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STRENGTH OF CEMENT TREATED CLAY AND DEGRADATION UNDER MAGNESIUM SULPHATE ATTACK

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Abstract: Lumpur Sidoarjo (Lusi) is an environmental issue in Indonesia that produce wasted soils, specifically clay soils, distributed to Porong River which causes a greater problem. Cement treated clay (CTC) becomes one of the solutions to overcome the problems caused by Lusi due to its ability in improving the strength of clay soils. This paper investigates CTC with lower cement amount (C <70 kg/m^3) for reclamation and higher cement amount (C >150 kg/m^3) for deep mixing marine clay for its strength and degradation due to the attack of magnesium sulphate as the main component of seawater which cause the degradation of CTC. The enhancement of soil strength is investigated by unconfined compression test (q_u) and the degradation by penetration test. Water content of the specimens for both tests are arranged in its liquid limit condition (60%) and two times of its LL (120%). The result of the cement amount addition for both water content shows the enhancement of q_u represented by linear and the tip resistance is increased. The characterictic of degradation for lower cement amount with close range present similar depth of deterioration, like-wise higher cement content. The value of tip resistance is not relatable with q_u.

Keywords: cement treated clay, magnesium sulphate, UCS test, penetration test, increasement of soil compression strength, degradation

INTRODUCTION

Soft soils such as dredged marine clay and unwanted soils present construction issues in providing sites for the soils (Vichan and Rachan, 2013). The characteristics of soft soils cause construction issues due to its swelling, low strength, and settlements (Sargent, Hughes and Rouainia, 2016). One of the unwanted soft soils which contribute to environmental issues is Sidoarjo Mud or Lumpur Sidoarjo (Lusi), located in Sidoarjo, Indonesia. Lusi is produced 100,000 m3/day where the area to provide the soils is limited. Lusi then distributed to the Porong River which causes greater issues to the environment. Improvement of Lusi for construction necessity is done in this research to reduce the environmental issues caused by soft soils, especially Lusi.

One of the methods to improve the strength of soils is soil stabilization. Soils stabilization method by utilizing additional admixtures has been investigated in many reports, i.e. lime (Tatsuoka, 2010; Liu et al., 2012), cement (Tatsuoka, 2010; Horpibulsk et al., 2011; Tsuchida and Tang, 2015), biopolymer (Chang, Im and Cho, 2016), microorganism (Liang, Ralf and A., 2013), and other additional admixtures. The most common admixture to stabilize soft soils i.e. clay is cement, and the mixture known as Cement Treated Clay (CTC). CTC used for reclamation has the advantage due to its high water content, it has a small unit weight, which can reduce the overburden pressure causing settlement in the original ground (Seng and Tanaka, 2011). Soils utilized by cement in high amount is suitable for deep mixing method due to its strength. Zhang et al. (2013) reported the amount of CTC are classified in three zone based on the working ranges of Unconfined Compression Strength (UCS) test result. Figure 1 presents the zone classification of cement-treated soils based on the working ranges. Zone I (C < 70 kg/m3) is an inactive zone with a low increment of soils strength (q_u), where zone II (C > 115 kg/m3) is an active zone which delivers significant increment of q_u. Zone III is inert zone due to its excessive amount of cement, lead to an insignificant increment of q_u. This study focused on the cement amount in Zone I and Zone II to stabilize soft soils.

As the application of CTC for reclamation and deep mixing method, the attack of seawater will affect the strength of CTC (Hara et al., 2014;

Yang et al., 2016). Sulphate content is known as a deteriorative component for hardened cement paste (Sherwood, 1962). Therefore, soils utilized with cement will present similar behavior of deterioration with hardened cement paste cause by the containing cement in soils. One of the sulphate content which contributes to the highest impact of deterioration is Magnesium Sulphate (Hara et al., 2014). Hara et al. (2014) and Yang et al. (2016) investigate the deterioration of CTC by penetration test. The apparatus of penetration test used by Yang et al. (2016) was micro-cone penetrometer. The cone probe had a diameter of 7 mm and a taper angle of 600 with the feeler lever is set with a diameter of 6 mm. Penetration test deliver the degradation depth (d) and tip resistance (R) of CTC cause by the attack of sulphate.

