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Comparative effectiveness research of palm tree pruning waste and geotextiles on subgrade stabilization

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Original scientific paper

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This paper proposes a novel and environmentally friendly solution for subgrade stabilization that not only contributes towards waste material recycling but also enhances the bearing capacity of subgrade soil. Laboratory plate load tests were conducted under static loads to evaluate the potential use of palm tree pruning waste (PTPW) as a soil reinforcement material instead of commercially manufactured geotextiles, as well as to analyse the impact of the reinforcement depth, number of reinforcement layers, and the relative density of the subgrade material. The results revealed that as the number of reinforcements increased, the load-bearing pressure behaviour of the reinforced subgrades improved. Furthermore, when the reinforcement depth decreased, the load-bearing pressure behaviour improved significantly. All PTPW-reinforced subgrades performed better than geotextile-reinforced subgrades under the same conditions. Additionally, the bearing capacity improvement in the reinforced subgrades was evaluated based on the bearing capacity improvement factor (BCIF). The highest BCIF was obtained when the PTPW was used as a reinforcement with two layers at a sand subgrade relative density of 80 %.

Key words:

palm tree pruning waste, geotextile, subgrade stabilization, ground improvement, waste material

Izvorni znanstveni rad

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Komparativna analiza učinkovitosti otpada od orezivanja palmi i geotekstila na stabilizaciju posteljice

Ovaj rad predlaže novo i ekološki prihvatljivo rješenje za stabilizaciju posteljice koje ne samo da doprinosi recikliranju otpadnog materijala već i povećava nosivost tla posteljice. Laboratorijska ispitivanja provedena su pod statičkim opterećenjima pločom za prijenos opterećenja kako bi se procijenila potencijalna upotreba otpada od orezivanja palmi (*Palm Tree Pruning Waste* - PTPW) kao materijala za ojačanje tla umjesto komercijalno proizvedenog geotekstila, kao i za analizu utjecaja dubine ojačanja, broja ojačanih slojeva i relativne gustoće materijala posteljice. Rezultati su otkrili da se s povećanjem broja ojačanja poboljšala nosivost ojačane posteljice. Nadalje, kada se dubina ojačanja smanjila, nosivost se značajno poboljšala. Sve posteljice ojačane PTPW-om imale su bolje rezultate od posteljica ojačanih geotekstilom pod istim uvjetima. Dodatno, poboljšanje nosivosti u ojačanim posteljicama ocijenjeno je na temelju faktora poboljšanja nosivosti (*Bearing Capacity Improvement Factor* - BCIF). Najviši BCIF postignut je kada je PTPW korišten kao ojačanje s dva sloja pri pješčanoj posteljici relativne gustoće od 80 %.

Ključne riječi:

otpad od orezivanja palmi, geotekstil, stabilizacija posteljice, poboljšanje tla, otpadni materijal

1. Introduction

Generally, traffic loads on pavement systems are distributed through the layered system over the subgrade, and such distributed loads are required to not exceed the bearing capacity of the subgrade soil to avoid common pavement deterioration such as rutting and cracking. Moreover, the extent of traffic load distribution over the subgrade decreases as the pavement layer thickness increases; however, increased pavement layer thicknesses result in an increased demand for natural resources and an increase in the cost of construction. Furthermore, the increasing demand for natural resources leads to rapid loss of natural resources. A rise in stone quarrying and crushing activities poses a threat to both the ecosystem and human health, as it produces huge amounts of stone dust [1].

In the last 50 years, geosynthetics have been frequently used as reinforcement materials in civil engineering applications such as wall retaining, slope stabilisation, and road construction [2-7]. As described in literature, geosynthetics (geocell, geogrid, geotextile, etc.) have been used to enhance the performance of layered pavement systems [8-12]. When geotextiles are used as a separating material between the granular base or subbase and subgrade, the intermixing of subgrade soil and base or subbase soil, which causes a decrease in the bearing capacity of the subgrade, can be avoided. Moreover, the exerted loads are distributed over a wider area, resulting in greater tension forces owing to the deflected geotextiles. Therefore, the vertical components of these forces help decrease the pressure over the subgrade. Figure 1 presents the aforementioned mechanism (i.e. membrane effect [13-14]).

