

Stabilization of Patimban Marine Soft Clay with Portland Composite Cement: The Effect of Initial Water Content Variations on Soil Bearing Strength

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ABSTRACT Marine clay soil generally exhibits poor physical and mechanical properties, such as high plasticity, low bearing capacity, and excessive settlement under pressure. Soil improvement techniques, such as cement stabilization are thus needed to enhance these characteristics. This study investigates the effect of clay water to cement content ratio (w_c/C) and curing time variations on the unconfined compressive strength (q_u) of Patimban dredged marine clay stabilized with Portland Composite Cement. Laboratory tests employed variations in ratio of initial water content to its liquid limit (w_0/LL), i.e., 1, 1.25, 1.5, and 2, as well as variations in cement content of 20% and 30% of the dry soil mass. Unconfined compressive strength (UCS) test was carried out at curing periods of 1, 3, 7, 28, and 56 days. The peak effective cement hydration process occurred in the first 7 days. The results revealed an inverse correlation between the w_c/C ratio and q_u , where an increase in the w_c/C ratio caused a decrease in the q_u values. The high-water content resulted in large voids between cement-soil particles, weakening the strength of the binder. The relationship between the w_c/C ratio and the q_u value indicated a good match yielded an R^2 value of 0.88-0.94. Further, the unconfined compressive strength of the soil continued to develop with the increasing curing time of 1-56 days. The Average Normalized Difference (A.N.D) value obtained from the relationship between the measured and the estimated compressive strength value was low (11.40%), meaning the estimation equation can be effectively used to estimate the compressive strength of marine clay soil stabilized with Portland Composite Cement at various curing times.

KEYWORDS Cement; Curing Time; Initial Water Content; Marine Clay; Unconfined Compressive Strength

1 INTRODUCTION

The construction of Patimban Port is one of Indonesia's National Strategic Projects, aimed at strengthening the national logistics system and supporting economic growth. As part of its development, soil dredging was required to deepen the navigation channel and construct port facilities. According to the Ministry of Environment and Forestry (2017) the total dredged volume reached approximately 26.05 million m³. However, most of this material was disposed of offshore, posing significant environmental concerns. Reusing dredged soil represents a more sustainable alternative to direct marine disposal. Nevertheless, the direct utilization of marine clay as reclamation or filling material presents substantial technical challenges. Dredging activities drastically increase the water content of the clay, resulting in reduced shear strength, high compressibility, and potential for excessive settlement. These geotechnical limitations prevent the immediate application of the dredged soils in construction without pretreatment.

One method of stabilizing dredged marine clay is cement stabilization. Physical properties of dredged marine clay are strongly influenced by water content, with natural water content exceeding

the liquid limit depending on the dredging method adopted. Marine clay has a low compressive strength (25–50 kPa) and high compressibility (Mohammed Al-Bared and Marto, 2017). Biological and chemical contamination in dredged marine clay also limits its direct use (Shahri and Chan, 2025). Portland Composite Cement is commercially available, effective stabilizer that can harden and bind soil particles, making them stronger and resisting deformation (Lesmana et al., 2016). Soil stabilization with cement has been widely studied by several researchers, such as Tsuchida and Tang (2015), Yamashita et al. (2020), Chian et al. (2017), Lesmana et al. (2016), Suksiripattanapong et al. (2022), and Zhang et al. (2024). To effectively apply cement for soil stabilization, optimum water and cement contents are required to achieve the desired soil strength.

This study was conducted to determine the optimum mixture of cement and water for marine clay soil, analyze the effects of water and cement content, and understand the effect of curing time on the stabilization process of marine clay soil. Through this research, it is expected that an appropriate approach can be developed for estimating the compressive strength value of stabilized soil, capable of considering variations in cement content, initial water content, and curing duration, thereby facilitating more efficient soil strength planning in the field.

2 MATERIALS

2.1 Marine clay

The marine clay soil used in this study came from Patimban Port, West Java, Indonesia (Figure 1). A photograph of Patimban marine clay is shown in Figure 2. A series of laboratory tests were then conducted to characterize the clay. The results are presented in Table 1, which summarizes the key findings regarding the soil's physical properties. The characteristic of Patimban soft soil were discussed extensively and reported by Yamada et. al (2024).

