Influence of the reinforcement in the compaction of the soil layers – an experimental analyses

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Abstract

Geosynthetics reinforcements are used for pavement structures and shallow fills as alternatives in the execution of roads over weak subgrades. The use of reinforcements involves a number of benefits, such as a better distribution of the traffic load and a higher lifetime of the pavement. Many researchers aim to analyze the reinforcement behavior and its characteristics under the cyclical loading of the trafficking during the lifetime of the paved roads, but little attention has been given to the quality of the compacted layer. This research discusses the influence of geogrid reinforcement during the compaction of reinforced soil layers, considering the ability to increase the resistance of the layer. As means for the work, a laboratory experiment was set simulating sections of the pavement with and without the insertion of a geogrid. Stiffness parameters were verified after the Plate Load test (PLT) and compared among them. The reinforcement enabled a high increase in the magnitude of the deformability modulus (E_{v2}), even though the boundary conditions were limited.

Keywords: Compaction of soil, geogrids, reinforcement.

1. Introduction

Soil compaction is an important technique used to promote soil conditions suitable for use in civil engineering constructions such as embankments, foundations and pavements. It is well know that the compaction process leads granular soils to exhibit better construction properties, such as increased stiffness and shear strength, and reduced permeability of the soil layer. In particular, for road structures, the strength properties are important parameters to evaluate in soil compacted layers taking into account the dynamic design loads to avoid shear failures or excessive settlements, according to project requirements.

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Frequently, in road designs, due to the high load volume and minimum deformation requirements, compaction of granular soils can become a problem if the subgrade below exhibits low bearing capacity. One of the techniques that allows a better execution of the soil layer compacted above weak subgrades is the insertion of geogrids as reinforcement (Berg et al., 2000).

Since the 1970s, geosynthetics, especially geogrids, have been used as base-reinforcement to afford better conditions for the execution of soil layers above weak subgrade, providing a rigid platform for road construction and increasing the subgrade bearing capacity. Moreover, several researches have shown that geogrids can improve the performance of pavement sections by reducing of the permanent deformation caused by vehicular loads. One of the main mechanics of geogrids in reinforcement function for roads is the lateral restraint (Abu-Farsakh, M., et al., 2016; Al-Qadi et al., 1994; Perkins et al., 2005; Perkins, 1999).

The lateral restraint, or confinement, is the effect due to the frictional and interlocking characteristics at the interface between the geosynthetic and the aggregate. The interaction between the aggregate and the geosynthetic allows the transfer of the shear load from the base layer to the geosynthetic reinforcements, thus reducing the shear stress developed in the upper layer. In addition, the shear resistance effect at the interface of the soil-reinforcement system increases lateral confinement and restraint the lateral movement of the layer above the reinforcement, and this increase in the confinement tension provides an increase in the layer's stiffness. Furthermore, this mechanism also provides better vertical distribution of tension in the subgrade due to the increase in the base elastic modulus and reduce shear stress along the top of the subgrade (Perkins, 1999; Berg et al., 2000; Zornberg & Gupta, 2010).

To obtain better results from this reinforcement mechanism a good soil-reinforcement interaction is needed, and that some characteristics of the reinforcement can enhance the lateral restraint, such as the geogrid apertures. This restraint between the soil and the reinforcement can provide a constructive platform capable of increasing the stiffness property of the layer above that reinforcement, even when in weak subgrades. Aware of this effect, if the stiffness of the layer above the reinforcement is increased, it can be expected that the compaction of this layer will be more efficient. However, the improvement of compaction due to reinforcement is little explored in the literature as a parameter for sizing or as a decision criterion in engineering projects. This can be attributed to the limited number of studies that address this topic and the difficulty of measuring this benefit (Perkins, 1999; Kwon & Tutumluer, 2009; Pei & Yang, 2018).

This paper presents an experimental analysis to investigate the influence in the support capacity of the compacted layer due to the presence of geogrid reinforcement. The analyses were made comparing the traditional compaction parameters, as dry density and moisture content, and stiffness parameters of the layers of three section configurations (one without reinforcement and two reinforced sections). To verify the stiffness parameters, plate tests were performed to check the deformability modulus (E_{v2}). Deformability modulus or reload modulus is an indicator of the bearing capacity of the soil or the flexible pavement under certain conditions simulated by loading and unloading a load plate. The load plate test is performed using fixed loading and unloading time steps and measuring settlement values.

2. Compaction and reinforcement of the soil layers

Soil compaction is one of the oldest and most commonly technique used to provide to the soil the stiffness properties that characterize the construction projects to which they are aimed. With the pioneering collaboration of Proctor, the process of soil densification by means of energy delivery under certain moisture content conditions is being researched showing itself as a very meaningful tool in soil construction projects.

Soil compaction process is based on obtaining a material with characteristics suitable for the intended application, and ensuring adequate conditions for construction during its service lifetime. The main benefits acquired in the soil compaction process are: increased soil strength and bearing capacity, in addition to reducing compressibility and permeability (Kodikara et al., 2018).