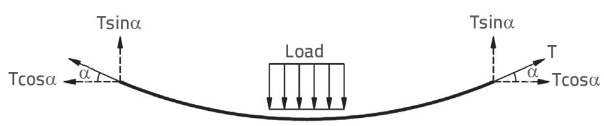

Figure 1. Membrane effect of geosynthetics (modified from Zhang et al. [14]

Several researchers have demonstrated that the most suitable types of geosynthetics for reinforcing subgrade soil are geotextiles, which exhibit high tensile strengths [15, 16]. Several experimental studies have focused on improving the performance of commercially manufactured geosynthetics as reinforcement materials for pavement systems by conducting static and cyclic plate load tests [8-14, 17-22]. Such studies have revealed that the performance of the reinforced layers improves significantly owing to the incorporation of geosynthetics. Al-Refeai [23] conducted a series of cyclic triaxial tests to determine the potential improvement in the performance of nonwoven geotextiles when placed at the interface of the subgrade and base system. The experimental results revealed that while the geotextiles slightly increased the resilient modulus (14 %), they significantly decreased the permanent deformation (50 %). Negi and Singh [24] conducted a series of California Bearing Ratio (CBR) tests using two different subgrade soil samples (clayey and sandy soil) and two geotextiles (woven and nonwoven) with different configurations. The results revealed that woven geotextiles increased the CBR value of the subgrade soil. Furthermore, compared to the nonwoven geotextile, the woven geotextile enabled better improvement of the subgrade. Moreover, the experimental results were verified with high consistency using a finite element program (ABAQUS). Kermani et al. [25] conducted accelerated pavement tests to evaluate the effectiveness of the geotextile at the interface of subbase and subgrade layers. They stated that rutting of the pavement decreased by 30 % when the geotextile was located on the upper surface of the subgrade layer. Tafreshi and Dawson [26] conducted laboratory model tests to investigate the improvement effect of geotextile-reinforced sand beds. The results revealed that the improvement in the bearing pressure factor was 1.88; however, the footing settlement decreased by 47 % with the inclusion of the geotextile.

Compared to commercially manufactured geosynthetics, natural materials, particularly waste materials, have become increasingly popular as reinforcing materials for pavement layers; this is because natural materials can improve the rutting performance and can be recycled. Subaida et al. [27] conducted an experimental study to evaluate the usability of woven coir geotextiles in a pavement system under monotonic and repeated loading. They emphasized that when the coir geotextile was used, a remarkable improvement was observed in the bearing capacity of the base course. Furthermore, the rutting performance of the base course under repeated loading improved owing to the incorporation of the coir geotextile. Anusudha et al. [28] investigated the reinforcement performance of the coir geotextile at the interface of the subbase and subgrade layers via plate load tests and concluded that the coir geotextile significantly increased the bearing capacity and stress distribution over the weak subgrade. Furthermore, the durability of natural materials in soil is an important issue. When utilizing organic matter in soil, certain durability concerns may arise. Consequently, the durability of organic materials in soil, which is affected by several biological or edaphoclimatic factors, has been extensively studied [29-33]. In recent years, the durability of different organic material in soil, such as the eucalypts wood, has also been investigated [33].

The aim of this study was to evaluate the usability of palm tree pruning waste (PTPW) as a bio-based geotextile in pavement systems, rather than commercially manufactured geotextiles. The PTPW used in this study was obtained by pruning a Mexican fan palm (i.e., Washingtonia robusta). Notably, palm trees bloom at least once annually and are generally pruned to remove old leaves. Consequently, abundant waste material is generated and is generally disposed of at dumpsites or burnt, which significantly deteriorates the environment [34]. Moreover, as Washingtonia robusta is a fast-growing palm species, the pruning activity generates massive amounts of waste (i.e., 35.70 kg/tree, annually) [35]. Therefore, for a cleaner and sustainable environment, it is necessary to use PTPW beneficially. In this context, extensive efforts have been made by several researchers to recycle PTPW in numerous civil engineering fields [36-46].

In this study, a comparative experimental study was conducted to introduce a novel bio-based and eco-friendly reinforcement material (PTPW) as an alternative to conventional geotextiles. To that end, we conducted 14 static plate load tests on unreinforced, geotextile-, and PTPW-reinforced subgrades at different relative densities (D_r) and reinforcement depths. The effects of D_r, the reinforcement depth, and the number of reinforcements were evaluated based on the bearing capacity improvement factor (BCIF).

