Numerical modelling of the behaviour of road pavement layers of cement-treated soils

Extend Abstract

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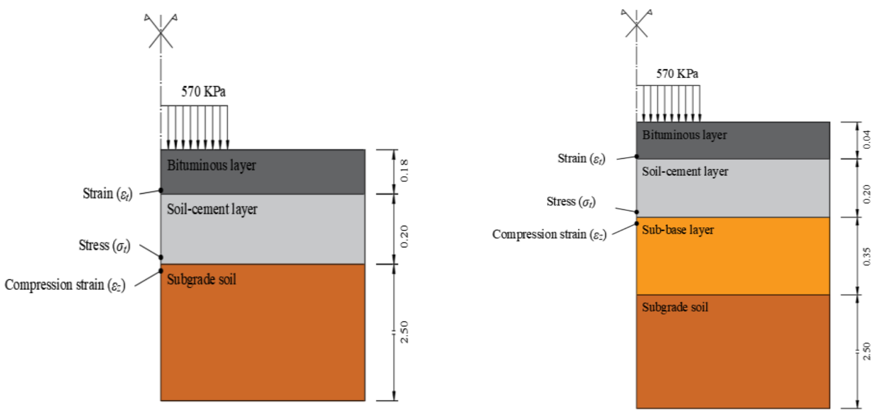
1 Introduction

The presence of cracks and their reflection is one of the most common distresses on semi rigid road pavements with soil-cement layers (Portland). When disregarded, they can produce a negative impact, either esthetical, on the living conditions or in the structural performance.

This thesis aims to improve the understanding of the reflection of craks by fatigue phenomena, as well as contributing to enrich the knowledge about mitigation methodologies used in the study of road pavements. The utilization of different techniques is also considered, in order to increase the quality of the road pavements. These techniques of mitigation are mainly (Von Quitus et al. (2009), PIARC (1991) and Penman et al. (2008)), quoted by Hernando and Val (2016): pre-cracking /transverse joints at the base of the soil-cement layer; curing conditions, cement type, aggregate type, water cement ratio and presence of additives; use in the interface of the asphalt surface and the soil-cement layer of SAMI (Stress Absorving Membrane Interlayer), glass fibber geogrids, geotextile, steel mesh; use of inverted pavement structures, incorporation of a granular material between the asphalt surface and the soil-cement layer.

Both types of pavement were designed using the BISAR software (Shell), based on the Portuguese Manual MACOPAV, JAE (1995) and the French Manual CEBTP, CEBTP (1984). Another objective of this thesis is the modelling of the sub-base layers treated with soil-cement, using the ADINA's finite element software. The behaviour of the pavement layers was also studied through the analysis of the stress and strain values in several points of the pavement structure, as shown in Figure 1.



a) Case 1 - MACOPAV b) Case 2 - CEBTP

Figure 1: Pavements and the locations of parameters considered in the numerical model calibration

2 Cement-treated layers

2.1 Pavement structures

There are three types of road pavements, which are classified according to the two classification criteria (material types and structural behaviour) into flexible, rigid and semi-rigid pavements. They differ mainly in their constitution and structural behaviour. The pavement studied in this thesis is semi-rigid with a Portland cement treated sub-base. The semi-rigid pavements are composed of asphalt mixtures in the upper layers (wear course and binder layer). The inferiorly layer is composed of stabilized aggregate with hydraulic binder, so-called base layer which is different from the base layers of a flexible pavement composed by unbound granular material. The base or sub-base layers are composed by a hydraulic binder and granular material or soil, we can distinguish two types of semi-rigid pavement structures: direct and inverse structures (Branco et al., 2011).

The mechanism of structural failure of these pavements is caused by the flexural tensile stresses to which the base layer is subjected, whose repetition causes its fatigue cracking. Another mechanism is the reflection of cracks that occur in the layers treated with hydraulic binders, as well as the loss of adhesion between the bituminous layers and the treated base (Jiménez, 2007).

2.2 Soil-cement layers

Soil treatment generally intends to modify the properties of materials according to the required objectives (Neves, 2017). According to Branco et al. (2011), there are two ways for stabilization of cement soils, which is applied to both cohesive and incoherent soils. The technique, known as “soil-cement”, is used on roads with heavy traffic, through a higher cement dosage, leading to a higher stiffness of the material. It can be done on site, but often, the mixing is performed in concrete mixers or central to ensure better homogeneity and quality.