The soil compaction technique is characterized by the performance of a mechanical load in a specific condition of moisture for each type of soil, which will provide a dry specific weight, capable of guaranteeing the cited benefits during its service life. Achieving the uniformity of the compacted layer is decisive to successful compaction process. Many studies have shown that the primary reason for road failures are due to an uneven degree of compaction with gives insufficient bearing capacity for the soil layer. Commonly, in-situ spot tests are required for the quality control and uniformity of the layer. However, this conventional density control method has many issues associated, as sometimes weak compaction areas may be not identified and the measured density of top bound layer is limited to indicate the structural capacity of the entire pavement layers (Kodikara et al., 2018; Heitor et al., 2012; Chang et al., 2011).

In view of this procedure of relevant importance, numerous techniques and equipment have been developed to ensure the effective application of the load on the soil and the adequate uniformity of the layer. In addition, several techniques for controlling field compaction

parameters, such as nuclear density and strength modulus analysis, were developed and applied in addition to traditional moisture content and unit dry weight checks. Currently, Intelligent Compaction Technology is an effectively method able to record the soil response (i.e. soil stiffness or modulus) while the soil is being compacted (Heitor et al., 2012; Chang et al., 2011).

Furthermore, several factors influences directly the result of the compaction, among them there are: the soil origin, moisture content, the compaction energy, compactor travel speed and tire inflation pressure, the transmission mode of the energy and the number of pass, the environment condition, the preparation conditions, stiffness of the subgrade, the layer thickness and the influence of the reinforcement characteristics. Each of these factors has its peculiarity in relation to the final parameters reached in the layer through of the compaction (Vidal, 1985, Canillas & Vilas, 2001, Ferreira, 2008).

The stiffness of the constructive platform was approached by Arquie et al (1976) and Valeux and Morel (1980) as characteristic that directly influences the efficiency of the compaction process due to it provides greater homogenization of the layer density in depth. The energy applied during compaction should be related to the quality of the subgrade, since soil layers over subgrades with low stiffness under high energy loads are not able to absorb the load in depth in an equivalent manner, compromising deep soil compaction compromised. In this case, it is important to observe whether the applied energy is within the acceptable range with the bearing capacity of the subgrade or not.

Some author had observed that inserting a reinforcement material above a low bearing capacity soil the material compacted above the reinforcement presents increases in its strength properties. The stiffness of the reinforcement together with the confinement effect given by the interlocking of the grains and the aperture of the geogrid enable the applied energy to be better used. This phenomenon usually produces a better efficiency in the process of compaction (Kwon & Tutumluer, 2009; Pei & Yang, 2018).

Cancelli e Montanelli (1999) present in their research a high efficiency of the reinforcement in the execution of the layers, being verified an immediate improvement in the execution of section with small thickness above a weak subgrade with the presence of reinforcements. The absence of rut depth observed during the first 500 cycles of traffic over the reinforced layers in comparison with the rut depth of many millimeters on the layers without reinforcement allows the forecast a beneficial improvement of the reinforcement in the executed layer.

Klein et al. (2002) and Turano et al. (2000) demonstrated, using laboratory experiments in which boulder subbases were simulated over a low bearing capacity subgrade, with and

without reinforcement, that the presence of reinforcement can increase the bearing capacity of the reinforced layer by about 30 % in relation to the non-reinforced layer. The authors attribute this resistance improvement to the conditions of the interface soil-reinforcement, together with the confinement provided by the geogrid actuation mechanism.

Kwon and Tutumluer (2009) demonstrated from numerical modeling and field studies of geogrid base reinforce pavement systems, a stiffening effect around geogrid reinforcement and its result in improving the response and performance of the pavement. The stiffened zone observed around the geogrid reinforcement is mainly caused by the interlocking of aggregate particles in the geogrid apertures. The height of the influenced zone, where the load-induced permanent residual stresses locked in around the geogrid, was approximately 15 cm above and below the geogrid. An increase in horizontal confinement caused by residual stresses resulted in significant increases in the moduli of the base and subgrade layers in the proximity of the geogrid reinforcement.

Pei and Yang (2018) used a discrete element method (DEM) model to simulate the development of compaction-induced stress in a granular base course, with and without reinforcement. In this research was observed that geogrid reinforcement helps granular bae courses to lock in additional compaction-induced stress during the roller compaction. This behavior is attribute to confining effect from the residual tensile stress in the geogrid, which increase with the number of compaction passes. Moreover, to mobilize the benefit of the geogrid reinforcement when the subgrade has low bearing capacity are needed more compaction passes.

3. Materials and Methods

3.1. Tests conception and materials

Aiming to gather experimental data to analyze the influence of the geosynthetic reinforcement in the improvement of the compaction of soils, laboratory tests were performed considering the superposition of the subgrade layer and the subbase layers with and without reinforcement elements, and with a separation element between them. In total, three tests were concluded with the following order: a test without the reinforcement element (referred to as E-1-SR) and two test with the reinforcement element. Between the reinforced tests, there was a variation in the stiffness of the reinforcement, where the first reinforcement has a low stiffness and the second has a high stiffness (referred to as E-2-GR1 and E-3-GR2, respectively).