2. Material and method

2.1. Subgrade material

Previously, experimental studies have been typically conducted using a single type of subgrade material [20, 47-49]; this subgrade material can have several different relative densities. In this study, two types of relative densities (loose and dense) were evaluated. Note that previous studies have also addressed similar relative densities [48-50].

In this study, poorly graded sand was used as the subgrade material according to the Unified Soil Classification System. Figure 2 depicts particle size distribution curves of the subgrade material. Table 1 summarizes the engineering properties of the subgrade material.

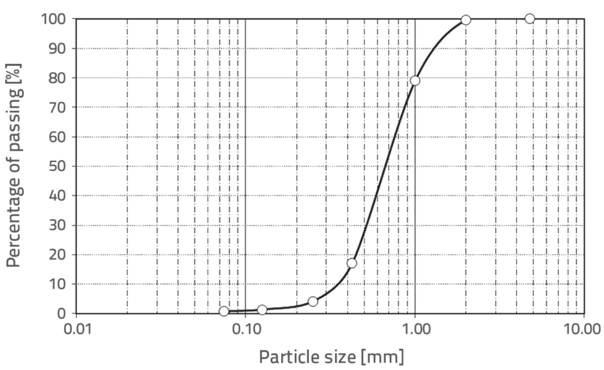

Figure 2. Particle size distribution of the subgrade material

Table 1. Properties of the sand subgrade

Properties	Value
D10 [mm]	0.38
D30 [mm]	0.50
D60 [mm]	0.70
Coefficient of uniformity, C_u	1.84
Coefficient of curvature, C_c	0.94
Specific gravity	2.74
Maximum dry density [kN/m^3]	16.57
Minimum dry density [kN/m^3]	15.00
Minimum void ratio, e_{min}	0.62
Maximum void ratio, e_{max}	0.79
Relative density [%]	80
CBR value [%] [41]	8

2.2. Palm tree pruning waste

To determine the tensile strength of PTPW, 200 mm long and 100 mm wide bone shaped PTPW specimens were prepared, and tensile tests were conducted. Figure 3 presents a photograph of the tensile test setup; the test was conducted at a speed of 1 mm/min. Table 2 presents the properties of PTPW.

Figure 3. Photograph of the PTPW specimen during the tensile test

Table 2. Properties of PTPW

Properties	Units	Value
Material composition	-	Mexican fan palm
Average tensile strength	kN/mm^2	2.7
Elongation at break	%	1.78
Water content	%	13
Thickness	mm	0.4
CBR value (PTPW reinforced at H/4) [43]	%	9.65
CBR value (PTPW reinforced at H/8) [43]	%	18.05

Figure 4. Untreated and treated PTPW

Table 3. Properties of the geotextiles

Properties	Units	Value
Material composition	-	Polypropylene (PP), white
Material density	g/m^2	250
Tensile strength, md/cmd*	kN/mm^2	0.013/0.015
Elongation at break	%	50
Static puncture strength	N	2500
Dynamic puncture strength	mm	20
Liquid permeability	m/s	0.06
Apparent opening	mm	0.12
UV resistance	%	70
CBR value (Geotextile reinforced at H/4) [43]	%	8.9
CBR value (Geotextile reinforced at H/8) [43]	%	15.45
*Note: md = machine direction. cmd = cross machine direction		

Figure 5. Computer-controlled loading system

The PTPW samples were prepared in the shape of circles with diameters of 600 mm. Figure 4 depicts the untreated (intact) and treated (tailored) shapes of PTPW.

2.3. Geotextiles

Geotextiles with the same dimensions as the PTPW samples were prepared for comparison. Table 3 summarizes the engineering properties of the geotextiles used in the experiments.

2.4. Experimental program

A cylindrical steel test tank 0.6 m in diameter and 0.6 m in height was used in the static plate load tests. As a loading plate, a circular steel plate 150 mm in diameter and 15 mm in thickness was used. Figure 5 presents a photograph of the test tank and static loading system.

To prevent boundary effects, the diameter of the loading plate was set to 0.25 times the test tank diameter, according to literature [51]. Furthermore, 14 plate load tests were conducted using the PTPW and commercially manufactured geotextile samples to examine the potential benefit of the novel soil stabilization technique and compare it with conventional methods. Table 4 summarises the experimental program.