2.3 Materials

Soils used in mixtures treated with hydraulic binders should be free of organic matter, expansive materials and any other substances that can affect the bonding with the cement and the setting time of the cement, as well as to prevent the evolution of the mixture resistance (EP, 2014). In general, any type of cement according EN 197-1 can be used in soil treatment, although the most common is the Portland cement (CEM I) (Neves, 2017). The water should be fresh, clean and should not contain oils, acids, organic materials or any other harmful substances that may influence setting times and the development of hardening (EP, 2014).

2.4 Requirements

Table 1 presents the characteristics required for cement-treated soils produced in situ and in factory. The requirements / properties of cement-treated soils (soil-cement) shall comply with the characteristics given in Table 2.

Table 1: Characteristics required for cement-treated soils (adapted from Cepsa, 2018).

Parameters	Soil-cement	
	in situ	in factory
Maximum particle size	100 mm	50 mm
Plasticity index, maximum	12%	12%

Table 2: Characteristics of cement-treated soils (adapted from Cepsa, 2018).

Parameters	Requirements
Binder content, minimum	≥ 3%
Minimum water content	≥ $W_{0,95}$% (*)
7-day indirect compression tensile strength	≥ 0.2 MPa
28-day indirect compression tensile strength	≥ 0.3 MPa
Unconfined compressive strength at 28 days	≥ 2.0 MPa

(*) Optimum water content obtained from Proctor test

In order to ensure the better quality of the materials, some laboratory tests should be performed to characterize the soil and the cement.

The control of the execution of the layers of materials treated with hydraulic binders is based on the strength of the mixture, the relative dry density of the layers and their geometric properties (layer thickness and regularity), as shown in Table 3 (Cepsa, 2018).

Table 3: Specifications and acceptance criteria of soil-cement sub-base layers (adapted from Cepsa, 2018)

Parameters			Acceptance / rejection criteria	Action
Soil-cement	Indirect compressive strength	Average ≥ 0.2 MPa 7 days	More of 90% of the values	None
		Average ≥ 0.3 MPa 28 days or project value	More of 10% of the values do not meet	Demolition and construction
	Relative compression	Average > 97%	90% of the values > 97%	None
			More of 10% < 97%	Demolition and construction
	Layer thickness	Average ≥ Project thickness (HP)	More of 95% of values ≥ HP	None
			85% × HP ≤ Average < 95% × HP No water retention	Offset with next layer
			Average < 85% × HP	Demolition and construction

2.5 Cracking

The cracking in semi-rigid pavements is associated to the hydration phenomenon during the cement mixture hardening and associated with material fatigue during life cycle of the road, due to traffic passage and weather conditions. In general, cracking starts in the soil-cement layer (Specht, 2000). According to this author, there are three types of cracks in the soil-cement layers: surface desiccation cracks, volumetric shrinkage cracking, and fatigue cracking.

The reflection of cracking is mainly caused by the thermal action and the passage of traffic. The first action causes the opening and closing of the cracks of the lower layers, stimulating stresses in the upper, uncracked layers. The second causes shearing and tensile stresses on the overlying bituminous layers (Cepsa, 2018).

2.6 Semi-rigid pavement design

The most current semi-rigid pavement design methodology is designated by empirical-mechanistic, because it uses the empirical approach for the mechanical characterization of materials and, for the definition of the failure criteria, the mechanical approach is used to calculate the stress-strain of the pavement structure (Pereira and Pais, 2017).

The most important criterion related to the structural failure of the stabilized layer with hydraulic binders is the fatigue cracking. According the South African Manual SAPEM, SANRAL (2014,) this criterion is defined as a function of the horizontal strain at the base of the hydraulic binder stabilized layer, $\varepsilon_{t.lh}$, given by the Equation (1):

$$N = SF \times 10^{c\left(1-\frac{\varepsilon_{t.lh}}{d \times \varepsilon_{ultimo}}\right)} \tag{1}$$

where N is the number of standard axle load applications; *c* and *d* are parameters depending on road category; $\varepsilon_{último}$ is the failure strain; and *SF* is the amplification factor that takes into account the thickness of the hydraulic binder stabilized layer, given by the Equation (2):

$$SF = \begin{cases} 1 & if \quad e < 102\ mm \\ 10^{(0.00285\ e - 0.293)} & if\ 102\ mm \leq e \leq 419\ mm \\ 8 & if \quad e > 419\ mm \end{cases} \tag{2}$$

where *e* is the layer thickness (given in mm).

