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A Numerical Study on the Implications of Subgrade Reinforcement with Geosynthetics in Pavement Design

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Abstract

The main purpose of this paper is to present a numerical study to demonstrate the implications of subgrade reinforcement with geosynthetics in road pavement design. A parametric analysis was carried out with the finite element program ADINA using two-dimensional modeling. This analysis considered different pavement materials and structures, traffic conditions and subgrade soil quality. The pavement reinforcement effect was analyzed in terms of fatigue and rutting design criteria. Overall, the results of numerical modeling confirmed the reinforcement effect and pointed out the most important factors influencing the use of geosynthetics at the subgrade level for this purpose.

Keywords: road, pavement, reinforcement, geosynthetics, modeling, ADINA

1 Introduction

The use of reinforced geomaterials – geotextiles and geogrids – has had an important influence on road pavement design with real cost savings (Barksdale and Brown, 1989; Zornberg, 2011; Zornberg and Gupta, 2010). The effect of geosynthetic reinforcement depends on numerous and complex factors, such as the pavement structure, the characteristics of the geosynthetic materials used and the location of the geosynthetics in the pavement structure. Several authors have demonstrated the mechanisms of geosynthetic reinforcement in pavements under different conditions (Erickson and Drescher, 2001; Mounes et al., 2011; Zornberg et al., 2012). Some studies have performed FE modeling in order to demonstrate the benefits of using geosynthetics (Kim and Lee, 2013; Saad et al., 2006; Perkins, 2011). In a recent study, a finite element analyses using ADINA was performed to investigate the effects of the base layer, subgrade quality, and interface friction between the

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geosynthetics and pavement layers on the performance of reinforced flexible pavements (Bohagr, 2013). A general benefit was confirmed for the use of geosynthetics in the subgrade layer.

The main objective of this paper is to demonstrate the influence of geogrid reinforcement on pavement design. A parametric study was carried out with the ADINA Finite Element (FE) program using two-dimensional (2D) modeling for this purpose. A numerical analysis was performed on flexible pavements, considering different types of pavement materials and structures, traffic conditions and subgrade quality. The results confirmed the impact of reinforcement on pavement design.

The contribution of this paper and the different information the study provides compared to those previously reported in the literature is the wide range of conditions analyzed in the numerical simulations of geogrid-reinforced subgrade: subgrade quality (stiffness), characteristics of the base and sub-base layers (thickness and stiffness) and the bituminous layer (thickness and stiffness). These conditions were based on experience in Portugal, but they are also representative of subgrade reinforcement situations around the world. Two ratios are presented in this paper for analyzing the benefit of geogrid reinforcement in terms of the increased admissible traffic and reduction of the bituminous layer it enables.

2 Methodology

2.1 Pavements and Materials

A numerical study of the influence of geogrids on the pavement design was performed based on the Portuguese experience in road construction and in the use of geosynthetics (Lima, 2013).

The effect of the geogrid reinforcement was analyzed taking into consideration the influence of different conditions: subgrade quality, traffic volume and pavement structure (layers and materials). The selection of these conditions was based on the Portuguese pavement design manual (JAE, 1995).

Subgrade quality – subgrade class – was defined in terms of the stiffness modulus. In the study, two classes were considered – F1 and F2 – which correspond to the equivalent stiffness modulus of 30 MPa and 60 MPa, respectively. The cumulative number of Equivalent Standard Axle Load (ESAL) of 80 kN that passes over the pavement during a 20-year period – N_{80}^{dim} – was used to describe heavy traffic volume: traffic class. Calculation of this value was based on the Average Annual Daily Traffic (AADT) of heavy vehicles, and considered a specific traffic growth rate and aggressiveness factor. Three traffic classes corresponding to low volume flexible pavements were considered: T7 ($N_{80}^{dim} = 1\times10^6$), T6 ($N_{80}^{dim} = 2\times10^6$), and T5 ($N_{80}^{dim} = 8\times10^6$) (Gonçalves, 2015; JAE, 1995).