Half of the planned tests were conducted at a relative density of 30 %, whereas the remaining were conducted at a relative density of 80 %. To obtain the desired relative density, a vibratory circular plate compactor with a diameter of 150 mm was used. The subgrade height was maintained constant (500 mm) for all tests, and the compaction process was performed every 100 mm. The reinforcements were placed at three different distances (50 mm, 100 mm, and both 50 mm and 100 mm from the surface of the sand bed), as depicted in Figure 6. The maximum reinforcement depth in this study was 100 mm from the surface of the sand bed located in the influence zone (approximately 1.5 times the plate diameter).

Table 4. Program of experiments

Exp. No	Reinforcement type	Relative density (D_r) [%]	Reinforcement depth (u) [mm]
1	Unreinforced (UR)	30	N/A
2	PTPW-reinforced (PTPWR-5)	30	50
3	Geotextile-reinforced (GR-5)	30	50
4	PTPW-reinforced (PTPWR-10)	30	100
5	Geotextile-reinforced (GR-10)	30	100
6	PTPW-reinforced (PTPWR-5-10)	30	50 and 100
7	Geotextile-reinforced (GR-5-10)	30	50 and 100
8	UR	80	N/A
9	PTPWR-5	80	50
10	GR-5	80	50
11	PTPWR-10	80	100
12	GR-10	80	100
13	PTPWR-5-10	80	50 and 100
14	GR-5-10	80	50 and 100

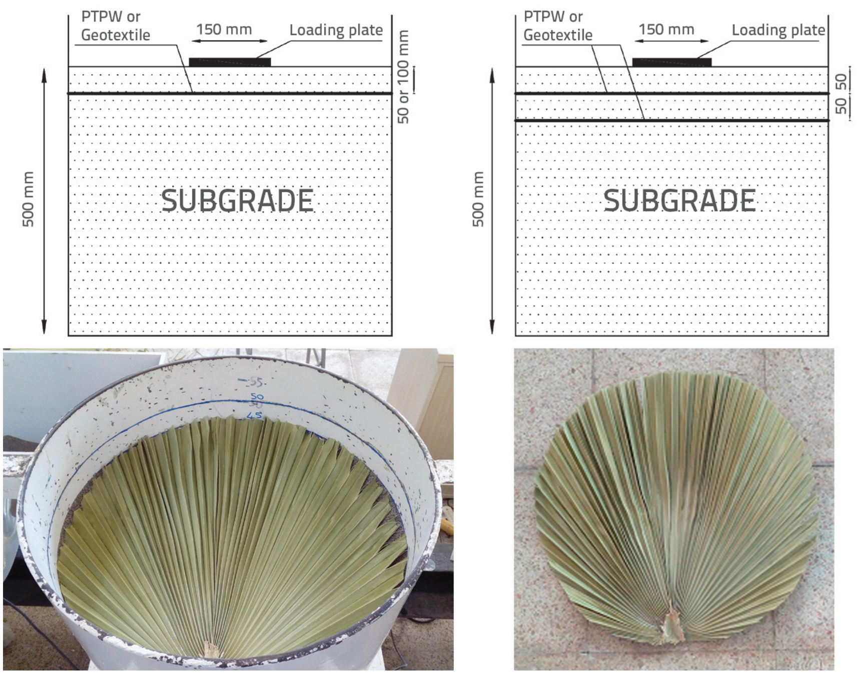

Figure 6. Schematic of the experiments and photograph of the PTPW specimen before and after the experiments

After the sand bed was ready for all the experiments, the loading plate was placed at the centre of the sand bed surface to avoid eccentric loads. Two linear variable differential transformers were installed on both sides of the loading plate to measure the vertical deformations of the loading plate. The average deformation of the loading plate was considered as the resultant deformation. Furthermore, the load exerted on the loading plate was measured using a 50 kN load cell. Furthermore, a data acquisition system was used to obtain the vertical deformation and load synchronously.

