The effect of lime $Ca(OH)_2$ to the constant of granulation rate (k) of Sidoarjo mud (LuSi) and its grain size distribution

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Abstract. Sidoarjo mud (LuSi) is very hot and sticky mud-like substance produced by eruption of Kujung, Kalibeng, and Pucangan formations caused by well exploration for gas in Porong, Sidoarjo, East Java, Indonesia. LuSi submerged villages, industrial areas, and rice fields in Porong. The eruption is still taking place so that it needs more area and higher dike surrounded to retain the mud. Therefore, it is very urgent to use LuSi in huge volumes such as for borrowed materials. LuSi grain size and its strength, however, do not meet the borrowed materials requirement. Therefore, the grain size was improved using granulator drum and lime $C_a(OH)_2$ was used to increase its strength. The grain size produced by granulator was affected by length, diameter, and rotation rate of granulator drum, and also by constant of granulation rate ‘k’ that was function of other parameters, inclination angle of granulator drum (S), moisture content (W), and water temperature (T). The results show that lime needed for stabilization is 10% of LuSi dry weight. The “k” is affected by lime where parameters (S) and (W) become smaller and (T) is higher. Lime also produces dryer granular, higher water resistance, and shorter granulation process. Besides, higher water temperature during granulation process is needed to develop bigger grain size for granular stabilized-LuSi.

1 Introduction

Sidoarjo mud (LuSi) is very hot and sticky mud-like substance produced by the eruption of Kujung, Kalibeng, and Pucangan formations [1] caused by good exploration for gas in Porong, Sidoarjo, East Java, Indonesia. LuSi submerged the existing community villages, rice fields, and industrial areas in Porong. The eruption started at 2006, in 2007 the area submerged by LuSi was 640 hectares, it kept increasing to be 728 hectares in 2008 and 850 hectares in 2009. Up to now, the eruption is still taking place, but its rate is getting slower. Consequently, it needs more area and higher dike surrounded to retain the LuSi mud. Due to that reason, it is very urgent to use LuSi in huge volume such as borrowed materials. However, LuSi (initial-LuSi) is dominated by 88% of fine materials (silt and clay) and the rest, 12%, is fine to medium sand (Fig. 1b), besides, it is very sticky and lumpy to handle

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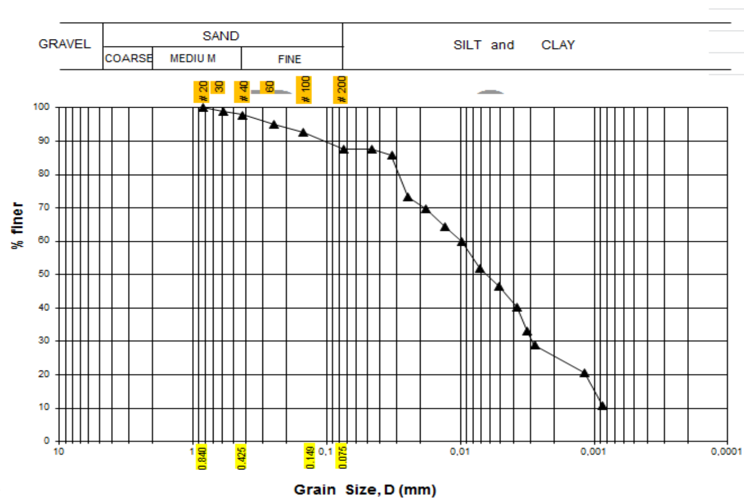
[2]. The liquid limit (LL) of the initial-LuSi is 81.58%, and its plasticity index (IP) is 49.56%. Based on the Unified Soil Classification System (USCS), the initial-LuSi can be classified as clay with high plasticity (CH) soil. In AASHTO, the initial-LuSi is classified as A-7-6.

(a)



(b)

Fig. 1. (a) Picture of the initial-LuSi in dry condition and (b) Grain size distribution curve of the initial-LuSi.