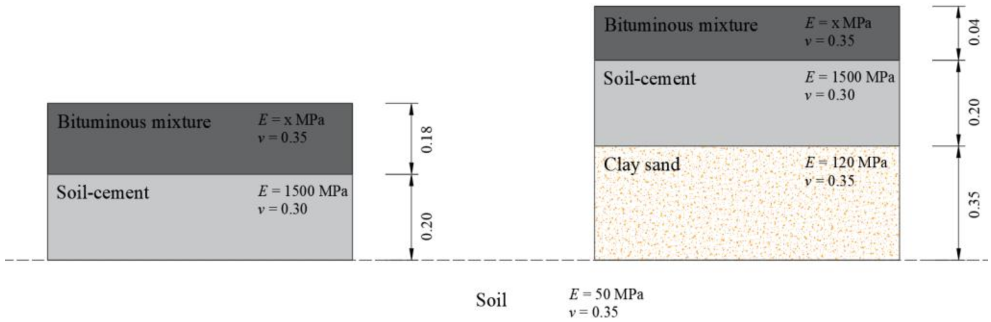
2.7 Use of design catalogues

Both the MACOPAV Manual and the CEBTP Manual adopt an empirical-mechanistic approach methodology for pavement design, including the case of semi-rigid pavements. For the use of these catalogues, certain input parameters are required to obtain the pavement structures such as traffic class, foundation class, weather conditions and paving materials.

3 Finite Element Modelling

3.1 Material properties

The three failure criteria considered in the semi-rigid pavements design are the fatigue in the bituminous mixture layer, fatigue in the soil cement layer and the permanent deformation in the pavement foundation. So, these three criteria were considered in the study using ADINA finite element software. ADINA considers 3D elements in the case of both MACOPAV and CEBTP pavements with the mechanical properties indicated in Figure 2.



a) MACOPAV b) CEBTP

Figure 2: Mechanical characteristics of layers.

3.2 Geometry, boundary conditions and finite element mesh

Conventional kinematic boundary conditions were adopted: sliding in all four vertical floor boundaries and fixed in the subgrade. Tetrahedral uniform elements of 4 nodes per element were adopted in all layers of the pavement. Figure 3 presents an example of the model taken from the ADINA software with a 3D finite element mesh.

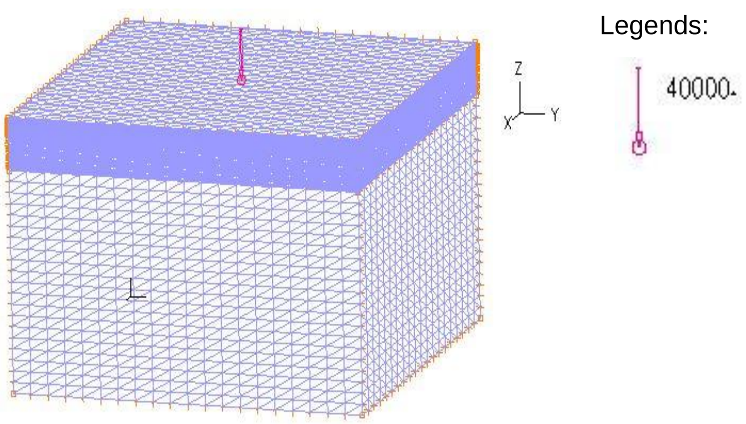


Figure 3: 3D model.

3.3 Loading and modelling analysis

The load considered was a load in the centre of the cross section of 40 kN. To achieve the main objective of this study, two different cases were investigated. The first case compares the pavement composed by materials with different stiffness modules and different pavements with the same stiffness, respectively. The second case studies the influence of the reflection of cracks in pavements, for the same conditions as those presented in the first case, by tracing the influence line, both in the centre and 0.5 m from the edge of the cross section of the pavement.

4 Results and discussion

Tensile stresses (σ_t), tensile strains (ε_t) and compression strains (ε_c) were evaluated and the following sections present the main results and discussion.

4.1 Case study 1 – varying the stiffness

Figures 4, 5 and 6 present the stresses and strains calculated for the case of MACOPAV continuous pavement versus CEBTP pavement.

