Consolidation settlement and buoyancy behaviour for different thickness of polyurethane foam as a ground improvement

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Abstract. Lightweight polyurethane (PU) foam is an alternative ground improvement method to resolve soft ground problem. In this study, Rowe Cell laboratory test is executed to determine the consolidation settlement of marine clay soil improved with polyurethane foam. The ground improvement is carried out by excavate the soft soil at shallow depth and replace with polyurethane foam. The performance for different thickness of PU foam as a ground improvement is evaluated. The comparison is made between partial replacement of PU foam on saturated marine clay and water in order to determine the buoyancy and uplift behaviour of the ground improved with lightweight PU foam. The percentage thickness of PU foam to soft clay layer and water varies from 20% to 80%. The correlation between PU foam thickness coefficient and compressibility index, Cc value for PU foam partial replacement on water and saturated soil are adopted in this study with the respective equations. The settlement reduces significantly with the increase of PU foam thickness for both soil and water conditions.

1. Introduction

Lightweight polyurethane (PU) foam is an alternative ground improvement method to resolve soft ground problem. Due to its lightweight properties, the problem with buoyancy is commonly arise when dealing with PU foam as a ground improvement. In this study, the buoyancy of PU foam is investigated by integrating the consolidation process using Rowe cell apparatus. Rowe Cell was developed at Manchester University, UK by Professor P.W. Rowe [1]. A detailed description of the principle and practice of Rowe Cell testing is given in Head [2]. In the Rowe Cell, the test sample is loaded hydraulically by water pressure acting on a flexible diaphragm. Drainage of the sample can be controlled, and pore water pressure is measured. Back pressure can be applied to simulate the in-situ soil condition. The application of hydraulic pressure and measurement of the variation of pore water pressure and volume change of the sample can either handled by a conventional pressure panel or by an automatic system. Rowe cell test can produce results faster than the conventional Oedometer test [3]. The advantages of Rowe Cell over traditional Oedometer are minimum vibration effects and ability to measure pore water pressure and volume of water expelled from the sample. Other than that, the saturation of sample under back pressure condition to simulate in situ condition can be done [2].
Various materials have been used as lightweight fills. For example, various cementitious materials with unit weights of 3.8 kN/m$^3$ – 12.6 kN/m$^3$ are available. Tire shreds were used as lightweight fill to improve slope stability for highway projects constructed on weak marine clay. Tire shreds, which are scrap tires that have been cut into 50 to 300 mm pieces, were chosen because they have an in-place density of 0.80 to 0.93 Mg/m$^3$ [4]. Another lighter, but more expensive option is to use expanded polystyrene (EPS) and extruded polystyrene (XPS), known as geofoam [5,6,7]. Various techniques have been reported to reduce the embankment deformation and prevent potential stability failure. These methods include improving the fill properties, using lightweight fill, excavation and replacement, pile embankment support and geosynthetic reinforced [8,9].

Major concern for lightweight materials as a ground improvement application is a buoyancy of the materials [10]. Buoyancy has been a cause to a lot of failures for ground improvement works using lightweight foam. It able to float off as the density of the foam is lighter than water when there is a rise of ground water table and the soil is fully saturated. Ghani [11] has carried out a study on the use of polyurethane for road flood damage control. Mohamed Jais [12,13] has undertaken the rapid remediation works using polyurethane (PU) foam injection system in road construction and maintenance works on soft soil. The materials have successfully reduced the settlement of soil and expedite the construction works on soft soil. On top of that, PU foam inclusion has successfully improved the compressibility of peat soil [14]. This study investigated the compressibility behaviour of marine clay soil improved with PU foam and the effect of buoyancy on the consolidation process of the improved marine clay soil.

2. Research Methodology

2.1 Laboratory consolidation test using Rowe Cell apparatus

The consolidation test using Rowe cell is conducted in a similar procedure with Oedometer test whereby each load needs to be applied constantly for about 24 hours. The reference is made to BS1377: Part 6 (1990b) for step loading test using Rowe Cell with some modification & Head (1985). Rowe cell is an alternative consolidation testing with application of continuous loading instead of incremental loading by conventional Oedometer test. Rowe cell is accommodated with cell pressure, back pressure and pore water pressure drainage line on top and bottom part of the Rowe cell apparatus. During saturation stage, the cell pressure and back pressure are applied alternately to achieve Skempton’s degree of saturation, B value of more than 0.95. The increase in surrounding pressure is applied by the cell pressure whilst the pore water pressure drainage will record the increase in pore pressure. During consolidation, the back-pressure valve is opened whilst pore pressure and cell pressure valve are closed whilst the load is applied continuously. The photogrammetric of Rowe cell equipment is as shown in Figures 1(a) and (b). Four (4) different thicknesses of polyurethane foam those are 5 mm, 10 mm, 15 mm and 20 mm which is equal to 20%, 40% 60% and 80% of soft clay thickness respectively as well as blank sample are tested. The data is recorded using Data System 7.2 (DS7) software by ELE International. The soil sample used in this study is a marine clay taken at Sabak Bernam, Selangor.