The subgrade was composed by a mixture of two industrial clays prepared in the laboratory. The clays, classified as kaolinite and bentonite, had more than 99 % of passing

material through the sieve # 325 and they were mixed with the ratio 4:1. For the mixture there was a liquid limit of 74 % and plastic limit of 24 %, that is, a plasticity index of 50 %. In the execution of the test the water content used was of 32 %.

The subbase was simulated by a graded gravel, as can be seen in Figure 1. From the characterization tests, the material was classified by the HRB (Highway Research Board) and by the USCS (Unified Soil Classification System) standards as A-1-a and GW, respectively. The Modified Proctor test provided an apparent dry unit weight of 23.4 kN/m^3 and optimal moisture content of 6.1%. These parameters guided the preparation of the material through the experiment.

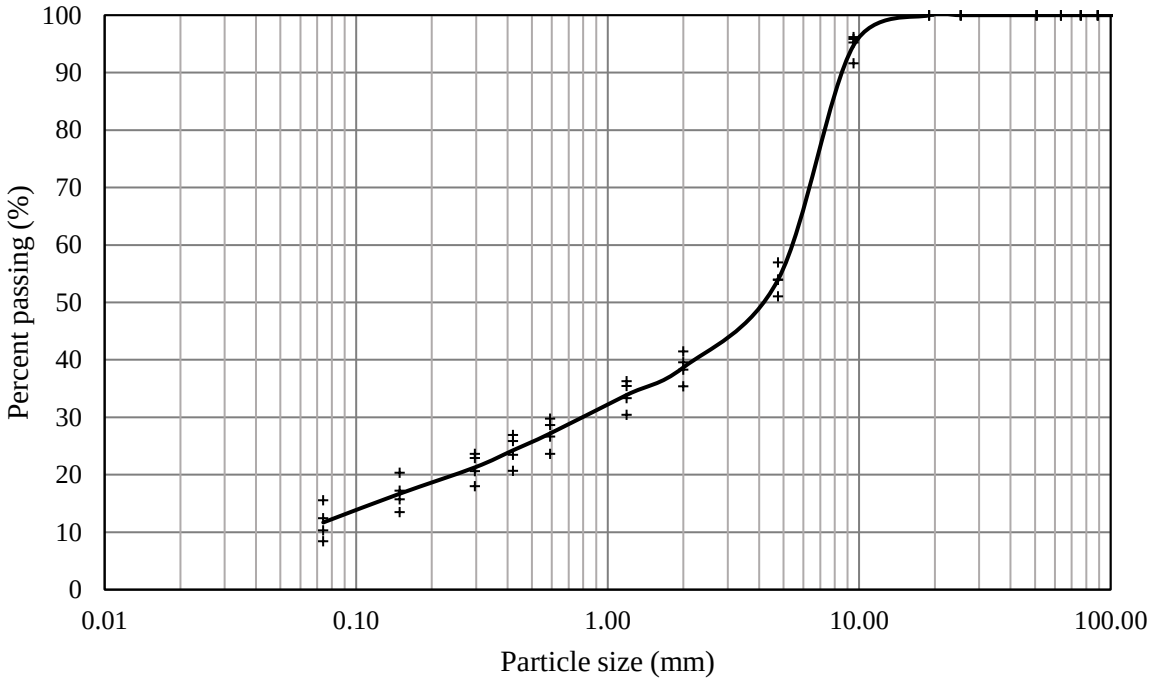


Figure 1: Particle size distribution curve for subbase material

Two biaxial geogrids with protective polymer coating (Huesker Basetrac® Grid PET 40 and Huesker Duo 80/80B 25FT, referred to as GR1 and GR2, respectively) were used in the test sections. These products were chosen to provide a range of parameters thought to control reinforcement ability in the compaction of soil layer. Moreover, these geogrids have been recommended for base reinforcements, and the choice for them was based on related research witch used the similar aperture for a similar particle-size distribution of the subbase material. The physical and mechanical properties of these geosynthetics as provided by the manufacture are presented in Table 1.

185 Table 1 Geosynthetic material properties (from the manufacturer)

Properties	**Unit**	**Test standard**	**Geogrid GR1**	**Geogrid GR2**
Aperture Size (MD x CMD)	mm	-	25 x 25	30 x 30
Mass per unit area	g/m²	EN ISO 9864	257	714
Tensile Strength (MD)	kN/m	EN ISO 10319	48,9 ± 0.3	92,4 ± 0.5
Tensile Strength (CMD)	kN/m	EN ISO 10319	44,2 ± 0.4	90,6 ± 1.2
Strain at maximal Tensile Strength (*MD*)	%	EN ISO 10319	10,2± 0.2	9,2 ± 0.5
Strain at maximal Tensile Strength (*CMD*)	%	EN ISO 10319	9,9 ± 0.2	7,9 ± 0.3
Stiffness at 2 % strain (MD)	kN/m	EN ISO 10319	580	970
Stiffness at 2 % strain (CMD)	kN/m	EN ISO 10319	530	1055

MD - machine direction CMD - cross machine direction

186 A non-woven geotextile with high deformability was used with separation and filtration
187 functions between the subgrade and subbase layers to guarantee there was no mixture of the
188 adjacent materials.