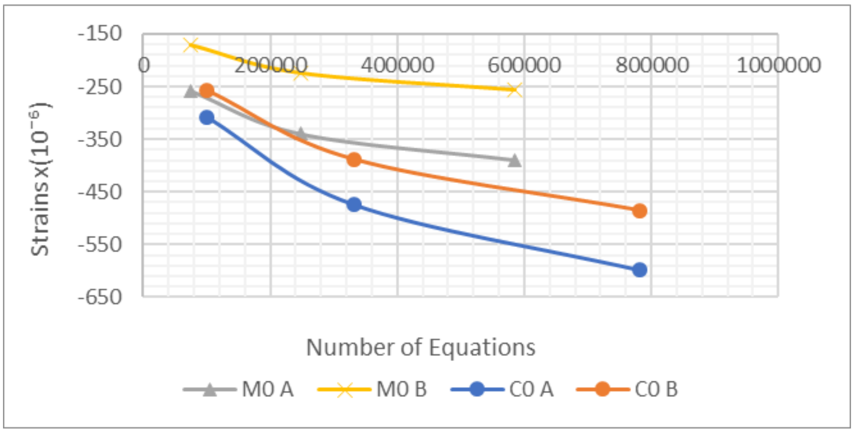


Figure 4: Strains at the top of the subgrade soil of MACOPAV pavement vs CEBTP pavement

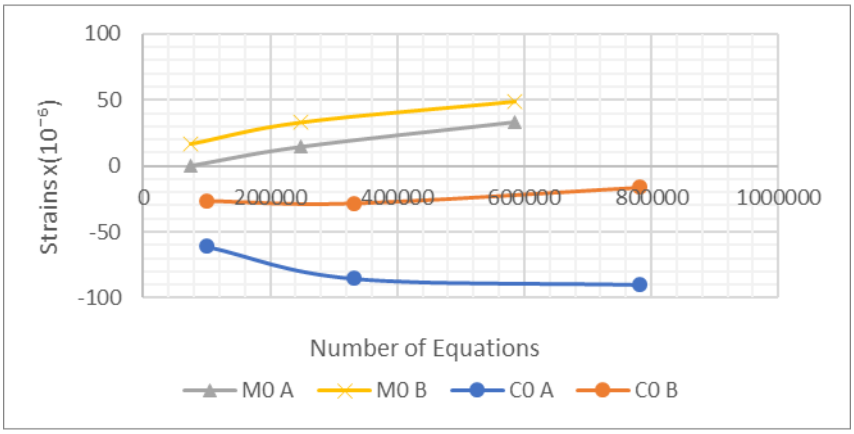


Figure 5: Strains in the bituminous layer of MACOPAV continuous pavement vs CEBTP pavement

From the analysis of figure 4 and 6 it can be seen that for different pavements, but with the same stiffness modulus, that both the compression strain and the tensile stress are higher in the French pavement than in the portuguese one, due to the fact that the layer thicknesses of the analysed structures of this pavement are larger. In the case of tensile strain (Figure 5), it is in the Portuguese pavement that the values are most critical since we have tensile strains in this zone.

It is also possible to conclude that for pavement with smaller stiffness modulus, the horizontal stress values were higher because the pavement is more flexible. The compression strain is higher in the pavement with the lowest stiffness modulus, while the tensile strain is higher in the pavement structure with the highest stiffness modulus (the opposite occurred in the CEBTP pavement).

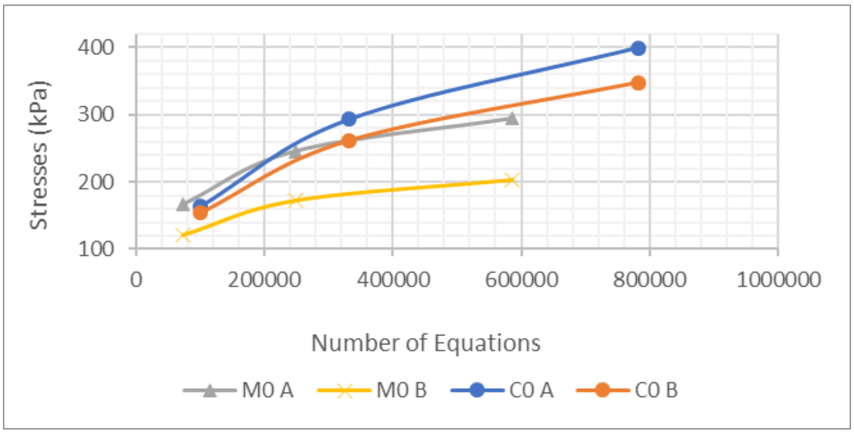


Figure 6: Stresses at the base of the soil-cement layer of MACOPAV pavement vs CEBTP pavement

4.2 Case study 2 - Moving load

4.2.1 Influence lines related to middle of the pavement

Calculations were performed in order to obtain the influence lines related to the middle of the pavement. Figures 7, 8 and 9 present the results related to the stresses and strains obtained in the MACOPAV pavement *vs* the CEBTP pavement.

