relation and so, the number of repetitions to fatigue for each load and kind of axle (Nf,j), based on fatigue models as presented.

The third step will be to define the relation between number of expected loads and number of loads to fatigue, for each type of load. After this procedure, the Miner rule could be applied to define the fatigue strength consumption for the material, defined by the relation:

$$\sum_{j=1}^{n} (Ne, j / Nf, j) \leq 1$$

If the above relation is not verified to the case under consideration, is necessary to adjust sucessively the thickness of the cemented base until the relation become valid. By this way it will be allowed to define the exact thickness of base necessary for each case.

CONCLUDING REMARKS

In this paper the authors described the relevant conduct in considering the fatigue behaviour on semi-rigid pavements, in order to define more apropriate thickness for cemented bases. It was discussed the possibilities of under-design of semi-rigid pavements, speccially concerning the base thickness, when adopting empirical models during the design.

A new fatigue models for cement treated crushed stone was presented as well as some theoretical models to define flexural stresses on the lower fiber of cemented bases, when the pavement is loaded by three diferent kinds of axles. A sequence for verifying the fatigue process on this material when used on semi-rigid pavement base is then presented, taking into account both the experimental fatigue model and the theoretical models.

The designer, despite the semi-theoretical process here presented, is noticed that fatigue models can present significant dispersion. So, carefully experimental fatigue studies for the adopted cemented base are strongly encouraged by the authors.

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