The flexible pavements considered in the parametric study are shown in Figure 1. The three pavements are composed of unbound granular layers of base and sub-base and a bituminous layer (asphalt concrete). The number and thickness of the granular layers varies: Pavement 1 has a single base layer 20 cm thick (Figure 1a); Pavements 2 and 3 have both base and sub-base layers measuring a total of 30 cm (Figure 1b) and 40 cm (Figure 1c), respectively. Table 1 presents the thickness of the bituminous layer – t1, t2 and t3 – according to the primary pavement conditions: subgrade and traffic classes. In the case of subgrade class F1, Pavement 1 was considered inadequate due to the low quality of the subgrade and the existence of a single granular layer of base (20 cm).

The pavement and subgrade materials were those currently used in Portuguese road construction. Crushed limestone aggregates 0/31.5 were considered in the base and sub-base layers. Fine or granular soils may exist in the subgrade to ensure the required stiffness. The bituminous layer was made up of asphalt concrete (AC): surface layer (AC 14 surf) and base layer (AC 20 base). Natural aggregates are granitic or basaltic in origin in the case of surface layer and limestone in origin in the base layer. The most commonly used bitumen binder has a penetration grade of 35/50.

The pavement design was based on fatigue cracking (asphalt concrete) and rutting (soil subgrade) criteria, in order to guarantee the cumulative number of ESAL during a 20-year period.

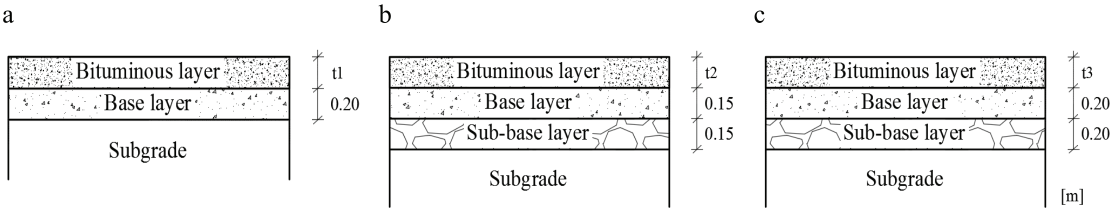

Figure 1: Pavement structures: (a) Pavement 1; (b) Pavement 2; (c) Pavement 3

Pavement type	Pavement layer	Thickness [m]					
		F1			F2		
		T5	T6	T7	T5	T6	T7
1	Bituminous layer (t1)	(*)	(*)	(*)	0.22	0.18	0.16
	Base layer	0.20	0.20	0.20	0.20	0.20	0.20
2	Bituminous layer (t2)	0.25	0.20	0.17	0.20	0.15	0.13
	Base layer	0.15	0.15	0.15	0.15	0.15	0.15
	Sub-base layer	0.15	0.15	0.15	0.15	0.15	0.15
3	Bituminous layer (t3)	0.23	0.19	0.17	0.19	0.15	0.13
	Base layer	0.20	0.20	0.20	0.20	0.20	0.20
	Sub-base layer	0.20	0.20	0.20	0.20	0.20	0.20

(*) Pavement structure not adequate.

F – subgrade class; T – traffic class; t – thickness of bituminous layer

Table 1: Conditions adopted in numerical simulations

The numerical simulations considered elastic linear behavior for all pavement materials including the subgrade soil, which is characterized by the stiffness modulus (E) and the Poisson ratio (ν). Table 2 presents the mechanical properties of the materials. In the case of the bituminous layer, the stiffness depends on the air temperature, as well as other factors, because asphalt concrete exhibits a viscoelastic behavior. The selected value – 3,000 MPa – intends to take into account the most unfavorable scenario to the reinforcement, in association to the highest air temperatures of the climatic regions in Portugal (Batista and Picado-Santos, 2002; Picado-Santos, 1994).