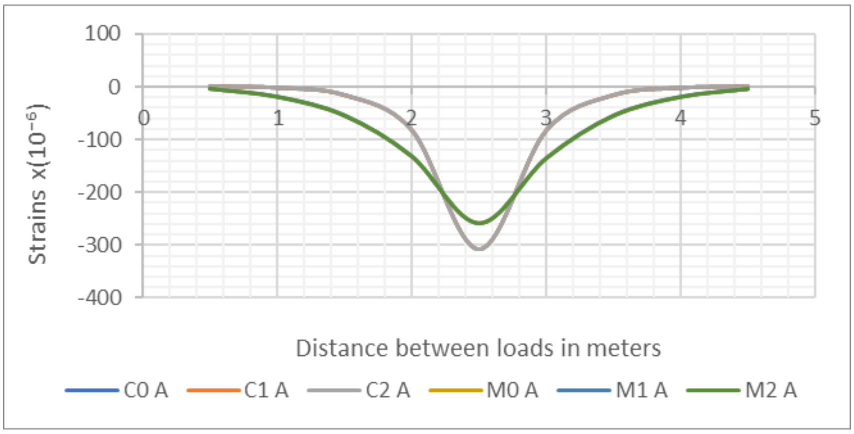


Figure 7: Strains at the top of the subgrade soil; MACOPAV vs CEBTP pavements

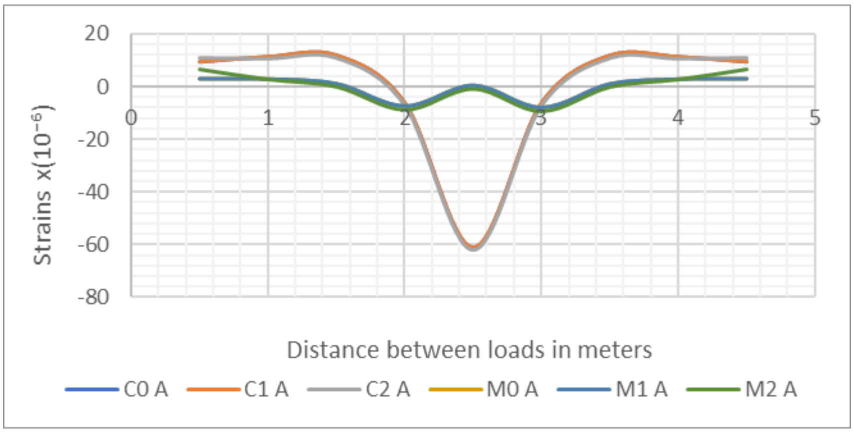


Figure 8: Strains at the base of the bituminous layer; MACOPAV vs CEBTP pavements

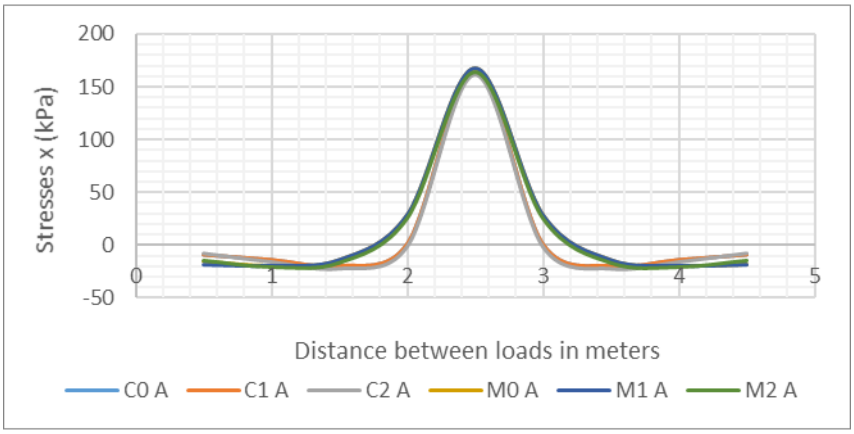


Figure 9: Stresses at the base of the soil-cement layer; MACOPAV vs CEBTP pavements

From the analysis of these figures it can be observed that for the structures without cracking (C0 A, M0 A), with cracks in the soil-cement layer (C1 A, M1 A) and totally with cracking (C2 A, M2 A), the values are all similar, but when comparing different pavement structures, both the compression and tensile strain (Figures 7 and 8) values are higher in the French pavement (C), while the tensile stresses are similar (Figure 9).