189 In execution of the tests each compacted layer had its physical (density and water
190 content) and mechanical characteristics evaluated. The mechanical behavior was evaluated
191 through plate loading tests, following the instructions of the German standard DIN 18134:2012,
192 which provided the deformability modulus (E_{v1} e E_{v2}) of each layer.

193 These compaction tests were performed in a wood box, constructed with two
194 compartments, an inferior compartment for the subgrade and a superior compartment for the
195 subbase. This configuration was required so there would be an anchorage of the geogrid on the
196 outside of the box. The box had internal lateral dimensions of 30 cm x 30 cm and height of 40
197 cm. The overall nominal design cross-section of the tests sections is given in Figure 2.

198 To avoid lateral displacements through the box walls, a locking system made of steel
199 angles was placed on the outer sides of the box in both compartments. In addition, to reduce the
200 friction with walls and soil, was used employing on the inner side of the box two plastic sheets
201 with graphite grease between the sheets.

202 Moreover, a drainage system was installed under the subgrade with the goal to avoid
203 that an excess of water could influence the results. This system, made up of a geomembrane, a
204 geospacer, and a filter geotextile, allowed to verify the existence of water carried to the drainage
205 system during the test.

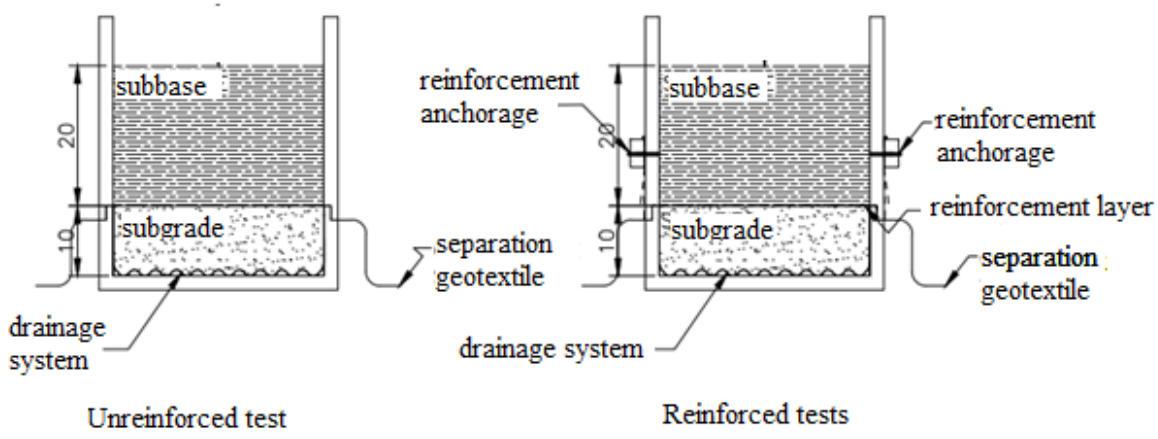


Figure 2: Test configuration (units in centimeter)

The applied force was visually monitored by a load cell placed directly over the receiving load surface. For the displacement measurements, two extensometers were installed in each step to observe the vertical displacement of the load plate tests in the subbases and for the verification of the stabilization of the settlements in compaction of the subgrade. The data acquisition of the extensometers was performed by connecting them to a computer, where an acquisition software collected the data from extensometers and recorded the average speed and the total displacement of the settlement for every 10 seconds of time.

3.2. Compaction process

The subgrade was compacted statically in three layers with 60 kN/m² loads (light compactor) applied over all of its surfaces through a rigid plate until the settlement velocity was inferior to 0.02 mm/min. At the end of the execution of the subgrade, the deformability modulus was measured as explained in the Section 3.3.

The compaction of the subbase layer was subdivided into two layers. Each layer received static loads of 150 kN/m² (Modified compactor) applied through a rigid plate over a third of the surface area (28 cm x 9,5 cm), during an interval of 10s, simulating the passing of a static roll.

The passing procedure was performed from the left to the right and after from the right to the left, repeating the process of loading and unloading four times in each layer, that is, simulating eight passing for each layer. At the end of the compaction of each layer, the height of the layer and its deformability moduli (E_{v1} and E_{v2}) were measured as explained in the Section 3.3.

For began the experiment without reinforcement the first step of compaction was performed in loads of 50 kN/m² for 10 s until to reach the 150 kN/m², just to calibrate the

apparatus. It was noted the necessity of adjustment of the high in load applicator due to the settlement observed. This adjustment of the high was necessary to all experiment, thus, in first three steps, the load of 150 kN/m² was applied, but the adjustment was also needed. The time of 10 s was considered only after the vertical displacements could occur without a new height adjustment in the loading system.