With respect to geogrid, Table 3 presents the main characteristics used in the modeling: thickness (t_G), stiffness modulus (E) and the Poisson ratio (ν). The table also indicates the references used to select these characteristics: t_G is based on Bohagr (2013); E and ν, on Erickson and Drescher (2001). A total friction between the geogrid and the subgrade was considered.

Pavement type	Pavement layer	Subgrade class			
		F1		F2	
		E [MPa]	ν	E [MPa]	ν
1	Bituminous layer	(*)	(*)	3,000	0.40
	Base layer	(*)	(*)	120	0.35
	Subgrade	(*)	(*)	60	0.35
2/3	Bituminous layer	3,000	0.40	3,000	0.40
	Base layer	120	0.35	240	0.35
	Sub-base layer	60	0.35	120	0.35
	Subgrade	30	0.35	60	0.35

(*) Pavement structure not adequate.

Table 2: Mechanical properties of pavement materials

Material	t_G [m]	E [MPa]	ν
Geogrid	2.54×10^{-3}	4,230	0.35

Table 3: Characteristics of the geogrid material

2.2 Numerical Modeling

Numerical modeling was carried out with the finite element program ADINA using two-dimensional modeling (2D) (ADINA, 2001; Gonçalves, 2015). The pavement layers, the geogrid material, and the subgrade were modeled with eight-node isoparametric elements. The modeled domain was 2.5 m wide and 2.5 m long of the subgrade layer. The boundary conditions of the mesh were characterized by roller support for the vertical boundaries (fixed horizontal movements) and fixed support at the bottom of the mesh (fixed movements in all directions).

For the 2D analysis, a circular tire contact area was considered with a diameter of 15 cm, a tire pressure of 570 kPa and a force of 40 kN, which is equivalent to the effect of the standard axle 80 kN.

3 Results and Discussion

Numerical simulations were performed in both scenarios: unreinforced and geogrid-reinforced subgrade. Strains and displacements were the main selected values extracted in each simulation (vertical and horizontal directions). A general reduction of strains and displacements was achieved due to the presence of the geogrid in all traffic and subgrade conditions. However, the most significant effect of the reinforcement was observed in terms of vertical strains and horizontal displacements (Gonçalves, 2015).

Figure 2 presents an example of the vertical strains obtained for the Pavement 2 (F1, T7): unreinforced subgrade (Figure 2a) and geogrid-reinforced subgrade (Figure 2b). A significant reduction in vertical compression strains at the subgrade level is observed. This fact is a result of increased pavement bearing capacity due to the geogrid reinforcement.

Similarly, Figure 3 shows the reduction in the horizontal displacements obtained for Pavement 2 under the same traffic and subgrade conditions. The unit of displacements in this figure is the meter.

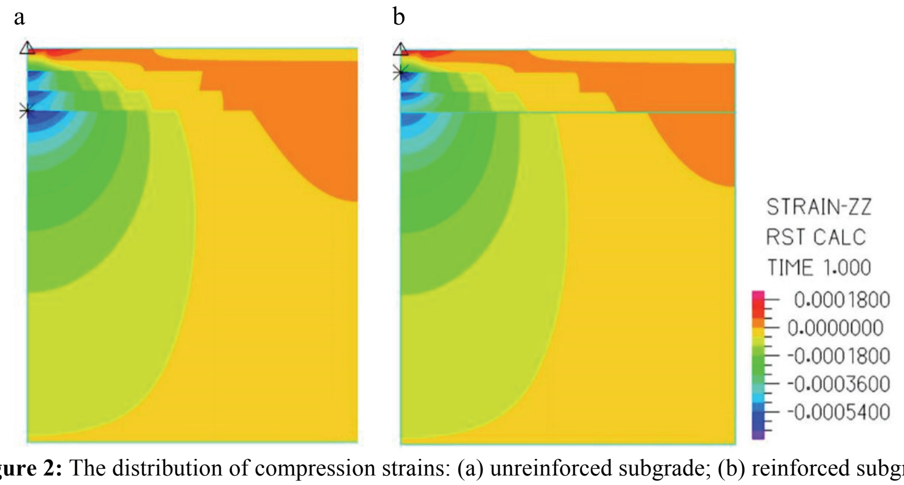

Figure 2: The distribution of compression strains: (a) unreinforced subgrade; (b) reinforced subgrade

