Evaluation Performance of Polyurethane (PU) and Concrete Foam as Filler for Road Embankment: - A Soft Soil Treatment Solution

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Abstract

Construction over soft soil has always possessed challenges for engineers as this type of soil is problematic due to its poor geotechnical characteristics. Overburden pressure over soft soil in road construction can cause cracks, ground instability, and settlement as the soil has low bearing capacity. This can reduce the quality of driving comfort to the road users, and high maintenance cost is required for repairing work. The lamination of Polyurethane (PU) and concrete foam as lightweight fill embankment can help to solve this problem due to its excellent mechanical properties such as high compressive strength. This study aims to quantify the engineering properties of Polyurethane (PU) and concrete foam as lightweight fill embankments for road subgrades through the Unconfined Compression Test (UCT), to compare the performance of natural soil and lightweight fill materials as pavement subgrades and to produce the best ratio lamination between Polyurethane (PU) and concrete foam. The laboratory test determined the physical properties of soft soil, and the Unconfined Compression Test (UCT) was conducted for natural soft soil, lamination of Polyurethane (PU), and concrete foam was tested with varied ratios of 1:4, 1:2, 1:1, 2:1, and 4:1. The laboratory test result shows that the unconfined compression test lamination of polyurethane and concrete foam significantly improves as compared with natural subgrades. The best ratio lamination was 4:1, where the achieved strength was 517.77 kPa with an axial strain of 8.57 %. It is expected that this study's result will help find a better alternative to lightweight material for road embankments. Lightweight material that is durable against high loading can overcome the ground instability preventing settlement and thus, promoting sustainability of the road pavement construction.

Keywords: - Polyurethane (PU), Concrete foam, road embankment, lightweight fill, subgrade stabilization.

Introduction

Rapid urbanization in Malaysia has led to the scarcity of good stable soil for development, especially road infrastructure. It makes engineering infrastructure in soft soil conditions unavoidable. Volume change of soft soil can happen due to consolidation settlement when subjected to overburden pressure. This can cause any construction over this type of soil to experience ground movement and, worse, can lead to structural failure. It is vital to have a good stable base for the road embankment to ensure its stability and ability to withstand the imposed load on the road structure without jeopardizing the condition of the soft soil beneath. There are many soil stabilization methods established that can be opted to mitigate this issue. Different soil stabilization methods are suitable depending on the in-situ ground conditions, project cost, time consideration, lifespan serviceability, and long-term benefits. Since the main problem of embankment construction on soft ground conditions is excessive overburden pressure, using lightweight material as an embankment filler is one of the innovative methods to resolve this issue.

This study focuses on using Polyurethane (PU) laminated with concrete foam as a lightweight material filler for road embankments. Polyurethane (PU) material and concrete foam are chosen because of the predicted increase in demand due to various consumption used from these materials in construction. As the demand increases, the availability of this material is easily accessible, and sustainable innovation will continuously grow.

Lightweight filler for road embankment

The low bearing capacity of soft soil may constitute geotechnical problems such as settlement if imposed by conventional soil fill load Nicholson (2015). This is because the existing soft ground could not 'carry' the overburden pressure of the excessive added load. Using lightweight material as an alternative to this problem helps reduce the overburden pressure and the possibility of settlement.

Previously, EPS Geofoam has commonly been chosen as a lightweight fill for road embankments. However, inadequate and improper design of the EPS Geofoam for internal stability and recent failures cases have raised issues on the suitability of the material used in the current market (Horvath, 2010).

Polyurethane (PU)

A mixture of polyol and isocyanate forms Polyurethane. There are four major classes of isocyanate, and isophorone diisocyanate (IPDI) is used specifically to make rigid PU which is implemented in the geotechnical application. A higher isocyanate ratio is required to make rigid Polyurethane (PU) foam (Lat et al., 2020). Resin with a suitable formulation will provide a strong bond and shear strength greater than excellent grade concrete (Lat, 2013). In many circumstances, expanding Polyurethane as a filling and lifting agent in soils has been described as a successful stabilizer, particularly for resolving issues linked with excessive and differential settlements (Al-Atroush & Asce, 2021). The Polyurethane foam volume's high expansion qualities were useful in repairing deformed pavement, buildings, and other subsurface structures when traditional or conventional approaches were infeasible (Saleh et al., 2018).

Originally, isocyanate was highly toxic in nature researchers from various countries have come to find innovations in Polyurethane (PU) by utilizing sustainable and environmentally friendly resources (Khatoon et al., 2021). Polyols made from vegetable oils (soybean, castor, palm oils, etc.) are being studied as viable replacements for petroleum resources (Khatoon et al., 2019). Polyurethane foam synthesized with rock wool reacting with Alkaline can absorb sound and be used in road pavement construction (Mohammadi et al., 2022). This will provide great comfort to the road users and the surroundings as it has noise reduction capability.