3.3. Finding the deformability modulus (Ev1 e Ev2) of the compacted layers

For each compacted layer, it was planned a disposition of the tests to verify the deformability modulus (E_{v1} e E_{v2}). The area of the box was divided into four quadrants. For each layer, the plate test was made in two diagonal quadrants as presented in Figure 3, exchanging the quadrants through the layers so the test in one layer would not interfere in the next test of the superior layer.

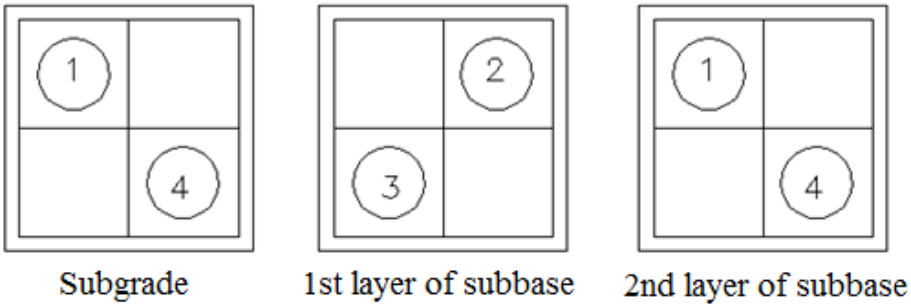


Figure 3: Plate load test quadrants for each layer

The plate test followed the procedure described by the German standard DIN 18134:2012 with exception of the plate dimension. Considering the area of the box and the thickness of the layers, it was decided to use a plate with 100 mm of the diameter so the next layer would not influence in the results, especially so the reinforcement would not directly influence in the settlements measured. The distance from the plate to the box wall was approximately 40 mm and the influence of the boundary condition was not considered, as this procedure was performed in ever test boxes, and these experiments are only for comparison between them.

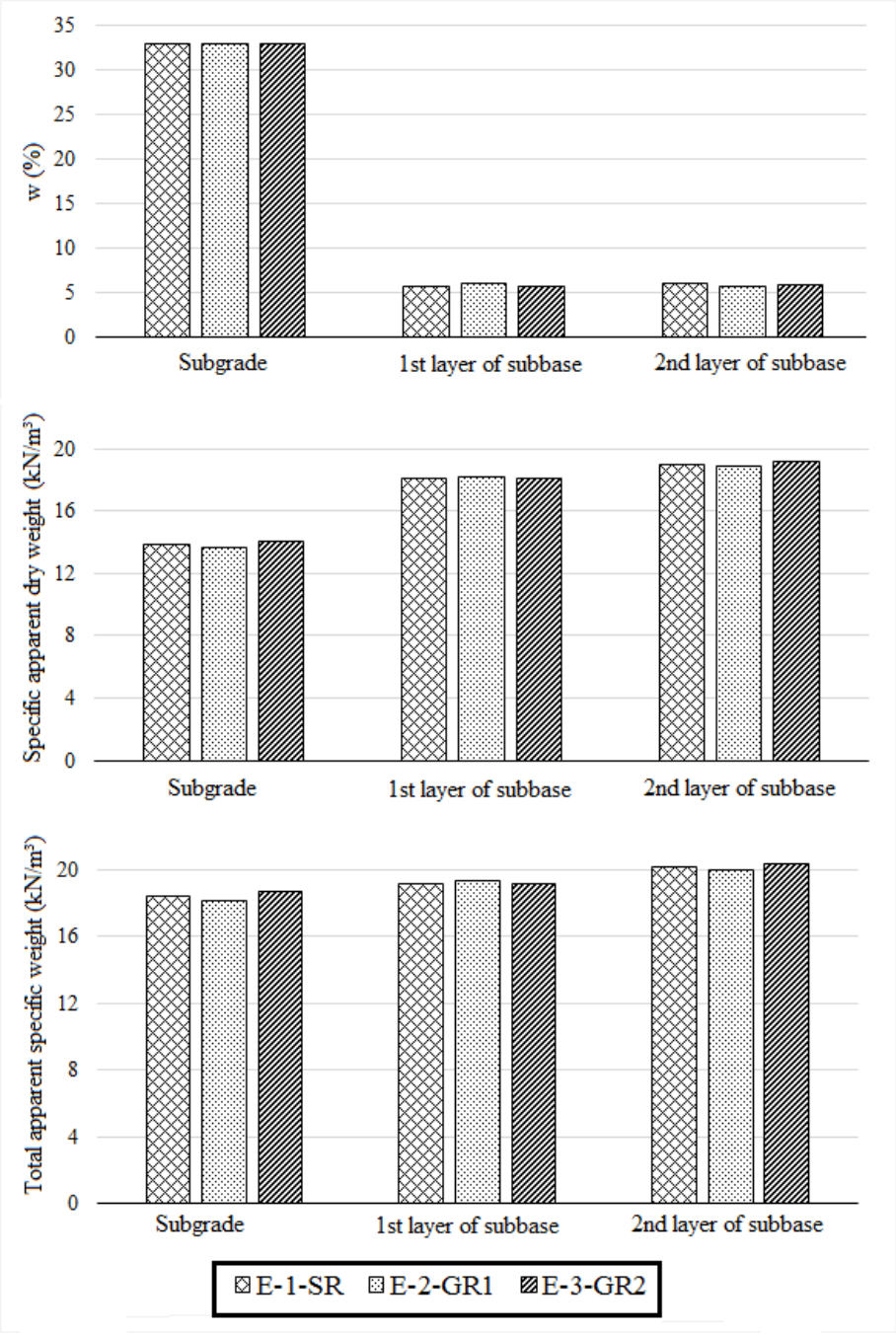
For the subgrade, the plate test was done with four stages of loading until to reach approximately twice of the compaction load. The sequence was of 20 %, 40 %, 70 % and 100 % of the maximum loading. Then, it was done two stages of unloading following the withdrawal of 60 % and 40 % of the maximum load. According to DIN 18134:2012, the loading was kept unaltered until the settlement velocity would become lesser than 0.02 mm/min in each stage, then, it proceeded to the next step of the loading or unloading. For the subgrade layer, the

