The Effect of Polyurethane Mix Ratio on the Strength of Polyurethane Treated Marine Clay

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Abstract. Marine clay (MC) is recognised as an unfavourable soil in the construction field, given it continues to present problems of bearing capacity, consolidation, and settlements. In this paper, polyurethane was used to improve the properties of MC using a different mix ratio of polyol and isocyanate. The marine clay was characterised examining the particle size distribution (PSD), specific gravity (SG), Atterberg limits (AL), and performing standard proctor tests. Aside from that, an unconfined compressive test (UCT) was conducted to investigate the strength enhancement of treated marine clay (TMC) at various polyol to isocyanate mixing ratios. The UCT results indicated that the TMC could be effectively improved at the polyol to the isocyanate mixing ratio of 45:55. The unconfined compressive strength (UCS) of the MC consequently improved from 146 kPa to 286 kPa due to the addition of polyurethane. At the same time, the axial strain at failure decreased from 5.3% to 2.9% due to the treatment of the MC using polyurethane.

1. Introduction
In general, marine clay (MC) has a low bearing capacity, low permeability, and high compressibility concerning engineering properties for construction given its high moisture content compared to the liquid limit. As such, this indicates that MC is found in a liquid state in a natural condition. In Malaysia, about 20% of the land area is occupied by soft clay. Along the west coast of Peninsular Malaysia, soft clay such as MC is normally found in Johor, Melaka, Port Klang, Pulau Pinang, and Alor Setar [1]. Since some of the major economic activities and social development is concentrated along the coastal area driven by the expansion of the population, the construction industry continues to face challenges when dealing with soft soils, such as MC. Further, MC that is deposited along the coastal line of both east and west parts of Peninsular Malaysia is considered as unfavourable soil as it creates considerable geotechnical issues. MC is considered as sensitive soil which causes detrimental shrinking and swelling in response to slight changes in the moisture content.

The use of polyurethane as a chemical stabiliser has recently been introduced due to its functional characteristics that can fulfil construction needs. It also improves the geotechnical properties of the soil with relatively low costs compared to other chemical stabilisers. Furthermore, given the expansion properties of polyurethane for filling void areas between the soil particles, the bearing capacity of the treated soil with polyurethane is increased significantly. As a soil stabilising agent, polyurethane decreases the rate of settlement and enhances soil strength [2]. As such, the inertness of polyurethane
after hardening makes it environmentally friendly as a more suitable replacement compared to other chemical stabilisers [3].

Numerous studies [4-5] has been undertaken to assess the strength of the improved soil mixed with polyurethane. Here it was found that the injection of an expandable PU resin significantly improved the dynamic resistance of sand, as well as increasing stiffness of the soil [4]. Polyurethanes are formulated from the reaction between polyol, isocyanate and other additives like catalyst and chain extender [6–8]. As such, it is essential to determine the actual quantity of polyurethane and the mixing ratio of polyol and isocyanate in order to establish the optimal strength characteristics of the modified soil due to the availability of different proportions of polyol and isocyanate. Most of the studies carried out on polyurethane did not consider the proportion of polyurethane compositions [9–13]. Furthermore, there is yet to be any research conducted on MC at various mixing ratios of polyol and isocyanate. Accordingly, it is anticipated that this study will extend the knowledge in this area.

2. Material and Method

This section explains the materials and method used in this study.

2.1. Materials

A disturbed sample of MC was collected from the campus of Universiti Tun Hussein Onn, Batu Pahat, Malaysia. Preliminary tests were conducted on the MC that included PSD, SG, AL, and standard proctor tests. The UCT test was also conducted in order to determine the strength of the untreated and PU-treated marine clay (TMC). The compressive strength of the untreated marine clay (UMC) was evaluated and used as a control sample. The reference standards used for conducting the tests are presented in Table 1.

| Test                        | Standard     |
|-----------------------------|--------------|
| Particles size distribution | [14]         |
| Specific gravity            | [15]         |
| Atterberg limits test       | [16]         |
| Standard proctor            | [17]         |
| Unconfined compression test | [18]         |

Polyurethane was used in this study as the chemical stabiliser. The content of the polyurethane was set to be constant at 8% [9]. The properties of the polyurethane were previously reported in the Author’s research conducted earlier [19], presented in Table 2. The compressive strengths of the TMC were then tested with a various mixing ratio of polyol and isocyanate at 20:80, 45:55, 50:50, 55:45, respectively, and 80:20 by the UCS test. The flow chart of the research methodology is shown in Figure 1.