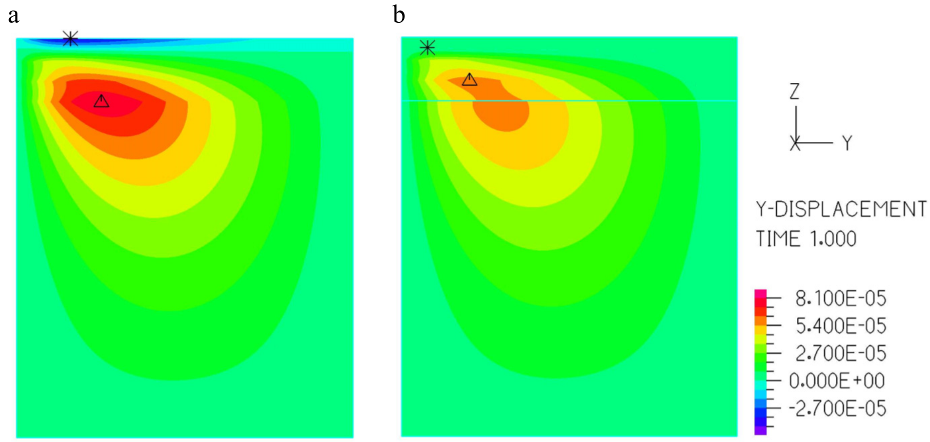

Figure 3: The distribution of horizontal displacements: (a) unreinforced subgrade; (b) reinforced subgrade

The benefit of the reduction in horizontal displacements is most significant close to the geogrid interface. In fact, the main mechanism involved in the benefit achieved by using geogrid reinforcement in pavements is expected to be the lateral constraint. Numerical calculations confirmed this significant confinement, not only in the base course material but also in the subgrade soil.

Taking into account the design criteria commonly used in flexible pavement design, maximum tensile strain of fatigue (ε_t^{max}) and maximum compression strain of rutting (ε_c^{max}) were evaluated, respectively, in the bottom of the bituminous layer and the top of the subgrade soil on the vertical line through the load center. Figure 4 shows the variation of the strains obtained in all the simulated cases: the variation of the maximum tensile strain ($\Delta\varepsilon_t$), horizontal, and the variation of the maximum vertical strain ($\Delta\varepsilon_c$), vertical. In general, it could be concluded that geogrid-reinforcement of the subgrade induced a an overall reduction in strains, which was more marked in the case of compression strains associated with rutting criterion. The maximum strain variation was achieved in the pavements with thick base and sub-base (Pavements 2 and 3), soft subgrade (F1) and thin bituminous layer (T7): 2% and 18%, respectively, in the cases of horizontal and vertical strains.

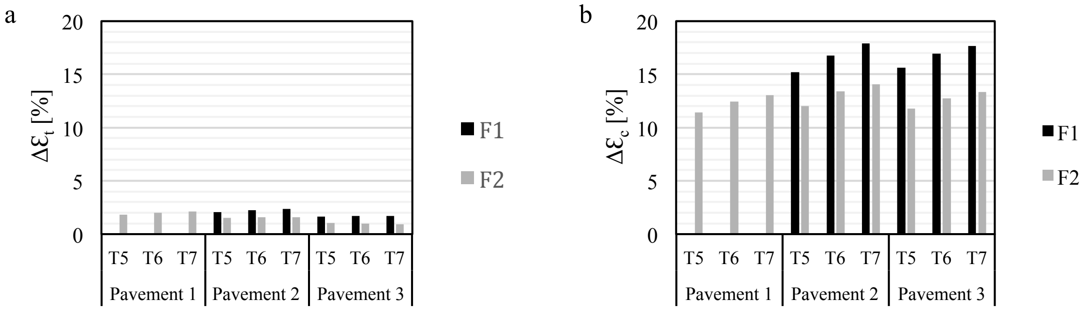

Figure 4: Influence of the geogrid on the strains reduction: (a) tensile strain; (b) compression strain

Two potential outcomes of the reduction in strains could be: (1) the increase in the admissible number of load cycles, and (2) a reduction in the thickness of pavement layers.