Concrete foam

Concrete foam, known as Lightweight Cellular Concrete, is a mixture of cement, water, and air with a density of only a quarter higher than the conventional granular fill (475 to 600 kg/m3) (Micheal L.J & John B, 2016). Applying concrete foam in subgrade modification on soil remediation helps reduce the bearing capacity and dead load (Sutmoller & Asce, 2020). This results in creating enhanced seismic stability and reducing the potential of settlement. In addition, concrete foam is cost-effective, labour-saving, and can be a great alternative to conventional fill materials.

Methods

The marine clay sample used for this study was taken along the coastal area in Pasir Gudang. The experimental laboratory work was done to identify the physical properties of soil and conducted according to the guideline from British Standard Institutions BS 1377: 1990. The disturbed soil sample will be dried in the oven, maintaining a temperature of 110^{o}C for 24 hours. The soil was fully dried with no water to ease the crushing and sieving. The sample was then used to determine the physical properties of marine clay. Unconfined Compression Test (UCT) is selected because this test determines the engineering properties of saturated cohesive soil, which is suitable for soft clay samples. In addition, unconfined compressive strength is often used as a parameter in subgrade pavement design.

The concrete foam used for this study is ready-made and ground to the required sample size. Meanwhile, the type of Polyurethane used for this study is Rigid Polyurethane (PUR). It is made up of a mixture of polyol and isocyanate with a ratio of 1:1.2. The properties of Polyurethane should ensure following the standard from Badische Anilin und Soda Fabrik (BASF). The sample lamination varied according to the ratio between Polyurethane and concrete foam.

Figure 1. Prepared sample of Polyurethane and concrete foam

Results and Discussion

A control sample with natural subgrade fill was prepared, and another sample was prepared with lightweight fill material of Polyurethane (PU) and concrete foam with ratios 1:4, 1:2, 1:1, 2:1, and 4:1. In determining the physical properties of soft soil, the test sample is performed, including particle size distribution, moisture content, Atterberg limit, and compaction to get Optimum Moisture Content (OMC). Samples were then tested for the Unconfined Compression Test (UCT) to evaluate the performance of lightweight fill embankment. The methodology of the experiment outline can be seen in Appendix A.

Particle size distribution

Table 1 shows the summary of particle size distribution results obtained using wet and dry sieving. It is shown that silt particle makes up more than the majority (55%) of the overall soil particle constituent, followed by Sand (28%) and Clay (17%). The effective coefficient of D10, D30, D50 and D60 for soil materials are simplified in Table 2. The Coefficients of Uniformity achieved is 16.43, and the Coefficients of Gradation is 0.34. The coefficients achieved for gradation are less than 1, meaning the soil is categorized as poorly graded soil.

Table 1. Summary result of Particle Size Distribution

Properties Name	Sample
Particle Size Distribution	(%)
Gravel	-
Sand	28
Silt	55
Clay	17
Total	100

Table 2. Coefficients of uniformity and gradation

Details	Unit
D_{10}	0.0014
D_{30}	0.0033
D_{50}	0.02
D_{60}	0.023
Coefficients of Uniformity, Cu	16.43
Coefficients of Gradation, Cg	0.34

Atterberg limit

Atterberg limit test was conducted to determine Plastic Limit (PL), Liquid Limit (LL) and Plasticity Index (PI) through Cone Penetrometer Method. Table 3 summarises the value obtained for the Atterberg Limit of the soil sample. The value of Liquid Limit (PL) and Plasticity Index (PI) were then plotted in a chart in Figure 2 and classified as Clay of High Plasticity, CH.

Table 3. Atterberg limit results

Details	Percentage (%)
Liquid Limit	59
Plastic Limit	28
Plasticity Index	31

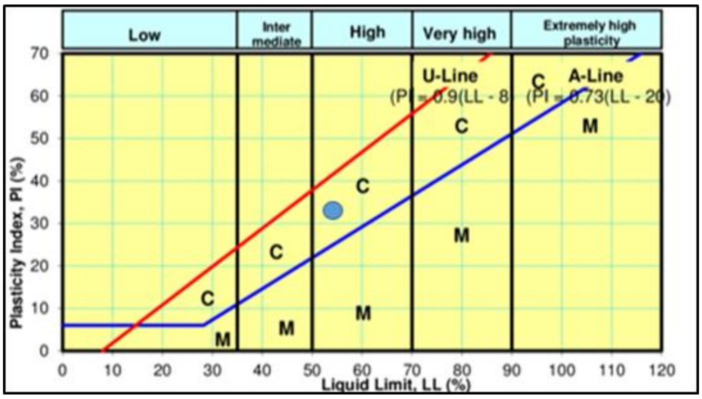

Figure 2. Soil Classification of the sample

Natural moisture content

The natural moisture content is obtained through oven dried method; the result is shown in Table 4. The data shows that marine clay has an extensive amount of water (72.44%). It is shown that the natural moisture content in this study makes up most of the soil sample; this is due to the location of the soil present within the coastal region. Moreover, the fine size particle of marine clay allows it to hold more water. Marine clay is highly compressible and has swelling potential in its natural state. The optimum moisture content value correlates with the plastic Limit (PL) (Rahman et al., 2022). The higher the value of the Plastic Limit will contribute to a higher percentage of Optimum Moisture Content.