| Properties                  | Unit          | Components of the Polyurethane |
|-----------------------------|---------------|-------------------------------|
|                             |               | Polyol                        |
|                             |               | Dark Brown Liquid             |
| Appearance                  | -             | Amber Liquid                  |
| Viscosity at 25 °C          | mPa.s         | 260 ± 50                      |
|                             |               | 185 ± 35                      |
| Specific Gravity at 25 °C   | -             | 1.15 ± 0.01                   |
|                             |               | 1.24 ± 0.01                   |
| Recommended Mixing Ratio    | g             | 125                           |
|                             |               | 140                           |
| Cream Time                  | sec           | 40.0 ± 3.0                    |
| Gel Time                    | sec           | 250.0 ± 10.0                  |
2.2. Unconfined Compressive Strength (UCS) Test

The unconfined compressive test (UCT) was carried out on the soil using a cylindrical specimen of size 38 mm × 76 mm (diameter × height). The specimens were prepared by mixing the MC with water equivalent to its optimum moisture content obtained from the compaction test. The MC was then well mixed at various mixing ratios of polyol and isocyanate. The mixture of the MC and polyurethane was then compacted in the UCT mould immediately prior to the polyurethane hardening. The compacted mixture of the MC and polyurethane was then allowed to remain in the mould for at least 15 minutes to allow the polyurethane to hardened before extruding the specimen. After 24 hours of curing the specimen in the humidity chamber under regulated conditions of 20°C, and not less than 90% humidity [9], the UCT test was conducted. Triplicate samples were used to obtain consistent and accurate results.

3. Results and Discussion

The results in determining the physical properties of the UMC and the results of UCT for both UMC and TMC are discussed in this section. The effect of different mixing ratios of polyol and isocyanate on the UCS of the TMC are also discussed.

3.1 Physical Properties of Untreated Marine Clay

The findings of the physical properties of UMC are shown in Table 3 below. Based on the particle size distribution curve, the sample contained 12% of sand (soil particles between 2 mm and 63 μm), 42% of silt (soil particles between 63 μm and 2 μm) and 46% of clay (soil particles below 2 μm). Fine particles which were smaller than 63 μm, formed more than 88% of the entire sample, which dominated the MC. It was found that the SG of the UMC was 2.50 Mg/m³; the average SG of MC obtained was within the acceptable range as reflected in a finding [16]. In this research, MC had a liquid limit of 54%, a plastic limit of 27.46% and a plasticity index of 26.54%. Therefore, based on the Casagrande plasticity chart, the MC was classified as CH, being high-plasticity clay. The results of the compaction
test also showed that the optimum moisture content of the MC was 22.33%, with a maximum dry density of 1520 kg/m$^3$.

**Table 3.** Physical Properties of Untreated Marine Clay

| Parameters                        | Values |
|-----------------------------------|--------|
| Sand, %                           | 12     |
| Silt, %                           | 42     |
| Clay, %                           | 46     |
| Specific Gravity, $G_s$            | 2.50   |
| Liquid Limit, LL (%)              | 54     |
| Plastic Limit, PL (%)             | 27.46  |
| Plasticity Index, PI (%)          | 26.54  |
| Optimum Moisture Content, OMC (%)  | 22.33  |
| Maximum Dry Density, MDD (kg/m$^3$) | 1520   |

3.2. Effect of PU Compositions on the Strength of Marine Clay

The results of the UCS values of both the UMC and TMC are shown in Figure 2 at the mixing ratios of 20:80, 45:55, 50:50, 55:45 and 80:20 polyol to isocyanate, together with the margins of errors shown by the error bars in representing the standard deviation of the data set. Triplicate samples were used to gain consistent and accurate results. In general, the reliability of the mean UCS value of both the UMC and TMC is high, thereby acting as a representative number for the data set.

![Figure 2. Result of UCS of untreated and treated marine clay](image-url)

Among the triplicated results of each sample, only one of the stress-strain curves of one sample was chosen to represent the discussion. Table 4 shows the summary of the UCS value of the UMC and TMC at various mixing ratios of polyol to isocyanate. Figure 3 shows the stress-strain curve of MC at varying mixing ratios. Based on the stress-strain curve, it is proven that the specimen of UMC shows higher ductile behaviour at a failure strain of 5.31% compared to the TMC specimen at various mixing ratios [20]. In contrast, in the TMC specimen, the ductility of the soil behaviour changes from being ductile to becoming brittle, where abrupt strength reduction occurred after the peak axial stress value reaches the
maximum limit. The axial strain value decreases from 5.31% to 0.65% in TMC at 20:80 polyol to the isocyanate mixing ratio.