4.2.2 Influence lines related to 0.50 m from the edge of the pavement

Similar analysis was performed in order to obtain the influence lines related to 0.50 m from the edge of the pavement. Figures 10, 11 and 12 present the results related to the stresses and strains obtained in the MACOPAV pavement versus the CEBTP pavement.

Regarding the results presented in the figures, it can be concluded that the critical value of, tensile strain was obtained in the case of total cracking of MACOPAV pavement (M2 A) and the tensile stress was similar on both pavements, while the maximum compression strain was the same on both pavement structures, but with a slight advantage in the case of MACOPAV pavement.

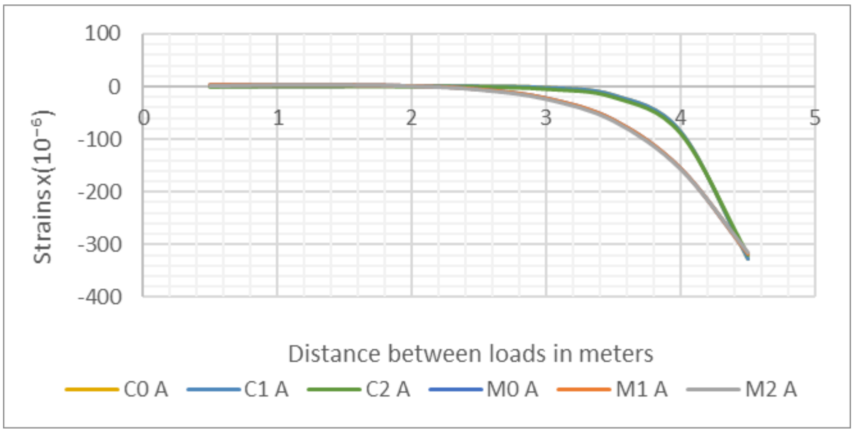


Figure 10: Strains at the top of the subgrade soil; MACOPAV vs CEBTP pavements

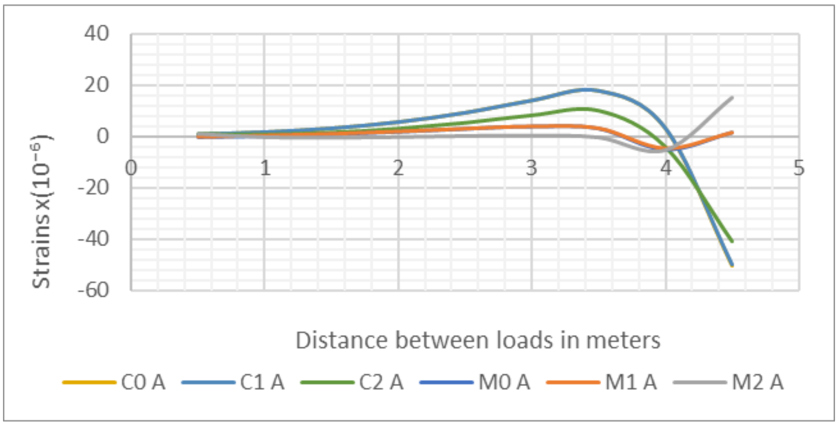


Figure 11: Strains at the base of the bituminous layer; MACOPAV vs CEBTP pavements