standard does not require the reloading, but in this experiment, in order to calculate the E_{v2} of the subgrade, the reloading was performed in at least one of the quadrants for each test.

For the subbase, it was performed 15 stages of loading, being 2 cycles of loading and 1 cycle of unloading. The maximum loading provided was approximately twice of the compaction load applied. The first loading process was performed in 6 stages with similar increments up to the maximum load. The unloading was performed in 3 stages, in sequence of 50 %, 25 % and 25% of the maximum load, then, followed by the second loading process in 5 stages with similar increments, as it was in first loading. Each loading or unloading stage was maintained for a period of time of 1 minute, as recommended by DIN 18134:2012.

4. Results and discussion

The results obtained by the compaction parameters such as water content and estimated dry and total apparent specific weight are presented in Figure 4. The values for the deformability modulus (E_{v1} e E_{v2}) obtained in the plate loading tests for each quadrant are presents in Figure 5



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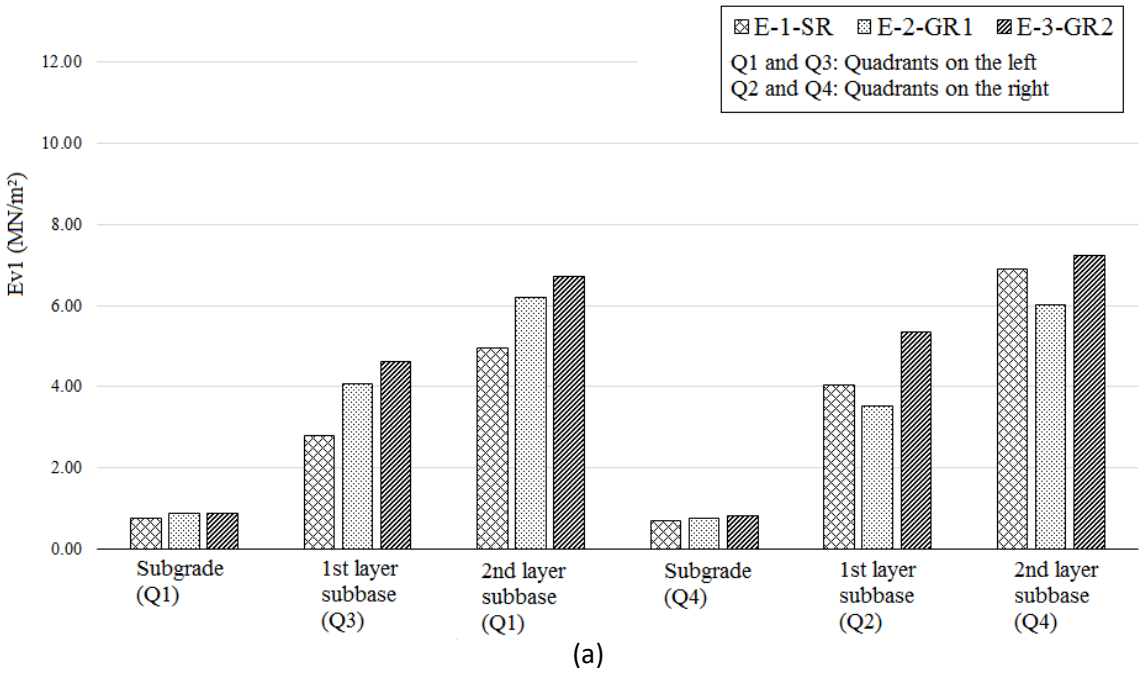
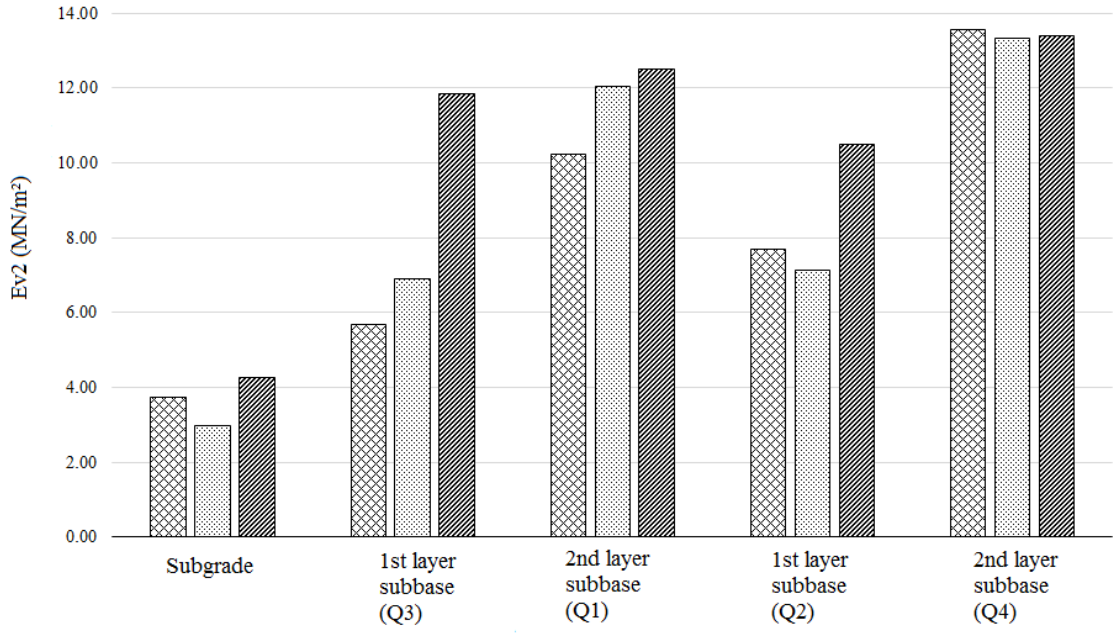
273 Figure 4: Compaction parameters