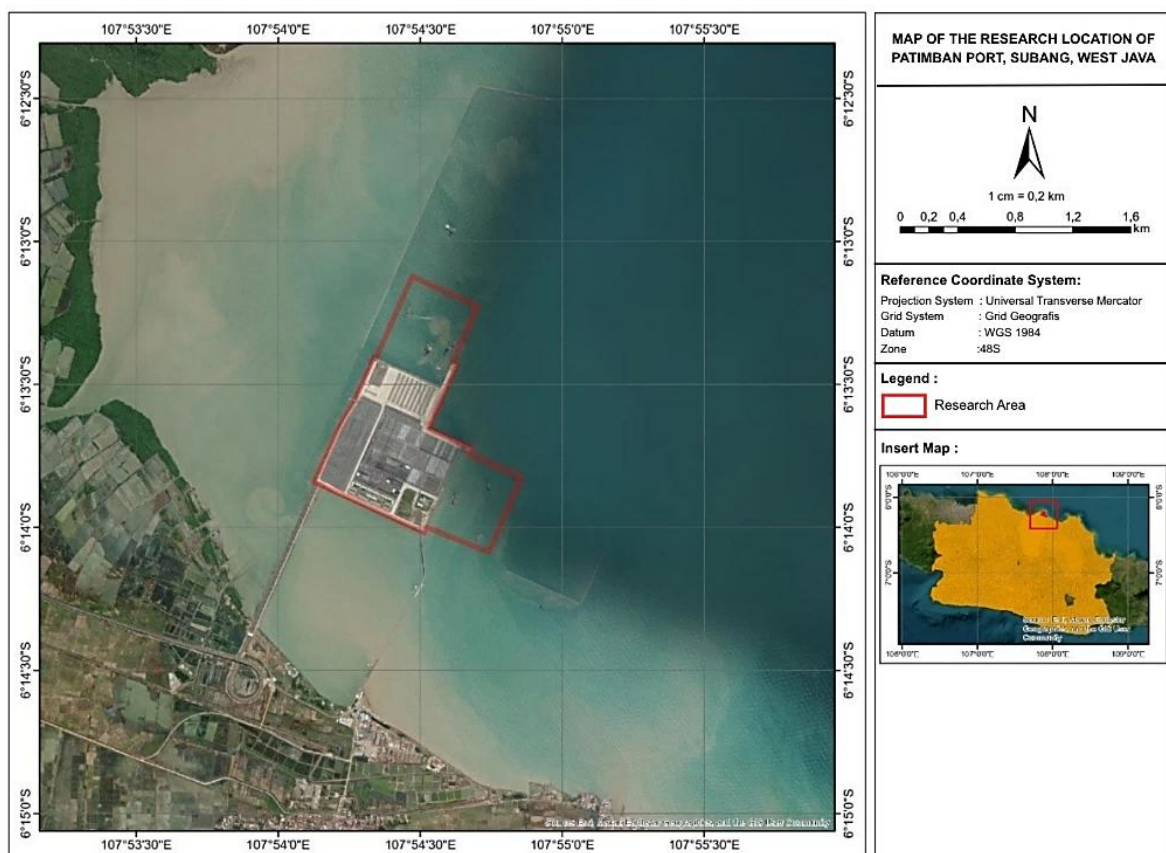


Figure 1. Location of marine clay soil extraction at Patimban Port

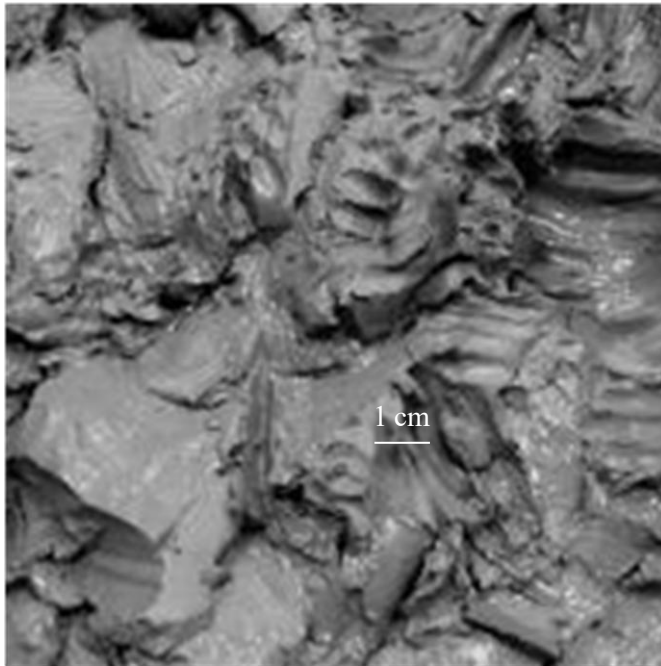


Figure 2. Patimban marine clay

Table 1. Physical properties

Soil sample	Specific gravity, <i>G_s</i>	Liquid limit, <i>LL</i> %	Plastic limit, <i>PL</i> %	Plasticity index, <i>PI</i>
Marine clay	2.70	85.38	43.31	42.07