**Table 4. Summary of UCS Results at Various Mixing Ratio of Polyol to Isocyanate**

| Polyol to Isocyanate ratio | Maximum UCS (kPa) | Axial Strain (%) | Strength Improved (%) |
|----------------------------|-------------------|------------------|-----------------------|
| Untreated                  | 141               | 5.31             | -                     |
| 20 : 80                    | 104               | 0.65             | -26.2                 |
| 45 : 55                    | 281               | 2.86             | 99.3                  |
| 50 : 50                    | 242               | 4.93             | 71.6                  |
| 55 : 45                    | 204               | 3.93             | 44.7                  |
| 80 : 20                    | 111               | 5.84             | -21.3                 |

**Figure 3. Stress-Strain Curve at Various Mixing Ratio of Polyol to Isocyanate**

The maximum enhanced compressive stress of the TMC is 281 kPa at 45:55 polyol to the isocyanate mixing ratio, followed by 242 kPa for a mixing ratio of 50:50 and 204 kPa in the mix ratio of 45:55. Therefore, based on the UCS results, it could be observed that the compressive strength of TMC can be effectively improved at 45:55, 50:50 and 55:45 polyols to isocyanate mixing ratio. Also, by observing the results of the soil samples at polyol to isocyanate mixing ratio of 45:55, 50:50 and 55:45, the strength of the TMC increases steadily as the ratio of isocyanate increases. This is due to the isocyanate that acts as the bonding agent, giving density and strength in the formation of polyurethane [20-21].

Although higher isocyanates ratio increases the hard segment composition and restricts the flexible chain motion in achieving higher compressive strength, its effect is not apparent in the 20:80 polyol to the isocyanate mixing ratio of the treated MC. Table 3 illustrates that the 20:80 mixing ratio of MC achieves 104 kPa compressive strength, which is lower than the untreated sample due to excessive isocyanate that further reacts with the urea and urethane group to produce allophan or biuret. This results in weak linkages as well as brittle and fragile structure foam [12]. The excessive isocyanate reacts with water (as a blowing agent) to produce carbon dioxide (CO₂), which causes bubbles and cellular structure of the soil samples [22]. The compressive strength decreases significantly given the larger and sporadic bubbles, which resulted in less uniform cellular structure [23].
Furthermore, the stabilisation of the MC in the 80:20 polyol to isocyanate mixing ratio is not effective whatsoever. The achieved maximum compressive strength of TMC at a mixing ratio of 80:20 is lower than the untreated one, where the strength decreased by 21.3%. Therefore, it is notable that a further increase of polyol does not help significantly in enhancing the compressive strength of MC. Generally, polyol acts as a soft segment in the formation of urethane cross-linkage, which is an expansion agent that contributes to the volume expansion of polyurethane [7]. Linear polyols and low amounts of isocyanates give flexible bond lines. Also, the increase in the polyols ratio leads to low density and compressibility due to lower urethane group linkages [14]. In addition, as the polyol content rises, the forming foam was also reported to be soft, structurally unstable and aggravated [15].

4. Conclusion
The physical properties of UMC were determined in this study and investigation of the influence of polyurethane compositions (polyol and isocyanate) mixing ratio on the UCS of treated MC. The following conclusions are consequently drawn from this study:

1. Marine clay (MC) is dominantly constituted of fine particles (42% of sand fraction and 46% of clay fraction), in which the average specific gravity obtained was 2.50 Mg/m³. Based on the Atterberg limits value, MC was classified as a high-plasticity soil, at which its liquid limit was 54%, plastic limit at 27.46% and plasticity index at 26.54%. The maximum dry density of the MC was 1520 kg/m³, which was achieved when 22.33% OMC was obtained.

2. The UCS of the UMC was 141 kPa. The strength of the marine clay increased when polyurethane was added. The compressive strength of marine clay improved from 99.3% to 281 kPa at 45:55 polyol to the isocyanate mixing ratio. Generally, the strength of polyurethane-TMC increases with an increasing isocyanate ratio. However, due to the reaction of excessive isocyanate to the urea and urethane groups, the excessive isocyanate ratio significantly decreased the strength of the TMC. This will further produce a weak, brittle, and fragile linkage structure, called allophanate or biuret. Polyol is an expansion agent that makes PU increase in volume. Due to lower urethane group linkages, excessive polyol in the blending ratio produced TMC with lower compressive strength than the UMC. Polyurethane-TMC at 80:20 polyol to isocyanate mixing ratio obtaining 101 kPa compressive strength.

Accordingly, this study concludes that; polyurethane is an excellent stabiliser for MC soil. Based on the UCS results, it shows that polyurethane works efficiently with MC, and the enhanced strength is most significant at 45:55 polyol to isocyanate mixing ratio.

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