3. Results and discussions

3.1. Effect of the number and location of reinforcement

Figures 7–12 illustrate the vertical pressure–deformation curves for the tests at relative densities of 30 % and 80 % and at different reinforcement depths. When the experimental results were analysed, first, it was observed that all the reinforced test sections exhibited better performance compared to the unreinforced test sections. Moreover, no failure was observed for subgrade sections with a relative density of 30 %, owing to the ongoing densification of the sand subgrade. However, although the subgrade sections were in the densification stage, the reinforcements noticeably improved the performance of the subgrade section. In case of the subgrade sections with a relative density of 80 %, apparent failure was detected at different points (different pressures and deformation) for each reinforcement type and depth. Nonetheless, the unreinforced section at a relative density of 80 % outperformed all the reinforced sections at relative densities of 30 % while achieving a vertical pressure of 172 kPa at a deformation of 30 mm. PTPWR-5-10 exhibited the best performance among all reinforced subgrades at a relative density of 30 %, exhibiting a vertical pressure of 143 kPa at a deformation of 30 mm. This indicates that the relative density of the subgrade is highly significant for examining the performance of geosynthetics.

Regardless of the relative density, both the PTPW- and geotextile-reinforced subgrades enhanced the bearing pressure of the unreinforced sections. Furthermore, PTPW-reinforced sections behaved better compared to the geotextile-reinforced sections in all the reinforcement configurations. Consequently, the best performance was achieved when reinforcements were placed 50 mm and 100 mm from the bottom surface of the loading plate (i.e., as a two-layer), followed by those placed at distances of 50 mm and 100 mm. In conclusion, the number of reinforcement layers has a crucial impact on subgrade stabilization.

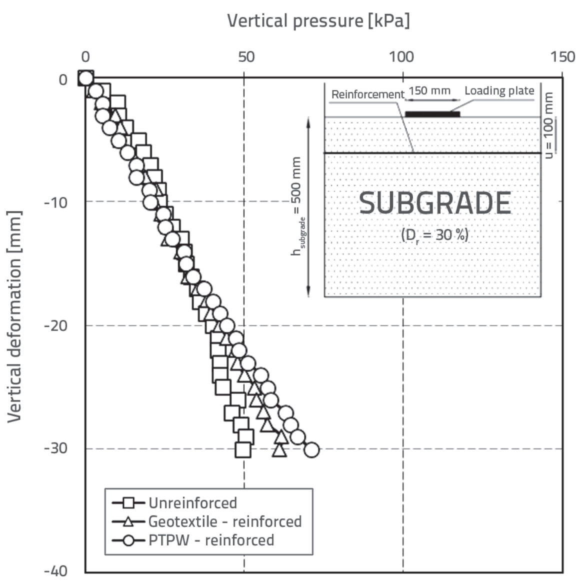

Figure 7. Vertical pressure–deformation curves of subgrades at u = 100 mm and D_r = 30 %

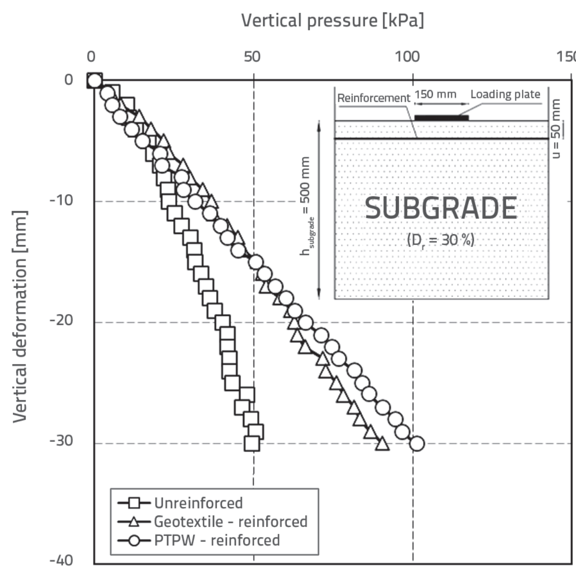

Figure 8. Vertical pressure–deformation curves of subgrades at u = 50 mm and D_r = 30 %