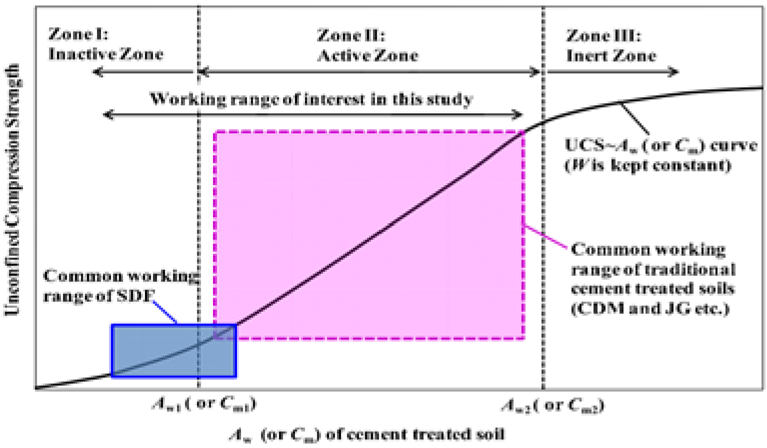

Figure 1. Zone classification based on working ranges of cement-treated soils (Zhang et al., 2013)

This paper presents the investigation of the increment of soil compression strength (q_u) by adding the amount of cement (C) classified in Zone I and Zone II. Furthermore, the deterioration of CTC in Zone I and Zone II are investigated with a penetration test to determine the tendency of d and R due to the added amount of cement.

EXPERIMENTAL

Materials

Soft soils used in this research is Lusi. Lusi as clayey soils has a specific gravity of 2.65 and the liquid limit (LL) reaches to 60%. The water content of Lusi for this research is set at its LL that is 60% and twice of its LL that is 120% to investigate the behavior of high water content soil. The specimen has to be homogenous to comply with the investigation.

The type of cement used is Ordinary Portland Cement (OPC) with a specific gravity of 2.92. The amount of cement classified into Zone I and Zone II refer to the research of Zhang et al. (2013). Zone I consist of C under 70 kg/m3 and Zone II consists of C above 115 kg/m3. Table (1) presents the mix design of CTC used in this study for both UCS test and penetration test.

Magnesium Sulphate (MgSO4) is used in this study to represent the attack of seawater to the water-cement reaction in CTC. The content of MgSO4 is 10 % out of the weight of water. It means in 1 kg of water will consist of 100 grams of MgSO4 powder. MgSO4 powder should be mixed uniformly with water for immersion necessity.

Specimen preparation

The specimen consists of water, cement, and soils based on mix design in Table (1). The water content (wc) of the specimen is set to 60 % and 120 %. The variation of cement content (cc) is set in Zone I and Zone II for both water content. The weight of cement and water is obtained by the determined percentage towards soil weight (Ws). The weight of soils (Ws) can be obtained by using Eq. (1).

$$W_s = \frac{G_s.V.\rho_w}{\left[1+\left\{G_s.\left(\frac{c_c}{G_c}\right)+\left(w_c.G_s\right)\right\}\right]} \quad (1)$$

Where Ws is the weight of soils, Gs is soil specific gravity, V is total volume, ρw is water density (1000 kg/m3), cc is cement content, Gc is cement specific gravity, and wc is water content. All materials were mixed 10 minutes uniformly for each specimen. The mixing specimen then poured into the mold and flattened with a spatula. The specimen mold is divided into two dimensions as shown in Figure 2. For the UCS test, the mold dimension is 5 cm Ø x 10 cm height, whereas the mold dimension for a penetration test is 8 cm Ø x 8 cm height.