Table 3. Results of moisture content

Sample no.	Moisture content (%)
MC1	79.89
MC2	65.04
MC3	65.70
MC4	73.41
MC5	78.17
Average Moisture Content	72.44

Compaction using Standard Proctor

Standard compaction results in Table 5 show that the Optimum Moisture Content achieved for the soil sample is 26% at a Maximum Dry Density of 1822 kg/m3. Usually, fine soil has a high value of Optimum Moisture Content as more air void is expelled and soil particle is compacted close to each other. While dry density is defined as the ratio of the mass of dry soil to the total volume of soil. Fine soil particles will have a higher dry density value, and the maximum dry density is obtained when the soil is in optimum moisture content.

Table 4. Standard proctor results

Details	Percentage (%)
Optimum Moisture Content (OMC)	26.0
Maximum Dry Density (Mg/m^2)	1.82

Unconfined Compressive Strength (UCS)

Evaluating unconfined compressive strength was obtained for marine clay as a natural soil subgrade and laminated Polyurethane with concrete foam. It is shown in Figure 3 that Pasir Gudang marine clay has a very low unconfined compressive strength. This shows that the marine clay is very soft in its natural state and would be very challenging to develop any construction on it. In the most natural state of marine clay, the strength of this soil is extremely low, and it usually cannot stand on its weight (Mohammed Al-Bared & Marto, 2017). Moreover, the strength of the marine clay gradually increases after several deformations, and it has reached excessive deformation (9.3%) only after small stress is applied (6.3 kPa). This is due to the water content in marine clay that plays a significant role in contributing to the strength of the soil. In a real construction site, it is impossible to get marine clay at optimum moisture content as this type of soil is usually located near the coastal region and easily loses its strength when exposed to excessive water. Conversely, the range of the unconfined compressive strength obtained is within 377 kPa until 517.77 kPa, as shown in Table 6. It is seen that a high-volume ratio of Polyurethane contributes to a higher amount of compressive strength.

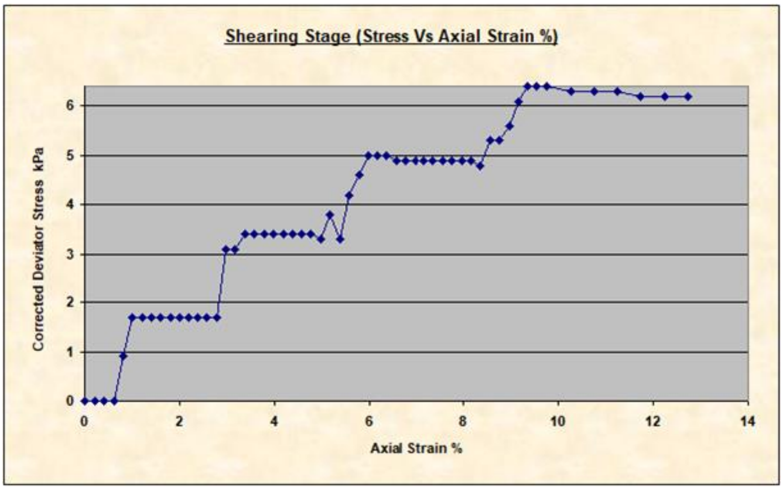

Figure 3. Stress-strain curve of natural subgrade

A compilation of standard guidelines and specifications was summarized in Table 7 from several national road associations. Generally, all guideline listed was stated for bonded-based material on pavement stabilization, such as cement and lime. Unfortunately, there are little few specific strength requirements and guidelines found outlining the lightweight fill for road embankments, although the application of these materials has been widely used around the world. Nevertheless, a comparison of unconfined compressive strength (UCS) between this study and guidelines from the national road association can be made to quantify the engineering properties of stabilized subgrade. It can be seen that the unconfined compressive strength obtained from this study for all ratio lamination of polyurethane and concrete foam did not satisfy the requirement from all national road associations listed in Table 7. The highest strength obtained in this study is about 26% lower than the minimum requirement outlined by Austroad (2017).