2.2 Binder

In this preliminary study, Portland composite cement (PCC) was chosen due to its high availability. PCC, a hydraulic cement produced by grinding Portland cement clinker with slag, mainly consists of hydraulic calcium silicate ground together with one or more crystalline forms of calcium sulfate compounds. Other supplementary materials may be added to achieve specific performance characteristics (Badan Standarisasi Nasional, 2004). In this study, Type I Portland composite cement was used, with its composition shown in Table 2.

Table 2. Chemical properties of Portland composite cement (Source: Badan Standarisasi Nasional, 2004)

No	Description	Types of Portland cement (%)				
		I	II	III	IV	V
1	SiO ₂ , minimum	-	20.0	-	-	-
2	Al ₂ O ₃ , maximum	-	6.0	-	-	-
3	Fe ₂ O ₃ , maximum	-	6.0	-	-	-
4	MgO, maximum	6.0	6.0	6.0	6.0	6.0
5	SO ₃ , maximum					
	If C ₃ A is ≤ 8.0	3.0	3.0	3.5	2.3	2.3
	If C ₃ A is > 8.0	3.5		4.5		
6	Glow loss, maximum	5.0	3.0	3.0	2.5	3.0
7	Insoluble part, maximum	3.0	1.5	1.5	1.5	1.5
8	C ₃ S, maximum	-	-	-	35	-
9	C ₂ S, minimum	-	-	-	40	-
10	C ₃ A maximum	-	8.0	15	7	5
11	C ₄ AF + 2 C ₃ A or C ₄ AF + C ₂ F maximum	-	-	-	-	25

3 METHOD

3.1 Mix Proportion and Sample Preparation

Test specimen preparation began with screening marine clay from Patimban Port using a No. 200 sieve, using a wet method to separate coarse particles. Portland Composite Cement (PCC) was also screened using a No. 100 sieve to maintain particle uniformity. The proportions of soil, cement, and sand were then determined based on the calculated mixture variations. The test specimen preparation process involved mixing the soil using a hand mixer, then adding a cement paste made from a mixture of cement and water at a temperature of approximately 2 °C. The reason to put chilled water in was to delay the hydration process during the mixing procedure. The soil and cement paste mixture was stirred until homogeneous, then gradually poured into a greased mold with compaction by light tapings to remove air bubbles. The mold was then wrapped in plastic wrap and soaked for 24 hours (the plastic wrap was punctured with holes to allow water to seep inside). The plastic wrap and mold were then removed, samples weighed, re-wrapped in plastic without the mold, soaked and cured again at room temperature (approximately 25°C) for another 0, 2, 6, 27 or 55 days before strength testing. Table 3 outlines the experimental cases; a total of 100 samples was prepared. The cement content (c^*) was calculated using the equation proposed by Tsuchida and Tang (2015).

$$c^* = \frac{m_{cement}}{m_{fine} + m_{sand} + m_{cement}} \times 100 \quad (1)$$

Table 3. Experiment cases

Variation	Initial water content w ₀ /LL	Cement content %	Curing time days
1	1.00	20	
2	1.00	30	
3	1.25	20	
4	1.25	30	
5	1.50	20	1, 3, 7, 28, and 56
6	1.50	30	
7	2.00	20	
8	2.00	30	

Note: water content is represented as ratio of initial water content to liquid limit, LL = 85.38%

3.2 Strength Test of Stabilized Soil

Unconfined compressive strength (UCS) is the maximum axial stress that a soil can withstand before it experiences shear failure. The UCS testing conducted refers to the ASTM D2166-06 procedure. Data related to axial stress and strain are obtained by processing data available on the unconfined compressive strength test apparatus, such as load, time, and strain data. The strain rate used in this study was 1 mm/min, with a maximum strain of 10% adopted as the test termination condition.