Table 1. Specimen Mix Design for UCS test and Penetration test

Zone Classification	Cement Content (%)	Weight of Cement (kg/m^3)	Water Content (%)		Label of Specimen	Curing with $MgSO_4$		Curing Without $MgSO_4$	
			60	120		UCS Test	Penetration Test	UCS Test	Penetration Test
Zone I	2	20,3	√	-	S60-2	-	√	√	-
	4	40,4	√	-	S60-4	-	√	√	-
	6	60,2	√	-	S60-6	-	√	√	-
	8	49, 9	-	√	S120-8	-	√	√	-
	10	62,1	-	√	S120-10	-	√	√	-
Zone II	12	117,9	√	-	S60-12	-	√	√	-
	14	136,6	√	-	S60-14	-	√	√	-
	20	121,6	-	√	S120-20	-	√	√	-
	22	133,2	-	√	S120-22	-	√	√	-
	24	144,6	-	√	S120-24	-	√	√	-

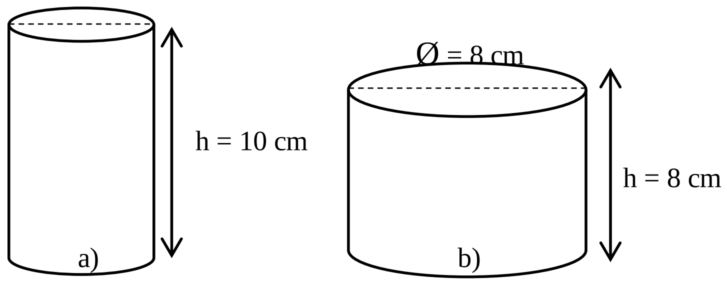

Figure 2. Specimen Mold Dimension for: a) UCS test; and b) Penetration test

The specimen for the UCS test is cured in a sealed container with uncontrolled temperature for 28 days. For the penetration test, the upper surface of the specimen is coated with pore paper to avoid the specimen fall apart during the curing time. The specimen for a penetration test is immersed in PVC contains an MgSO4 solution to represent the attack of seawater for 28 days. The opening of PVC is coated due to keeping MgSO4 solution in stable condition. UCS and Penetration test is done right after curing and immersing time.

CEMENT REACTION

Water-cement reaction

cement has been utilized for soil improvement in some research (Chian et al., 2011; Horpibulsuk, Rachan and Suddeepong, 2011; Suzuki, Fujimoto and Taguchi, 2014). The type of cement which commonly used for soil improvement is Ordinary Portland Cement (OPC). Major components for strength development of OPC are C3S (Tricalcium silicate), C2S (Dicalcium silicate), C3A (Tricalcium Aluminate) and C4AF (Tetracalcium aluminoferrite) (Amin et al., 2007). The reaction of water and cement are hydration (I) and pozzolanic (II) reaction.

Hydration reaction develops as the reaction of water-cement through curing time. Eq. (2) and (3) deliver hydration reaction of the water-cement mixture.

$$C_3S + H_2O \rightarrow C-S-H_{(I)} + Ca(OH)_2 \qquad (2)$$

$$C_2S + H_2O \rightarrow C-S-H_{(I)} + Ca(OH)_2 \qquad (3)$$

The pozzolanic reaction occurs subsequent to hydration reaction by the assistance of SiO2 to obtain the increment of soil strength, where Si is contained in Lusi. Eq. (4) shows the scheme of pozzolanic reaction.

$$Ca(OH)_2 + SiO_2 \rightarrow C-S-H_{(II)} \qquad (4)$$

C-S-H (Calcium-Silicate-Hydrate) as the product of hydration reaction delivers the strength development of concrete. Additional C-S-H bonds produced by pozzolanic reaction present higher strength for concrete, as well as for soil improvement.

Deterioration by sulphate attack

Deterioration is the result of a seawater attack on CTC as the application of CTC for reclamation and deep mixing method. The potency of deterioration can be caused by the aggression of Magnesium Sulphate (MgSO4) which is contained in seawater to cement hydrates (Hara et al., 2014). The reaction of MgSO4 and cement hydrates is presented in Eq. (5) and (6).

$$MgSO_4(aq) + Ca(OH)_2 \rightarrow CaSO_4.\ 2H_2O + Mg(OH)_2 \qquad (5)$$

$$MgSO_4(aq) + C-S-H \rightarrow CaSO_4.\ 2H_2O + M-S-H \qquad (6)$$

MgSO4 and cement hydrates reaction forms gypsum which produces poor strength. Mg2+ replace Ca2+ and form M-S-H (Magnesium-Silicate-Hydrate) which reduces the amount of C-S-H bond. The replacement causes deterioration of the attacked surface and leads to strength degradation of CTC.