(a)



(b)

Figure 5: Deformability Modulus (a) E_{v1}, (b) E_{v2}

As the experiments were disassembled, the capacity of the reinforcement to preserve the integrity of the bottom of the subbase was noted. By raising the upper box in the experiment without the reinforcement, the subbase soil disaggregated, as for in the cases with reinforcements the granular material of the base was kept confined by the geogrid, even when the aperture was much bigger than the size of the grains.

4.1. Compaction parameters analysis

From the results presented, it was noted that the mean density obtained were close to each other in all the tests. The density values for the subbase layer were little affected by the presence of the reinforcement. It stands out that the second layer of the subbase presented a density a little higher, as it was expected. From the values of the specific weight obtained for the subbase, it appears that the degree of compaction did not exceed 82 % of the Modified Proctor Test, even for the second layer.

During the execution of the compaction test, at the beginning of the compaction, with the loading plate on the left side of the box, the material on this side of the layer was moved to the right side during loading, providing this side with a higher final height in the layer. The lateral confinement of the box limited the movement of the material leading to a higher concentration of the material in the right part of the box.

4.2. Analysis of the deformability modulus

For a better understanding between the deformability modulus of the tests, it was prudent to separate the box on the left and right sides, given the influence of the compaction path process and the lateral confinement. This effect was observed especially during the first passing for all tests. In the case of the test E-1-SR, this ascending movement from the soil to the right side was more evident.

On the left side quadrants, where the compaction was done first, there was a significant improvement in Ev2 modulus due to the reinforcement. As of on the right side of the box, the reinforcement contributed less to the improvement of the deformability modulus of the first layer and nothing to the second layer, being this fact probably related to the aforementioned phenomenon of the lateral confinement during the compaction. As can be seen in (b)

Figure 5, it is noted that the first and second layers of the right side (quadrants Q2 and Q4) of the reinforced layers presents a deformability modulus smaller than what was observed for the layer without the reinforcement material. However, the quadrants located on the left side present more significant values of deformability modulus to compare the reinforced and non-reinforced section.

To evaluate the difference between the reloading modulus of the subgrade of the three tests, Figure 6 presents the relation between the modulus of the first layer of the subbase and the subgrade. There is a tendency of reinforcement to provide an increase proportional to the geogrid stiffness for both sides of the box, considering that the average stiffness at 2% of GR2 (average of MD and CMD values) is 82% higher than the average of GR1. There is also an

increase in less intensity on the right side of the box, where, due to the conditions mentioned, the E-1-SR test showed a high Ev2 value.