Strength estimation equation is adopted to predict the strength of stabilized soil based on the UCS tests results. The Japan Cement Association (2007) proposed calculating the UCS of cement-stabilized soil using equations based on Abrams' law to obtain more accurate results.

$$q_u = \frac{a}{\left(\frac{w_c}{c}\right)^x} + b \quad (2)$$

where,

q_u : Unconfined compressive strength of soil stabilized with cement (kN/m²)

$\frac{w_c}{c}$: Water-cement ratio

a, b, x : Constants obtained from equations (values are shown in latter section)

4 RESULTS

4.1 Stress-Strain Curve of Marine Clay Stabilized with Portland Composite Cement (PCC)

Variations in initial water content and cement content affect the stress-strain characteristics of soil obtained from the UCS tests. Figure 3 shows the stress-strain curves for soil-cement mixtures with various ratio of initial water content to liquid limit, (w_0/LL) at a 28-day curing time. The graphs indicate that stress increases with strain until reaching a peak, then decreases after the peak. Mixtures with higher water content exhibit more ductile behavior than those with lower water content for both 20% and 30% cement content. A high strain at failure indicates a more ductile soil, although this is generally accompanied by a decrease in unconfined compressive strength. According to Darwis (2017), the brittle behavior of cement-soil mixtures occurs due to the transformation of pore water into bound water during the cementation reaction, which forms rigid crystals in the soil matrix. Figure 4 shows the typical failure in stabilized soils under compression load. Most of the UCS samples failed in shear failure mode. Shear failure occurs after the maximum load is reached, characterized by the formation of a crack plane inclined to the load axis due to shear stress. This type of failure often occurs in stabilized soils with cement.

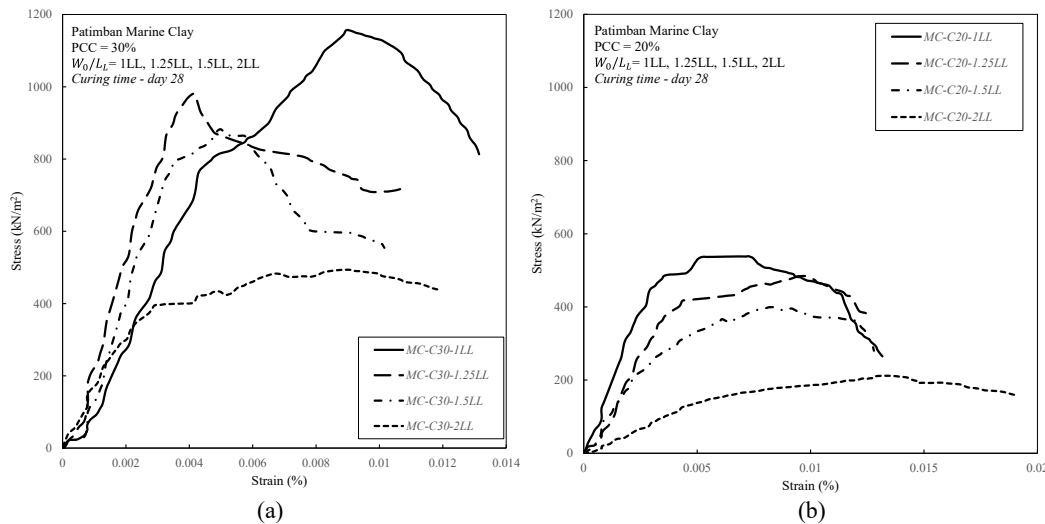


Figure 3. Stress–strain response of stabilized soil after 28-day curing time. (a) Stress-strain behavior of soil mixtures at PCC = 30%, (b) Stress-strain behavior of soil mixtures at PCC = 20%