RESULT AND DISCUSSION

UCS Test

UCS test is conducted immediately after the curing time of CTC for 28 days. 20 specimens were tested on cement-soil mixtures with water content (wc) of 60% and 120% for Zone I and Zone II. Figure 3 shows the UCS test result on the specimen labeled as S60-2.

The dots represent the result data from the laboratory test. Soil strength (q_u) is shown by the peak of the strain-stress curve. The theoretical water content (wct) is calculated to predict the final water content (wcf) of CTC. The theoretical water content (wct) can be obtained by Eq. (7).

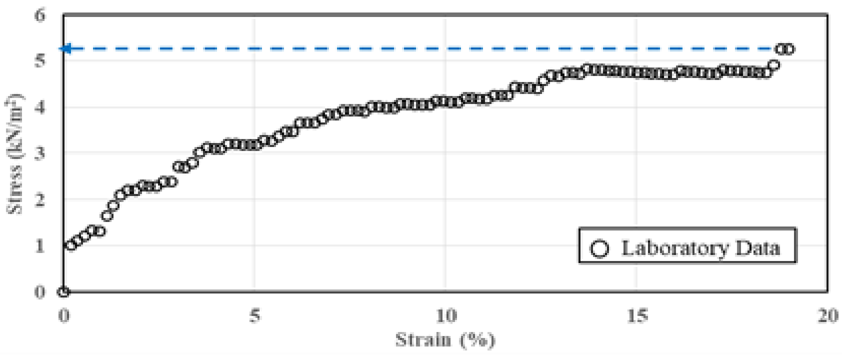

Figure 3. Result of UCS Test on S60-2

$$w_{ct} = \frac{m_w}{m_s + m_{cem}} \qquad (7)$$

Where w_{ct} is theoretical water content, m_w is the weight of water, m_s is the weight of soil, and m_{cem} is the weight of cement. Due to analyzing the variation of q_u caused by the addition of C, Figure 4 are presented as composite data for CTC with the water content of 60 % and 120 %.

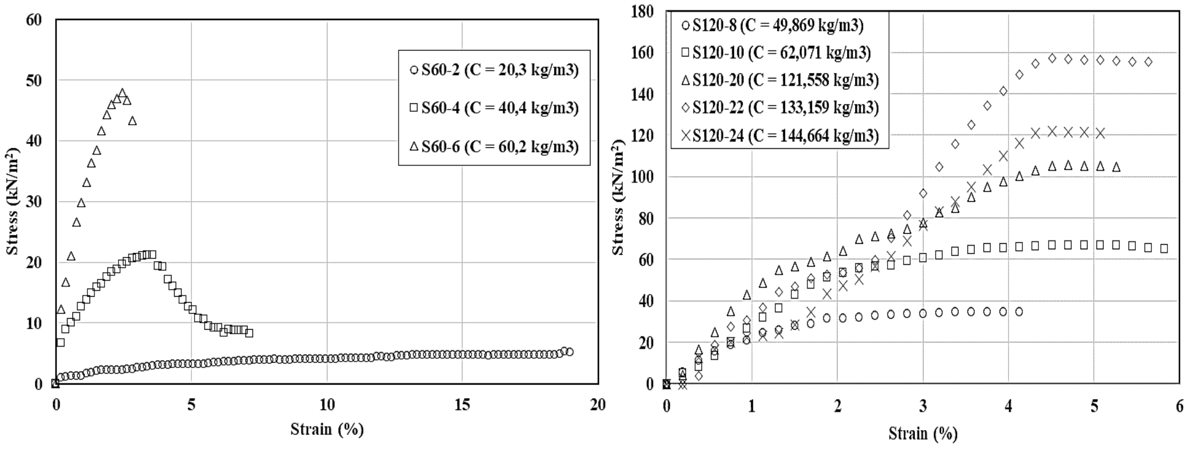

Figure 4. Results of the UCS test with the water content of 60 % and 120 %

Based on the result of the UCS test with the similar water content, the value of q_u increase due to the addition of C. However, S120-24 presents anomaly data of q_u for which is lower than S120-22. This anomaly may be occurred due to the final water content (w_{cf}) of S120-24 is lower than S120-20 and S120-22 as shown in Table (2). The theoretical water content (w_{ct}) of the CTC specimen shows that the water content of higher C should be lower than the specimen with lower C. Therefore, the wcf value of S120-24 might be the reason for the lower q_u value.