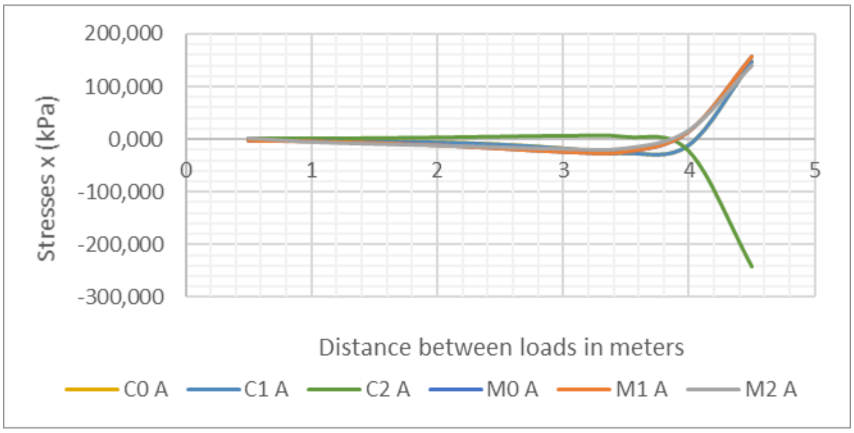


Figure 12: Stresses at the base of the soil-cement layer; MACOPAV vs CEBTP pavements

5 Conclusions

A series of finite element simulations were performed to evaluate the effects of soil-cement cracking on the fatigue and deformation criteria of semi-rigid pavement layers. The following conclusions can be addressed from the parametric study of the model:

1. When comparing different pavement structures with the same stiffness modulus that have thicker layers, both the compression strains and the tensile stresses are higher in CEBTP pavement because it is composed by thinner bituminous layers. Tensile strains are critical in the case of MACOPAV pavement.

2. In the case of pavements with different layers stiffness, both the compression strains and the tensile stress are higher in the pavements with smaller stiffness. The tensile strain is larger in the structure with higher stiffness (CEBTP pavement).
3. From the influence lines in the middle of the pavement structures, it was concluded that compression and tension strains were higher on CEBTP pavement, while the tensile stress was similar in both pavements.
4. The influence lines for the case related to 0.5 m from the pavement edge, it was concluded that the maximum tensile stress and the compression strain were the same on both pavements. However, a slight advantage on MACOPAV pavement was observed because the tensile strain was critical on the pavement totally crack.

The results presented above correspond to a simplified approach of the finite element modelling that needs further research studies. More details and complexity regarding materials behaviour and moving loads during the pavement life cycle should be considered. Besides soil-cement design, pavement construction methods and quality control are also very important to ensure the best performance and durability of a semi-rigid pavement. This type of pavement is very important in certain countries where pavement materials restrictions are a reality, and it can have an adequate mechanical performance and durability due to traffic and weather conditions.

References

ADINA, http://www.adina.com, accessed in February 2019.

Branco, F., Pereira, P., Santos, L. P., *Pavimentos rodoviários*, Almedina, Coimbra, 2011, ISBN 978-972-40-2648-0.

CEBTP *Publics*, C.-C.E.d.R.e.d.É.d.B.e.d.T., *Guide Pratique de Dimensionnement des Chaussées pour les Pays Tropicaux,* França, 1984.

Cepsa Portuguesa Petróleos, *Manual de pavimentação*, 3ª edição, Espanha, 2018.

EP, Caderno de Encargos Tipo Obra, – Pavimentação - Capítulo 14.03: Características dos Materiais, Volume 03, Estradas de Portugal, Almada, 2014.

Hernando D. e Val M.- *Guidelines for the design of semi-rigid long-life pavements; ScienceDirect - International Journal of Pavement Research and Technology*, 9; pp 121–127, 2016. https://doi.org/10.1016/j.ijprt.2016.03.003

JAE, Manual de Conceção de Pavimentos Para a Rede Rodoviária Nacional, Junta Autónoma de Estradas, Almada, Portugal, 1995.

Jiménez, F. E. P., *Manual de pavimentação*, 1ª edição, Espanha, 2007.

Neves, J., *Materiais tratados e reciclados em infraestruturas de transporte*, LNEC, Lisboa, 2017 ISBN 978-972-49.

Pereira P., Pais J., Main flexible pavement and mix design methods in Europe and challenges for the development of European method, *journal of traffic and transportation engineering*, 4(4), pp 316-346, 2017. https://doi.org/10.1016/j.jtte.2017.06.001

SANRAL, South African pavement engineering manual (SAPEM), *Pavement Design, Prepared by the South African National Roads Agency SOC Ltd (SANRAL),* Chapter 10, Pretoria, South Africa, 2014.

Specht, L., Comportamento de Misturas Solo-cimento-fibra Submetidas a Carregamento Estáticos e Dinâmicos Visando a Pavimentação, Dissertação de Mestrado em Engenharia Civil, Universidade Federal do Rio Grande do Sul, Porto Alegre, 2000.