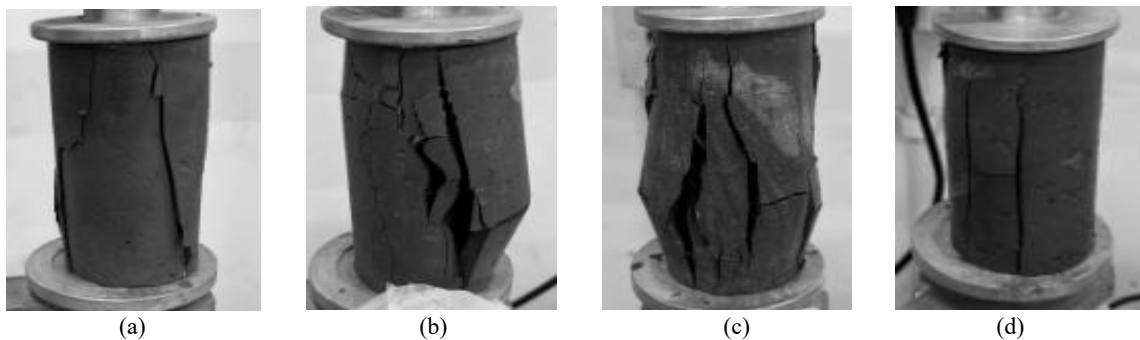


Figure 4. Photographs showing soil sample failure after unconfined compressive strength testing, (a) sample C20-1LL, (b) sample C20-1.25LL, (c) sample C30-1LL, (d) sample C30-1.25LL

4.2 Effect of Soil Water/Cement Ratio (w_c/C) Against Soil Compressive Strength (q_u)

The soil water-to-cement ratio (w_c/C) is one of the key parameters influencing the success of cement-based soil stabilization. This ratio reflects the proportion of water in the mixture (initial water content of dredged marine clay plus water in cement slurry) relative to the cement used as binder. Tsuchida

and Tang (2015) demonstrated that soil water content and cement content are considered two key factors that determine the strength development of stabilized soil, where the compressive strength of the soil increases as cement content increases but decreases as soil water content increases.

Figure 5 shows the relationship between the w_c/C and the unconfined compressive strength of stabilized marine clay obtained from this research. The graph shows that a higher w_c/C ratio, results in reduction of soil compressive strength, regardless of curing time. This is likely because high water content causes larger voids between solid particles and reduces the strength of the binder (Li et al., 2024). Conversely, a lower w_c/C ratio indicates a relatively smaller amount of free water compared to cement, resulting in a denser and stronger cement paste after hydration. The graph shows that the largest w_c/C ratio = 6.83 (i.e., an initial water content of 2LL and a cement content of 20%), yielding the lowest compressive strength value across all curing time. Meanwhile, the smallest w_c/C ratio = 1.99 (i.e., an initial water content of 1LL and a cement content of 30%), yielding the highest compressive strength among all variations.

Furthermore, the high coefficient of determination (R^2) also indicates that the w_c/C Ratio has a significant effect on soil compressive strength. The R^2 values for each regression curve ranged from 0.88 to 0.94, indicating excellent performance of the nonlinear power regression model. Therefore, the w_c/C Ratio is a crucial parameter for controlling soil stabilization with cement. The more precisely the ratio of soil water to cement is managed, the more optimal the resulting soil strength.

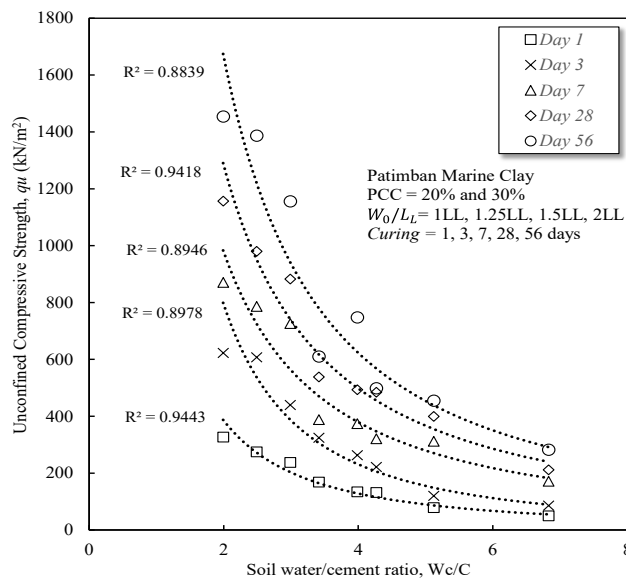


Figure 5. The relationship between the value of the soil water/cement content ratio (w_c/C) and the value of the unconfined compressive strength (q_u).

4.3 Effect of Curing Time on Compressive Strength

In addition to the w_c/C Ratio, curing time also plays a crucial role in increasing the strength of cement-stabilized soil. The length of curing time also influences the increase in intergranular strength. Increasing the intergranular bonding strength also increases the interlocking ability of the grains (Lesmana et al., 2016). Figure 6 shows the relationship between curing time and the unconfined compressive strength (q_u) of stabilized Patimban marine clay with Portland cement (PCC).