Table 2. Water Content of specimen with w_c = 120%

Zone	Label of Specimen	Weight of Cement (kg/m^3)	Theoretical Water Content (%)	Final Water Content (%)
		C	w_{ct}	w_{cf}
I	S120-8	49,869	111,111	97,012
	S120-10	62,071	109,091	98,096
II	S120-20	121,558	100	90,4196
	S120-22	133,159	98,361	89,8552
	S120-24	144,664	96,774	91,4944

Zhang et al. (2013) illustrate the increment of q_u for zone I as insignificant enhancement, while Zone II presents significant enhancement of q_u due to the increased of C. However, the increment of q_u to weight of cement (C) in this research can be presented with linear contour as shown in Figure 5 for Zone I and Zone II in both water content. This result does not correspond with the investigation of Zhang et al. (2013).

Penetration Test

The result of the penetration test is drawn in the chart of tip resistance (N) to penetration depth (mm) of CTC immersed in 10% of $MgSO_4$ solution. The specimen with water content of

60% and 120% was immersed for 28 days. The result of the penetration test on S120-20 is presented in Figure 6. The dots represent the laboratory data and the solid line represents the fitting line. Fitting line in this study is proposed using Eq. (8).

$$R = R_{reff} - \frac{R_{reff}}{\left(1+\left(\propto d\right)^{\beta}\right)^{\gamma}} \quad (8)$$

Where R is cone resistance, R_{reff} is reference cone resistance, d is penetration depth, α, β, γ are fitting constant and z is the deterioration depth. All constants are obtained from the Matlab program. The closer fitting line to the laboratory data means the fitting line is more accurate. The increment resistance of the specimen represents the increased strength of CTC. The resistance increase then shows constant behavior indicate that the specimen reaches its actual resistance.

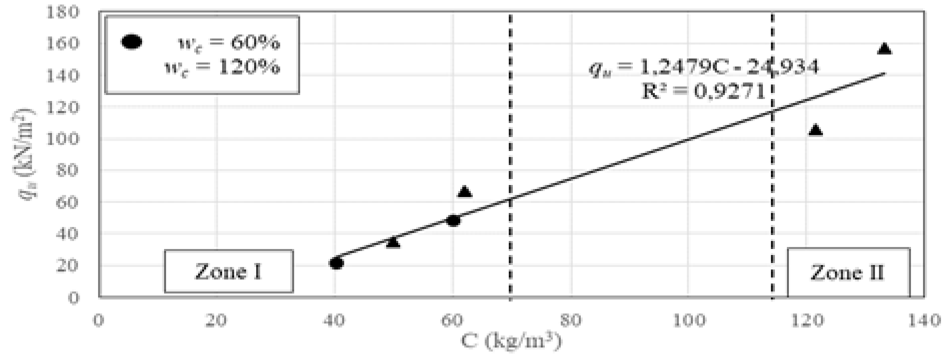

Figure 5. The correlation of q_u to the additional weight of cement (C) in Zone I and Zone II