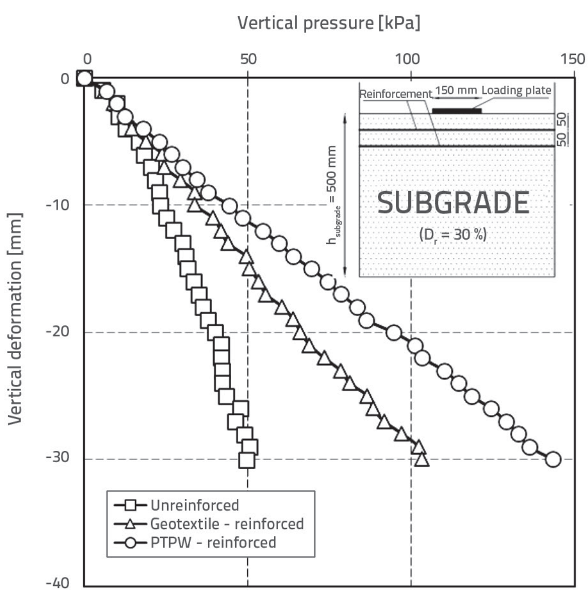

Figure 9. Vertical pressure–deformation curves of subgrades at both u = 50 mm and 100 mm and D_r = 30 %

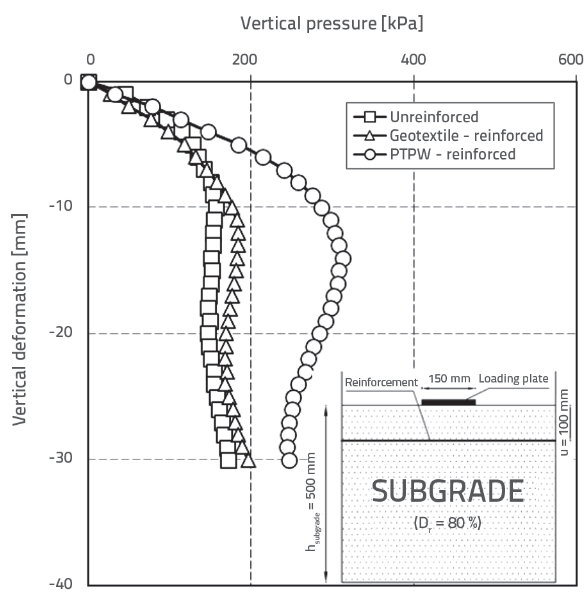

Figure 10. Vertical pressure–deformation curves of subgrades at u = 100 mm and D_r = 80 %

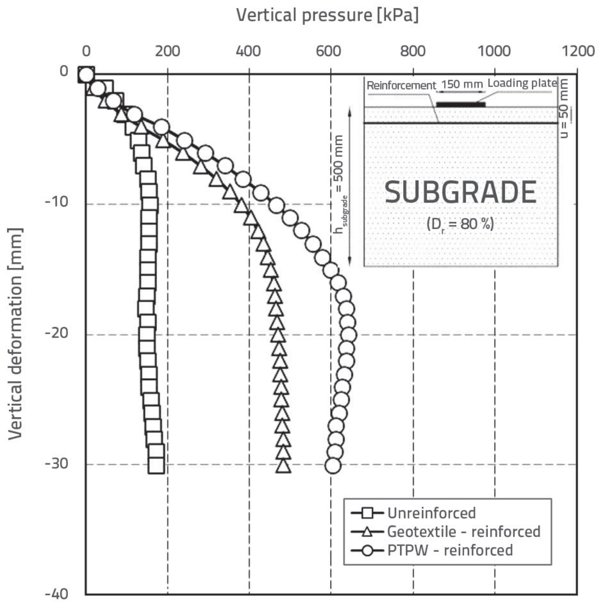

Figure 11. Vertical pressure–deformation curves of subgrades at u = 50 mm and D_r = 80 %

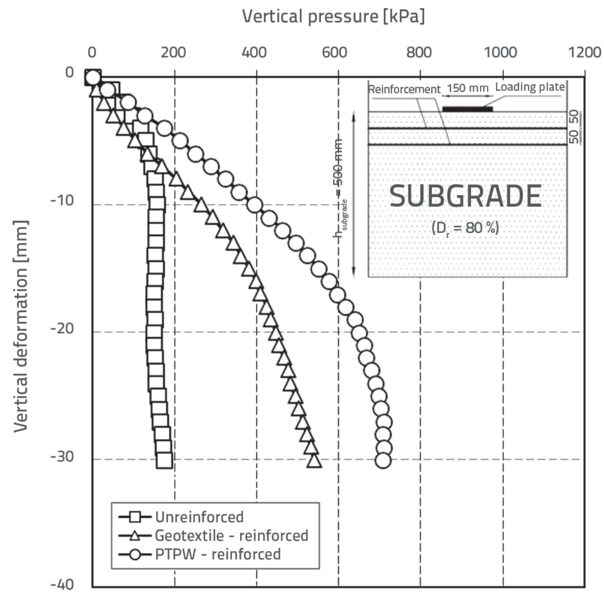

Figure 12. Vertical pressure–deformation curves of subgrades at both u = 50 mm and 100 mm and D_r = 80 %