The cementation reaction that occurs in the soil-cement mixture forms new, harder grains, making them stronger in resisting the applied load (Lesmana et al., 2016). According to research by Liu et al. (2024), Darwis (2017), strength development is relatively fast in the first 7 days (168 hours), which is caused by the cement hydration reaction. However, after the 28th day (672 hours), the cement hydration process begins to slow down because most of the cement has reacted and formed a dense structure, so that space and water for continued hydration are more limited. The graph also

explains that from the first day to the seventh day, the slope of the line is steeper than the slope of the line from the seventh day onwards, which is gentler. The age of the cement-soil has a nominal effect on increasing the strength and stiffness of marine clay stabilized with cement. Therefore, curing time is also an important factor in achieving the desired soil strength.

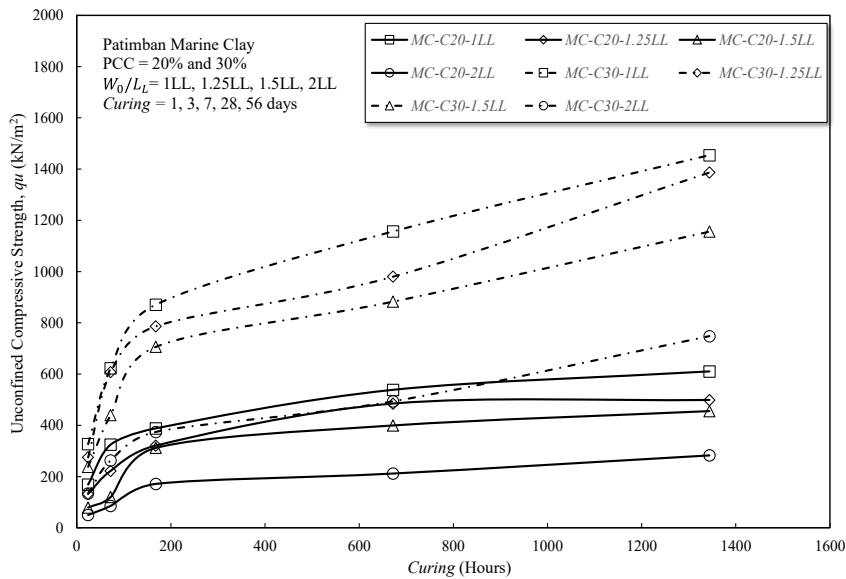


Figure 6. Relationship between curing time and unconfined compressive strength (q_u).

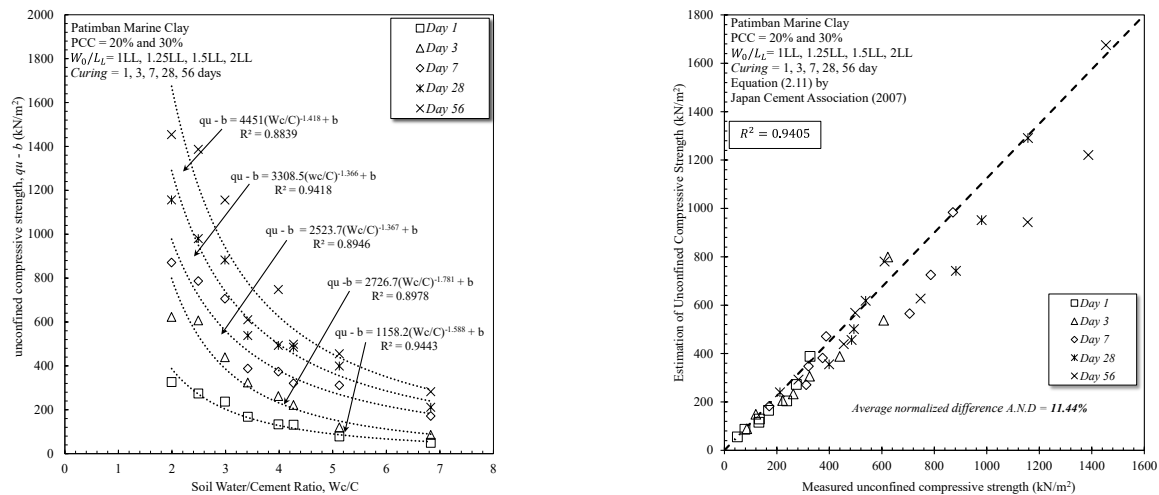
4.4 Estimation of Unconfined Compressive Strength Using the Japan Cement Association Equation (2007)