Figure 1. (a) Rowe Cell Test Equipment (b) Rowe Cell Test connected to data acquisition system.
2.2 Preparation of PU foam sample
The prepared polyurethane (PU) foam was removed from the mould after 24 hours and have been cut into average size of 150 mm in diameter that fixed into Rowe cell body. There were four (4) numbers of sample with various thickness. The samples were weighted using analytical balance and recorded to determine the unit weight of all tested samples. Figure 2 shows the preparation of PU foam for the consolidation test.

Figure 2. (a) Polyol and isocyanate raw materials (b) Mixing process of chemicals (c) Chemical reaction to produce PU foam, expand and harden (d) The PU foam after cut.

Figure 3 shows the soil sample was placed inside the mould followed by partial replacement of PU foam with respective thickness. On the other hand, for PU foam replacement on water, the soil sample as shown in Figure 3a was replaced with water followed by the placement of PU foam on water.

Figure 3. (a) Soil sample is placed inside the mould (b) PU foam partial replacement of the clay.

3. Results and Discussions

3.1 Comparison of PU foam partial replacement on water and on saturated soil.

3.1.1 Relationship between load and settlement. Void ratio, \( e \) is the relative volume of void (air and water) and the solid (soil) in a soil. The void ratio for saturated soil with PU foam partial replacement is higher compared to the void ratio for water with PU foam partial replacement. This is because for fully saturated condition (\( Sr = 100\% \)), \( e = wG_s \) whereby \( w \) refers to water content and \( G_s \) is specific gravity. With condition of water only, the water content is 100\% whilst specific gravity, \( G_s \) for water is 1. Therefore, the void ratio is 1. Whilst for soil condition, as the water content and specific gravity for the marine clay soil are 80\% and 2.35 respectively, thus the void ratio is higher which is equal to 1.88. It has been proved by the Rowe Cell consolidation test whereby the void ratio for PU foam partial replacement on saturated clay is more significant compared to PU foam partial replacement on water as shown in Figure 4. Higher void ratio increment, \( \Delta e \) causes higher compressibility that lead to significant soil settlement. Water is very slightly compressible, therefore, the void ratio is lesser compared to the soil condition.

With the replacement of PU foam on both conditions, the increase in thickness of PU foam causes further reduction in void ratio as the soil or water has been partially replaced with PU foam. On top of that, buoyant force is produced by replacement of PU foam on both soil and water conditions which
causes the foam to float off thus reduces the soil compressibility. Higher thickness of PU foam causes more water to be displaced by PU foam, therefore, buoyant force increases and causes less settlement. It is in line with Archimedes’ principle whereby the upward buoyant force that is exerted on a body immersed in a fluid, whether fully or partially submerged, is equal to the weight of the fluid that the body displaces and acts in the upward direction at the centre of mass of the displaced fluid [15].

However, the effect of buoyancy is more significant in water condition. In saturated soft soil condition with PU foam partial replacement, the buoyant force is produced by the mass of water content of the soil. Therefore, with PU foam partial replacement, higher moisture content of the soil will produce higher buoyant force which is acting upward direction and capable to resist the downward overburden load.

Figure 4. Relationship between void ratio and log stress.

Figure 5. PU foam thickness versus settlement and uplift with variation of loads for PU foam partial replacement on saturated soil and water.
The void ratio increment, $\Delta e$ reduces with the increases in PU foam thickness as the void ratio in the soft soil is replaced by the non-porous rigid PU foam, thus settlement is reduced as shown by the relationship between void ratio and log stress in Figure 4. Figure 5 shows similar trend occurs as shown by relationship between settlement/uplift and PU foam thickness with variation in loads. However, insignificant reduction in downward displacement for PU foam replacement on water is recorded compared to saturated soil even though the same thickness of PU foam is used for both conditions. This is because larger buoyant force is produced in water condition as compared to saturated soil condition which is very helpful to resist the downward overburden load. Figure 6 shows no settlement occurs at zero load. The settlement increases with the increases in load, however, lesser compressibility is recorded for PU foam on water condition compared to soil condition.