The literature establishes some parameters that are used to measure the improvement of bearing capacity in pavement structure provided by the presence of the geogrid. These include the Traffic Benefit Ratio (TBR) and the Base Course Reduction (BCR) ratios (Mounes et al., 20111; Zornberg and Gupta, 2010). The TBR is the ratio between the number of load cycles on the reinforced pavement

(N_R) and the number of load cycles on the unreinforced pavement (N_U), for the same pavement structure and a specified rutting depth (Equation 1). The BCR is the ratio between the base course thickness on the reinforced pavement (t_R) and the base course thickness on the unreinforced pavement (t_U), to reach the defined failure state (Equation 2).

$$\mathrm{TBR} = \frac{N_R}{N_U} \tag{1}$$

$$\mathrm{BCR} = \frac{t_R}{t_U} \tag{2}$$

With respect to the overall reduction in strains, an increase in the admissible number of load cycles can be achieved. Considering the maximum values of the strains from the numerical calculations, Gonçalves (2015) estimated the admissible number of load cycles by using Shell failure models for fatigue (Equation 3) and rutting (Equation 4) (Claessen et al., 1977; Gerritsen and Koole, 1977).

$$\varepsilon_t = (0{,}856\ V_b + 1{,}08)\ E^{-0{,}36}\ N^{-0{,}2} \tag{3}$$

$$\varepsilon_c = 0{,}018\ N^{-0{,}25} \tag{4}$$

where: ε_t – fatigue strain; . ε_c – rutting strain; V_b – volumetric percentage of bitumen (9%); E – AC stiffness modulus; and N – admissible number of load cycles.

In this paper, a modified TBR – TBR_m – was evaluated as defined in Equation 1 but using the calculated admissible number of load cycles obtained from the failure models (Equations 3 and 4). Figure 5 presents the TBR_m values for all the simulated cases. In the case of the fatigue criterion, the effect of the geogrid is negligible (Figure 5a). However, in the case of the rutting criterion, a significant influence of the geogrid is observed (Figure 5b). This effect is more pronounced when the subgrade is of lower quality (when the subgrade class is F1) and the traffic volume is lower (meaning that in this case the bituminous layer is thinner). The other pavements showed identical behavior. In general, TBR_m values for rutting criterion were in the range of 1.6 to 2.2.

The bituminous layers have a significant influence on the final cost of the pavement construction. For this reason, the viability of reducing the thickness of the bituminous layer can be very important if the geogrid used in the subgrade can achieve this objective. For this purpose, a modified BCR was selected as defined in Equation 2 using the thickness bituminous layer of the reinforced (t_R) and unreinforced pavements (t_U), respectively: Bituminous Layer Reduction (BLR). For this ratio, the design of reinforced pavement is established for the same admissible number of load cycles of the unreinforced pavement. Results demonstrated that this influence is negligible for the fatigue criterion. The Figure 6 shows that it is possible to achieve a reduction in the thickness of the bituminous layer for the rutting criterion in a geogrid-reinforced pavement.