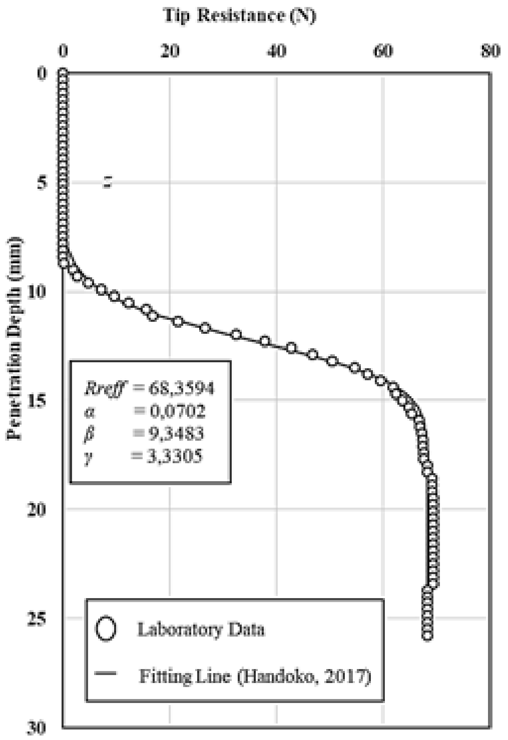

Figure 6. Result of Penetration Test on S120-20

Figure 7 present composite data of penetration test with a water content of 60% and 120%. The penetration test for the water content of 60% and 120% in Figure 7 shows the addition of C to improve the resistance of CTC from the attack of $MgSO_4$. Penetration test on CTC in Zone I with C < 70 kg/m^3 results in higher deterioration then Zone II. The reference tip resistance in Zone II shows higher strength than Zone I. Figure 8 present similar deterioration depth in Zone I and Zone II for both water content where the range of cement amount is 10-12 kg/m^3 for Zone I and Zone II respectively.

However, several specimens of CTC with the cement content of 60% result higher reference tip resistance (R_{reff}) and improved deterioration depth (z) then CTC with a water content of 120%. This condition may be caused by the value of volumetric solid content (Y) of CTC. Y value is obtained by Eq. (9).

$$Y = \frac{V_s + V_{cem}}{V_s + V_{cem} + V_w} \quad (9)$$

Where Y is volumetric solid content, V_s is the volume of soil, V_{cem} is the volume of cement, and V_w is the volume of water. The higher value of Y delivers higher value of q_u. In this research, Y value of CTC with water content of 60 % is higher then 120% as shown in Table (3). Therefore, the q_u value of CTC with w_c=60 % is higher then w_c=120 % as presented in Figure 7 and 8.