Table 5. Results of Unconfined Compressive Strength (UCS)

Lamination ratio of Polyurethane (PU) and concrete foam	Weight of the sample (g)	Average q_u (kPa)	Average Axial Strain (%)
Natural subgrades	348.7	6.3	9.3
1:4	48.79	377	5.47
1:2	45.02	431.67	6.76
1:1	34.43	445.2	9.56
2:1	24.82	496.73	8.96
4:1	21.82	517.77	8.57

Table 6. Standard guidelines for subgrade stabilization

Standard Guideline	Requirement of UCS range (kPa)	Curing period	Applications
Austroads, (2017)	1000 - 1500	28 days	Lime stabilized subgrade
	1000 - 2000	28 days	Cemented material subgrade
The Portland Cement Association, (2020)	700 - 2100	Seven days	Cement stabilized subgrade
Jabatan Kerja Raya (JKR), (n.d.)	2942 – 3922.66 (30 – 40 kg/cm^2)	7 days	Cement stabilized

In addition, the unconfined compressive strength was compared between lightweight fill embankment of lamination polyurethane and concrete foam with the natural subgrade. The comparison shown in Figure 4 was done to visualize the condition of the subgrade with lightweight embankment and untreated conditions. It can be seen that the lamination of polyurethane and concrete foam significantly improved (up to 98.78%) compared with natural marine clay as road subgrade for all ratios. Besides, the weight of the lightweight subgrade is remarkably reduced up to 94.3% compared to the natural subgrade. This can help mitigate the overburden pressure experienced by the existing subgrade and hence, reduce the possibility of road settlement.

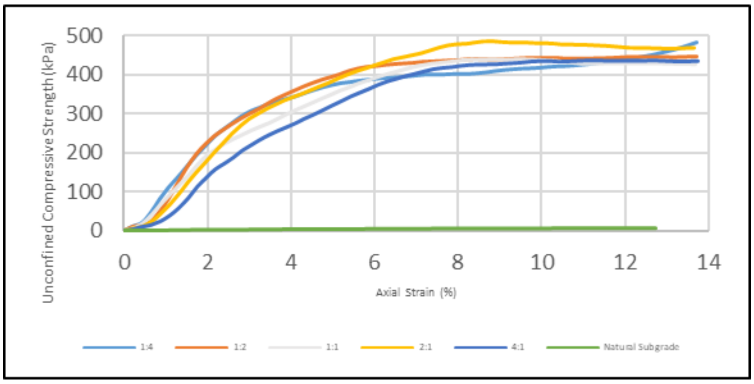

Figure 4. Stress-strain curve comparison between natural subgrades and lamination of polyurethane and concrete foam.

The graph shows the compilation of ultimate unconfined compressive strength achieved by all ratio lamination of polyurethane and concrete foam with their respective axial strain. The best ratio lamination of polyurethane and concrete foam is achieved at a ratio of 4:1. This is because the ratio lamination of 4:1 is capable of achieving the highest unconfined compressive strength with lower axial strain than ratios 2:1 and 1:1.

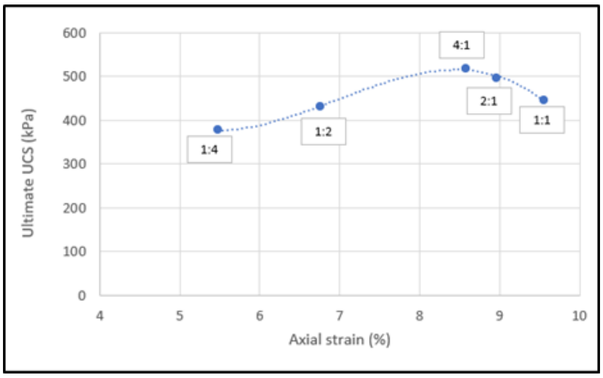

Figure 5. Ultimate USC vs Axial strain for lamination of Polyurethane and concrete foam

Conclusions

From the experimental work and analysis carried out, the following conclusions have been drawn: -

i. Unconfined Compression Test (UCT) was used to determine the engineering properties of the lightweight fill lamination of polyurethane and concrete foam. The highest value achieved was 517.77 kPa with an axial strain of 8.57% at ratios of 4:1. Polyurethane material contributes to better strength and lower weight of the lightweight filler for road embankments. Stress-strain correlation shows that the lamination exhibits better stiffness after ratios of 1:1. However, the strength of the lightweight filler does not satisfy the requirements outlined by national road associations.

ii. Unconfined Compressive Strength (UCS) was compared between lightweight fill embankment of lamination polyurethane and concrete foam with the natural soil subgrade. Results show that the lamination of polyurethane and concrete foam significantly improved up to 98.78% compared with natural marine clay as road subgrade for all ratios. The weight of Polyurethane and concrete foam lamination is reduced to 94.3% from natural soil subgrades.

iii. The best ratio lamination of polyurethane and concrete foam is achieved at a ratio of 4:1. This is because the ratio lamination of 4:1 Polyurethane and concrete foam is capable of achieving the highest unconfined compressive strength with lower axial strain.

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