3.2. Bearing capacity improvement factor

To better understand the enhancement in the bearing capacity of reinforced subgrades with respect to unreinforced ones and express it mathematically, the BCIF was used as a performance indicator. The improvement in the bearing capacity was represented by a non-dimensional parameter called BCIF, which denotes the ratio of the bearing pressure in the reinforced test to that in the unreinforced test at any given deformation, denoted by d_i in Equation (1).

$$BCIF = \left(\frac{P_{\text{reinforced}}}{P_{\text{unreinforced}}}\right)_{d=d_i} \tag{1}$$

where P denotes the bearing pressure at any given deformation, and d denotes the deformation of the loading plate. Figure 13 depicts the parameters required for calculating the BCIF.

As this study was conducted at different relative densities of the sand subgrades (i.e., 30 % and 80 %), evaluations were carried out individually, as depicted in Figures 14 and 15. As can be observed from Figure 14, the BCIF values of both the PTPW- and geotextile-reinforced subgrades for the same reinforcement configuration exhibit similar trends. However, the PTPW-reinforced subgrades seem to be an improved version of the geotextile-reinforced subgrades, which is also true for the tests conducted at a relative density of 80 %. Moreover, the PTPWR-5-10 subgrade presents a maximum BCIF value, as depicted in Figure 14.

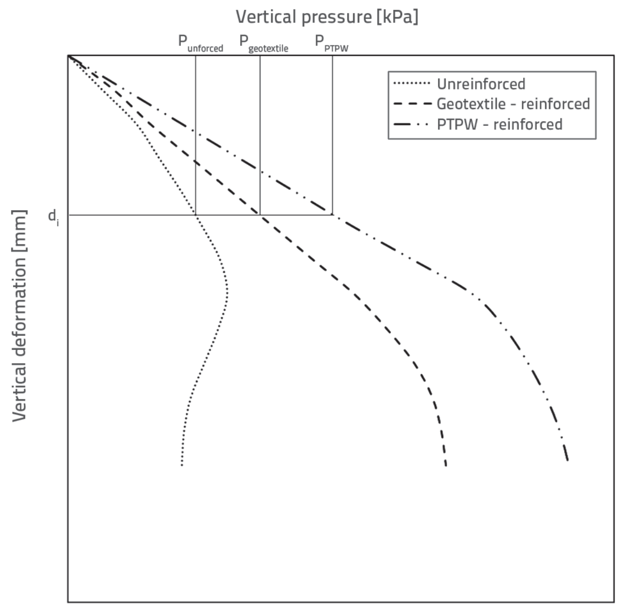

Figure 13. Related parameters for calculating the bearing capacity improvement factor (modified from Tafreshi and Dowson [26])

At a vertical deformation of 30 mm, the BCIF value approaches 2.90, indicating that PTPW used in the form of two layers is the most beneficial, while commercially manufactured geotextiles provides a BCIF of 2.09. Similarly, when considering reinforced subgrades at relative densities of 80 %, as depicted in Figure 15, PTPWR-5-10 with a BCIF of 4.10 at a deformation of 30 mm outperforms the other reinforced subgrades; the next