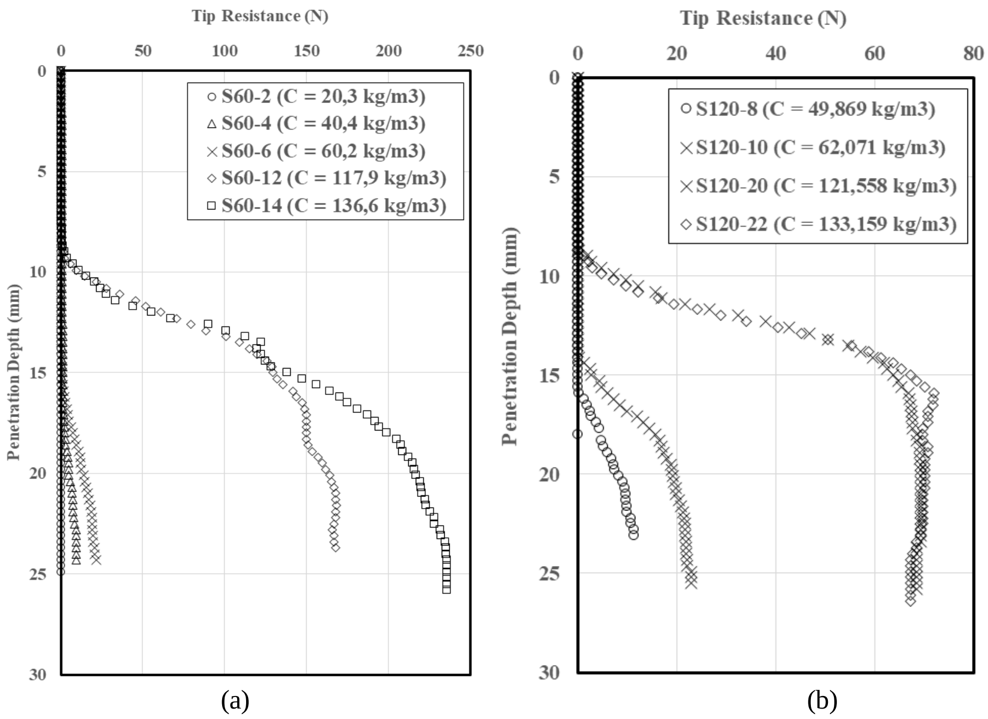

Figure 7. Results of Penetration test with the water content of 60% and 120%

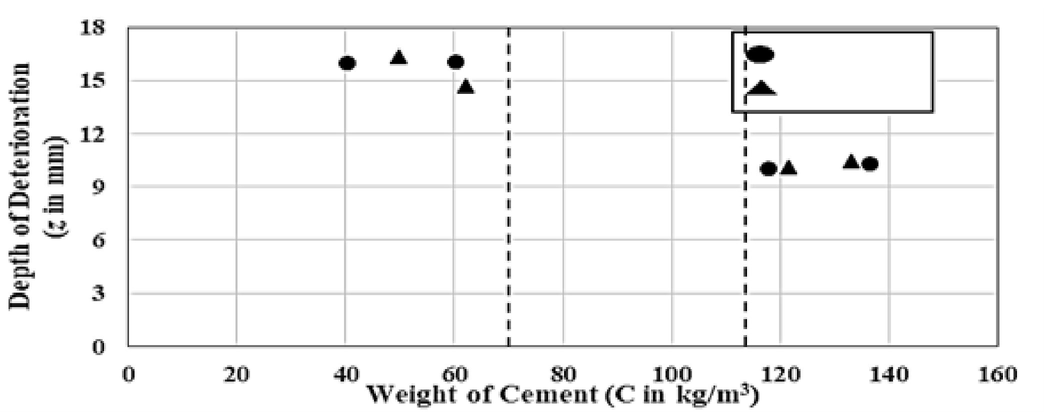

Figure 8. Data of deterioration depth (*z*) to weight of cement (*C*) in Zone I and Zone II with the water content of 60% and 120%

Table 3. Data of Volumetric Solid Content and Reference Tip Resistance

Composition		Weight of Cement (kg/m3)	Volumetric Solid Content (%)	Reference Tip Resistance (N)
wc	*cc*	*C*	*Y*	*Rreff*
60%	2%	20.3321	39.004	-
	4%	40.383	39.426	-
	6%	60.158	39.841	-
	12%	117.888	41.056	168.377859
	14%	136.617	41.45	235.537119
120%	8%	49.869	25.197	-
	10%	62.071	25.515	23.149
	20%	121.558	27.065	68.3594
	22%	133.159	27.368	69.329
	24%	144.664	27.668	-

R_{reff} and q_u Correlation

UCS test is a common method to achieve soil strength (q_u) data. Reference tip resistance (R_{reff}) as the output of the penetration test presents the strength of CTC. Thus, q_u and R_{reff} should represent data mutually. In this paper, data of q_u and R_{reff} are compared to define the correlation of both values. The correlation in Figure 9 present R^2 = 0,6912 whereas to prove the correlation the value of R^2 have to approach 1. It means there is no correlation between q_u and R_{reff} from this investigation.

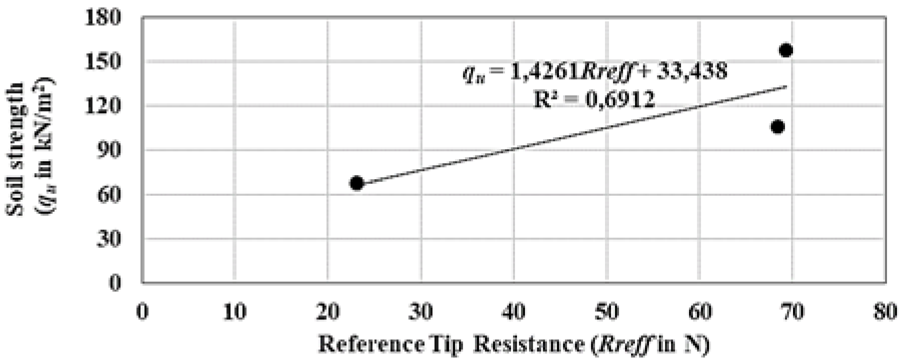

Figure 9. Correlation of soil strength to reference tip resistance

CONCLUSION

In this study, the increment of CTC depends on the amount of CTC can be represented as a linear line. The impact of Magnesium Sulphate attack as the increment amount of CTC, however, the deterioration depth shows a similar pattern with the amount of cement between 10 – 12 kg/m^3. Volumetric solid content affects the soil strength as the enhancement of its value in CTC. Correlation of R_{reff} and q_u is unable to be determined in this study.

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