The Japan Cement Association (JCA) equation considers the soil water/cement ratio (w_c/C) as the main factor affecting the increase in the unconfined compressive strength of Portland cement (PCC) stabilized soil. The JCA proposed an estimation equation with a power function containing 3 (three) other constants that are influenced by the characteristics of the soil and the binder used, namely the constants a , b , and x . Based on the research of Yamashita et.al. (2020) in the application of the strength estimation equation, the equation shows the relationship between the soil water/cement ratio (w_c/C) and the unconfined compressive strength ($q_u - b$), where the parameters a , b , and x are determined using the power regression line from each curing time (Figure 5). The following equations are obtained for each curing time (note that the constant b is equal to 0 for all cases).

$$\begin{aligned}
 q_u &= 1158.2 (w_c/C)^{-1.588} && (1 \text{ day}) \\
 q_u &= 2726.7 (w_c/C)^{-1.781} && (3 \text{ days}) \\
 q_u &= 2523.7 (w_c/C)^{-1.367} && (7 \text{ days}) \\
 q_u &= 3308.5 (w_c/C)^{-1.366} && (28 \text{ days}) \\
 q_u &= 4451 (w_c/C)^{-1.418} && (56 \text{ days})
 \end{aligned} \tag{3}$$

In the obtained equation, the constant a increases with increasing curing time. This equation is then used to estimate the unconfined compressive strength of marine clay stabilized with Portland cement. Once the estimated unconfined compressive strength is obtained, it is compared with the measured compressive strength, as shown in Figure 7b.

By applying the estimation equation proposed by the Japan Cement Association (2007), the coefficient of determination (R^2) was obtained as 0.94, and the average difference between the measured values (A.N.D) was 11.44%. This value indicates a good agreement between the unconfined compressive strength values calculated using the estimation equation and the unconfined compressive strength values measured from UCS testing in the laboratory. Therefore, the unconfined compressive strength values of Patimban clay stabilized using Portland cement can be accurately estimated by applying the JCA estimation equation at curing time periods of 1, 3, 7, 28, and 56.



(a) The relationship between the value of the soil water/cement content ratio (w_c/C) and the value of the unconfined compressive strength (q_u).

(b) Comparison between measured unconfined compressive strength and estimated unconfined compressive strength.

Figure 7. Analysis of the application of the estimation model Equation (3).

5 CONCLUSIONS

Based on research conducted, it is concluded that Patimban marine clay can successfully be stabilized by cement. The behavior of cement stabilized Patimban marine clay follows the typical behavior stabilized clay in which soil water/cement ratio (w_c/C) is proven to be a parameter that correlates with the unconfined compressive strength (q_u). The w_c/C ratio is inversely proportional to the q_u value, where the higher the w_c/C ratio yields smaller q_u . Excess water increases voids between particles and reduces the strength of the binder. This can be seen in the highest w_c/C ratio of 6.83, the unconfined compressive strength recorded was lowest (50-300 kN/m²), whilst the highest compressive strength value (1500 kN/m²) is obtained with the lowest w_c/C ratio of 1.99. The R^2 value obtained from the power regression, which is 0.88 – 0.94, also shows that the w_c/C ratio has a strong relationship with the soil compressive strength value (q_u). Curing time also plays an important role in increasing the unconfined compressive strength (q_u) of marine clay stabilized with Portland Composite Cement. Unconfined compressive strength (q_u) increases with increasing curing time due to the ongoing cement hydration process that strengthens the bonds between soil particles. A significant increase occurs in the first 7 days, then the rate of strength gain decreases after the 28th day as most of the cement has reacted and formed a dense structure. The Japan Cement Association (JCA) estimation equation can predict the unconfined compressive strength (q_u) of Portland cement (PCC) stabilized clay based on the water to cement ratio (w_c/C), using a power regression model with three constants adjusted for each curing time. The constants increased with curing time, reflecting the effect of cement hydration on soil strength. Validation against laboratory data shows high accuracy with an R^2 of 0.94 and an A.N.D of 11.44%, so the JCA model is effective for estimating the strength of stabilized Patimban soil in construction planning.

DISCLAIMER

The authors declare that they have no conflict of interest.

AVAILABILITY OF DATA AND MATERIAL

All data are available from the author.

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