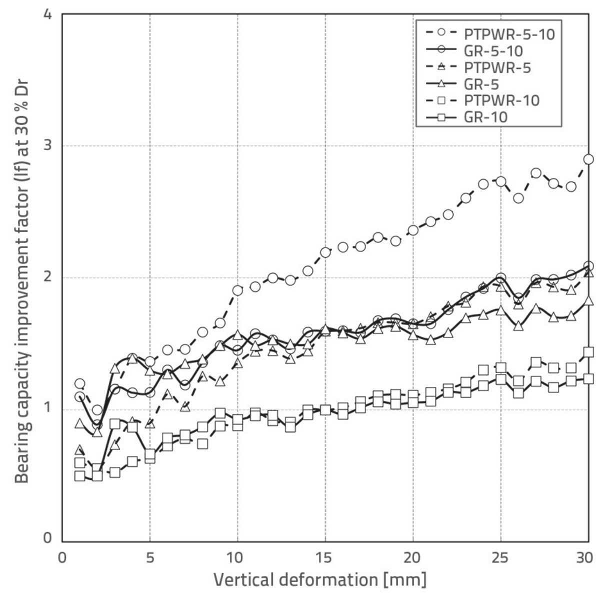

Figure 14. BCIFs of all the reinforced subgrades at 30 % D_r

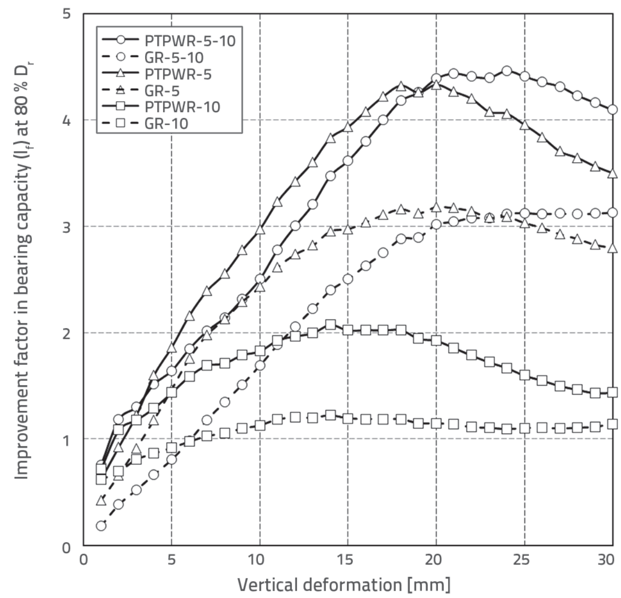

Figure 15. BCIFs of all reinforced subgrades at 80 %D_r

best performance is demonstrated by PTPWR-5 with a BCIF of 3.50 and a deformation of 30 mm. As depicted in Figure 16, the peak vertical pressure increases owing to reinforcement for both relative densities of 30 % and 80 %. The PTPW-reinforced specimen outperforms the geotextile-reinforced specimen in terms of the peak vertical pressure, regardless of the reinforcement location.

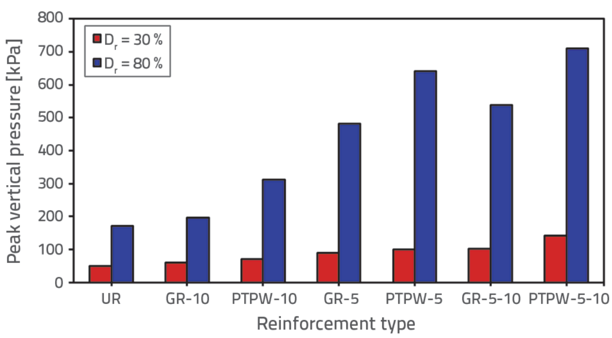

Figure 16. Peak vertical pressure for all experiments

4 Conclusion

In this study, we conducted 14 static plate load tests to evaluate the potential use of PTPW as a reinforcement material. Furthermore, we compared conventional geotextiles with PTPW, a biowaste. Moreover, the effect of the number of reinforcements, reinforcement depth, and relative density (D_r) of the subgrade was investigated. Based on the results of this study, the following conclusions can be drawn:

- All reinforced subgrades exhibited higher bearing pressures compared to unreinforced subgrades at the same relative density.
- As the number of reinforcements increased, the bearing pressure of the subgrades increased significantly.
- The closer the reinforcement material to the subgrade surface, better the load-deformation behaviour of the subgrade.
- According to the laboratory scale test results, PTPW-reinforced subgrades demonstrated better performance compared to geotextile-reinforced ones under the same reinforcement configurations.
- In this study, the behaviour of PTPW under static loading was investigated at a laboratory scale. Although the results of the laboratory experiments are a good indicator, they are not sufficient for the practical application of PTPW in this field. Therefore, to better support our results, durability, installation, and field-scale studies of PTPW are recommended.

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