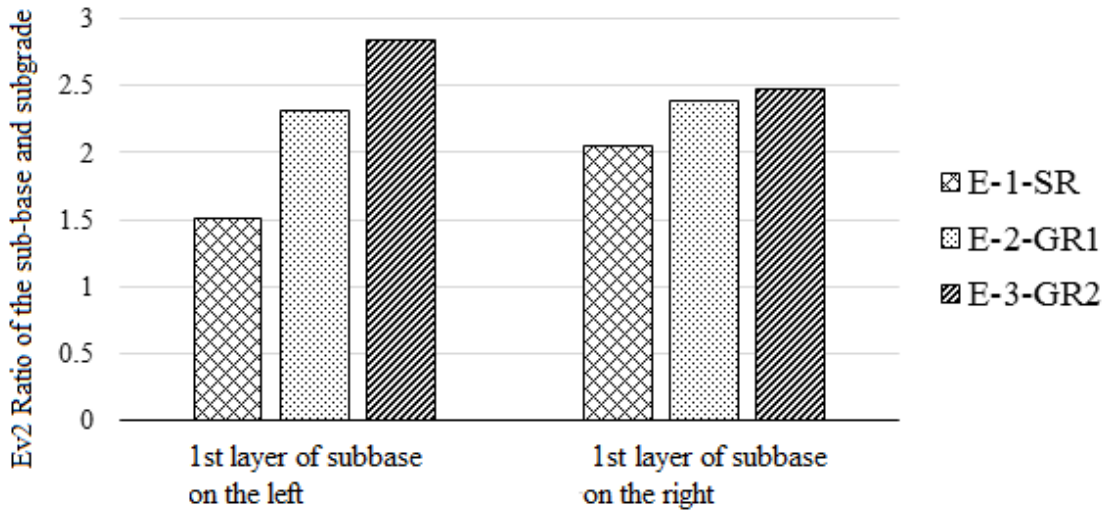


Figure 6: Relation between Ev2 of the first layer of the subbase and subgrade

Table 2 presents the percentage of the gains of the reinforced subbase layers in relation with the non-reinforced layers, normalizing the E_{v2} modulus of the subbase layers in relation to the modulus of the respective subgrade layer. To better understand the significance of these values, is interesting to remember that the average stiffness at 2% of GR2 is 82% greater than that of GR1.

Table 2 Reinforced subbase layer increase percentage

Geogrid	1st layer on the left	2nd layer on the left	1st layer on the right	2nd layer on the right
GR1	52	48	16	24
GR2	84	8	20	-13

Based solely on the values obtained by the quadrants on the left side, the insertion of the reinforcement provided, in both tests, a gain in the deformability modulus higher in the first layer than for the second layer. This behavior was expected since the inferior subbase layer already is a stiffer constructive platform for the second layer. As for the first layer, which was in direct contact with the subgrade, the stiffness gain at the interface provided by the reinforcement contributed to better compaction and a higher deformability modulus, proportional to the stiffness of the reinforcement. For the second layers, as mentioned, it was observed that the reinforcement did not significantly influence the stiffness gain, even showing no gain for the E-3-GR2 test.

5. Conclusions

The performance of the geogrid in the contribution of the properties of the soil-reinforcement system is subject of many researches and its benefits are evident. However, the efficiency of the reinforcement in the process of compaction is little discussed in the literature.

The test executed in this research enabled the conclusion that the reinforcement contributes to the improvement of the quality of the compacted layer above it, which can be an important characteristic for road constructions. The insertion of reinforcements provides a significant improvement for the deformability modulus of the first compacted layer above a subgrade with low bearing capacity and this gain is directly proportional to the stiffness of the reinforcement, as was observed by Kwon and Tutumluer (2009).

The values for the apparent specific weight of the layers compacted above a subgrade with low bearing capacity have no significant changes with the insertion of reinforcement in the cases tested. Probably the adoption of an identical compaction process for the reinforced and non-reinforced cases did not allow to achieve bigger densities that would be achievable for the reinforced case if the compaction energy was higher. Perhaps, with more compaction energy the increase in modulus increase would be more significant, as suggest Pei and Yang (2018).

The deformability modulus (E_{v2}) of the subgrade layer has strict relation with the need for reinforcement. For the reinforcement to be considered necessary, the behavior of the lower layer after many repeatedly loadings should continue critical, that is, its stiffness should be little benefited by the application of compaction loads on the superior layers because these layers gains its stiffness during the compaction of the superior layer. The reinforcement may not be necessary, presenting low efficiency.

The relation between the grid aperture and the size of the grains presents a condition to be considered when proposing reinforced solutions to the section, given that besides the high stiffness of the reinforcement, this should also guarantee a better interlocking among the grains in a way to increase the efficiency over time (Das & Sivakugan, 2016). In this case the GR2, despite its aperture 7 times the d_{50}, showed the best interlocking, may be there is an ideal opening range for the interlock that goes beyond the value suggested by literature, however, future research should be explored to ascertain this issue.

To obtain a more expressive relation of the reinforcement in the compaction and to be able to separate the reinforcement influence during compaction and during cyclic loading, more studies are necessary, considering field and laboratory tests.

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