![Figure 6. Load and settlement relationship with variation of PU foam thickness for PU foam partial replacement on saturated soil and water.](image)

![Figure 7. Correlation between PU foam thickness coefficient and Cc value for PU foam partial replacement on water and saturated soil.](image)

Graphs in Figure 7 show the correlation between PU foam thickness coefficient and compressibility index value, $C_c$ for PU foam partial replacement on water and on saturated marine clay respectively. The graphs show the compressibility index, $C_c$ value for both saturated soil and water condition decrease exponentially with the increase in PU foam thickness. However, the $C_c$ value reduces very slightly for water condition as the behavior of water itself very slightly compressible to incompressible. For
saturated soil condition, the compressibility index, $C_c$ significantly reduces exponentially with the increases in PU foam thickness. This behaviour indicates that the compressibility of the saturated marine clay soil has improved with the increase in thickness of PU foam partial replacement. The determination of compressibility index for PU foam partial replacement on saturated soil and on water respectively are shown in Equations 1 and 2.

\[
C_{c_{\text{pu-soil}}} = 0.63e^{-0.086T_{pu}} \quad (1) \\
C_{c_{\text{pu-water}}} = 0.17e^{-0.1T_{pu}} \quad (2)
\]

*PU foam thickness coefficient, $T_{pu}$: 100% thickness of PU foam to soft clay ratio is equivalent to 25. If 20% thickness of PU foam to soft clay thickness, $T_{pu}$ will be equal to 20% x 25 = 5.

3.1.2 Relationship between load and excess pore water pressure. The graph of load versus excess pore pressure for each of PU foam thickness (Figure 8) shows the increase in load cause the increase in excess pore pressure. For existing condition of water only, the excess pore pressure is equivalent to the load applied. This is because the load applied is resisted by the water since it is undrained condition. The reduction in excess pore pressure depends on the PU foam thickness as the weight of water has been replaced by lesser weight of PU foam.

![Figure 8](image_url)

**Figure 8**. Load and excess pore pressure relationship with variation of different PU foam thickness for PU foam partial replacement on saturated soil and water (a) for 5mm PU foam (b) for 10mm PU foam (c) for 15mm PU foam (d) for 20mm PU foam.

On the other hand, for saturated soil condition only, the excess pore pressure is equivalent to the load applied provided the condition is fully saturated ($Sr = 100\%$) whereby zero or no air void contains in the soil. However, in this study the excess pore pressure almost equivalent to the load applied as it is
hard to obtain 100% saturation. However, with PU foam improvement, there is a significant reduction in excess pore pressure as the weight of the soil has been replaced by the lightweight PU foam and the buoyant force is produced by the water content in between the soil particles. With the increase in PU foam thickness, the difference of excess pore pressure between blank sample of soil only and improved soil increases indicated the increases in buoyant force. This is due to the excess pore pressure is acting downward, and with the increase in PU foam thickness the upward buoyant force increase, therefore, the excess pore pressure reduces significantly compared to the blank sample of soil. Figures 9 and 10 show the condition of PU foam before and after Rowe Cell consolidation test. The conditions of PU foam after test show insignificant defect or deterioration indicating higher stiffness and strength of the PU foam.

![Figure 9. Condition of PU foam before and after Rowe Cell consolidation test.](image1)

![Figure 10. Condition of different thickness of PU foam after Rowe Cell consolidation test.](image2)

4. Conclusions
Higher thickness of PU foam causes more water to be displaced by PU foam, therefore, buoyant force increases and causes less settlement. However, the effect of buoyancy is more significant in water condition. This is because, in saturated soft soil condition with PU foam partial replacement, the buoyant force depends on the water content of the soil. The buoyant force is produced by the mass of water (water content) in between the soil particles. Therefore, with PU foam partial replacement, higher moisture content of the soil will produce higher buoyant force which is acting upward direction and capable to resist the downward overburden. The void ratio increment reduces with the increase in PU foam thickness as the void ratio in the soft soil is replaced by the non-porous rigid PU foam, thus
settlement is reduced as shown by relationship between settlement, uplift, PU foam thickness with variation of overburden load for both conditions of PU foam partial replacement on saturated soil and water. The compressibility of PU foam replacement on water condition is insignificant compared to soil condition as the behaviour of water itself is very less compressibility to incompressible. Compressibility index, $C_c$ value for both saturated soil and water condition decrease exponentially with the increase in PU foam thickness. However, the compressibility index value reduces very slightly for water condition as the behavior of water itself is very slightly compressible to incompressible. For saturated soil condition, the compressibility index significantly reduces exponentially with the increase in PU foam thickness. This behaviour indicates that the compressibility of the saturated marine clay soil is improved with PU foam partial replacement. The equations for determination of compressibility index for PU foam replacement on saturated soil and on water respectively are produced in this study those are $C_{cp_{\text{soil}}} = 0.63e^{-0.086T_{pu}}$ and $C_{cp_{\text{water}}} = 0.17e^{-0.1T_{pu}}$.

Acknowledgments
Special thanks to technical supports at Geotechnical Laboratory Universiti Teknologi MARA (UiTM) for the valuable assistance to complete this research work.

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