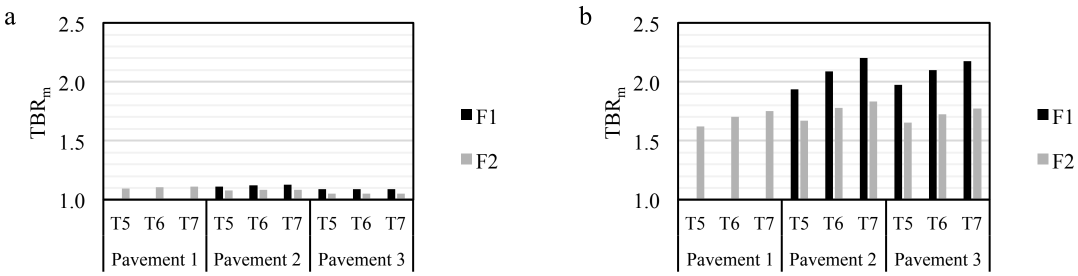

Figure 5: Influence of the geogrid on the admissible number of load cycles: (a) fatigue; (b) rutting

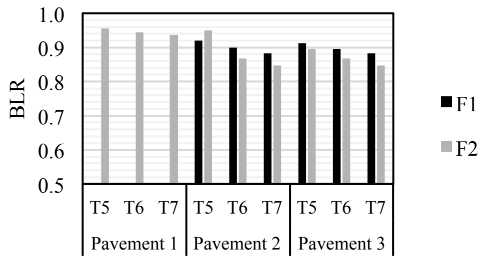

Figure 6: Influence of the geogrid on the thickness of bituminous layer considering the rutting criterion

Maximum reduction of the bituminous layer was possible in the case of thick base and sub-base layers (Pavements 2 and 3) and thin bituminous layers (corresponding to the T7 traffic class). This sensitivity is more marked in the case of the F2 subgrade class: the minimum value of BLR is 0,85 that corresponds to 2 cm of maximum reduction of the bituminous layer.

4 Conclusions

This paper presented a numerical study through a 2D FE modeling of geogrid reinforcement of the subgrade of flexible pavements with the main objective to demonstrate more comprehensively the impact of subgrade reinforcement on pavement design.

Three pavement structures and different conditions were analyzed: traffic, subgrade quality and pavement layers thickness. The results of FE modeling were discussed in terms of variation in strains and displacements on pavement layers and subgrade soil, comparing the reinforced and the unreinforced pavements. The reduction observed in these values confirmed the impact of geogrid reinforcement on the pavement design: fatigue and rutting criteria.

The influence of the geogrid on the reinforced pavement was demonstrated by the discussion of results through the increase of the admissible number of load cycles (increasing of the pavement life cycle), and the reduction of the bituminous layer thickness (reduction of pavement costs). Two modified ratios were created to become these two geogrid effects more comprehensive: the modified Traffic Benefit Ratio (TBR_m) to quantify the increase of the admissible number of load cycles calculated by the use of failure models of fatigue and rutting criteria; the Bituminous Layer Reduction (BLR), as a consequence of the admissible traffic increasing due to the geogrid reinforcement.

The main conclusions presented in the paper are:

- A general reduction of strains and displacements was observed in modeling due to the subgrade reinforcement with the geogrid.
- The most significant effect of the geogrid reinforcement on the pavement strains was achieved for rutting criterion. An important reduction of vertical compression strains at subgrade level was observed. The maximum strain variation – 18% – was obtained in the pavements with thick base and sub-base, soft subgrade, and thin bituminous layer.
- A reduction of the horizontal displacements was also obtained for the same conditions: pavements with thick base and sub-base, soft subgrade, and thin bituminous layer. This effect was more marked near the interface of the geogrid, not only in the base course material but also in the subgrade soil.
- The TBR_m values for rutting criterion, expressing the increase in the admissible number of load cycles in the reinforced pavement, were in the range of 1.6 to 2.2.
- The reduction of the bituminous layer was also possible and the minimum value of BLR was 0,85, i.e., 2 cm was the maximum reduction of the bituminous layer.

- In general, the most significant benefit of the geogrid reinforcement on pavement design was obtained for the rutting criterion and for the most flexible pavement structures, those with low quality subgrade, thick unbound granular layers of base and sub-base and thin bituminous upper layers.

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