All types of soil actually can be used as borrowed materials except soil classified as CH or A-7-6 with Plasticity Index (PI) higher than 6.0 [3]. Since the initial-LuSi is CH or A-7-6 soil and its PI is 49.56%, so that the initial-LuSi cannot be used as borrowed materials. To meet the borrowed material requirement, therefore, the initial-LuSi has to be coarse grains materials with PI ≤ 6.0. For this purpose, the granulator drum (Fig. 2) can be used to change the fine grain of the initial-LuSi to be coarse grain materials and lime stabilization can be adopted to reduce the PI value.

The grain size produced by granulator drum is affected by the diameter, length, and rotation rate of granulator drum. Besides, it is also affected by the constant of granulation rate ‘k’ that is the function of other parameters, inclination angle of the granulator drum (S), moisture content (W), and temperature (T). All of those parameters have to be determined by trial and error to produce well graded grain size distribution of the initial-LuSi. In this study, those parameters were determined by using the mathematical model with simulation as done by [2]. The parameters obtained from the simulation which gave well-graded grain size distribution were adopted in the laboratory experiment to produce well graded granular of the initial-LuSi as expected.

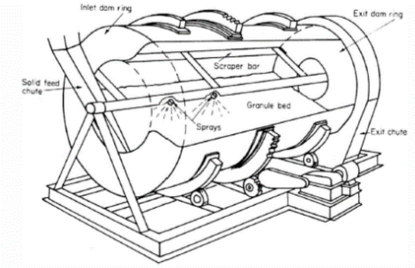
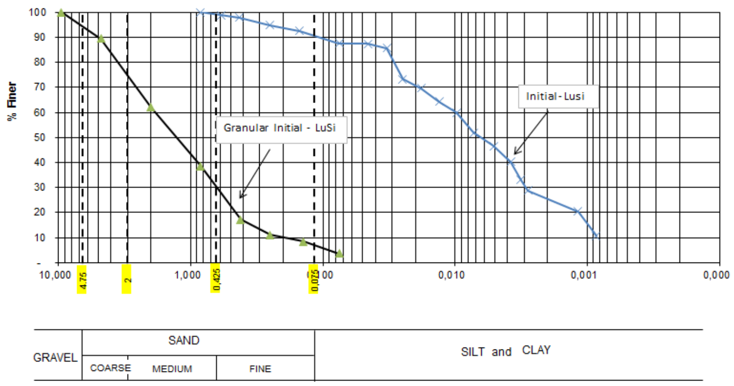


Fig. 2. Sketch of granulator device [4].

The granulation process of the initial-LuSi was already performed by using granulator drum with 2.0 meters in length and 0.4 meters in diameter [2]. The variables adopted for the granulation process were drum inclination angle = 2.5^{O}, drum rotation speed = 10 rpm, water content = 39%, and water temperature = 25^{O}C. The result shows that the granulator drum can produce granular initial-LuSi as shown in Fig. 3, where its uniformity coefficient (Cu) = 8.10 and its gradation coefficient (Cc) = 2.17. In the USCS, the granular initial-LuSi is classified as well graded sand (SW) because of its value of Cu ≥ 6.0 and its value of Cc ≤ 3.0 but higher than 1.0. Plasticity of the granular initial-LuSi, however, is still the same (LL= 81.58% and IP= 49.56%) so that the granular initial-LuSi is classified as SW-SC (well-graded sand with clay).

(a)



(b)

Fig. 3. (a) Picture of granular initial-LuSi as product of granulation process using the granulator drum and (b) Grain size distribution curve of the initial-LuSi and the granular initial-LuSi.

The granular initial-LuSi is also not water resistance so that the grains are melting as mud-like substance when they are submerged into water. In this study, therefore, the initial-LuSi was stabilized with lime $Ca(OH)_2$ before the granulation process and then the granular stabilized-LuSi produced were cured. The effect of stabilization material $Ca(OH)_2$ to the granulation rate (k), and the grain size of the initial-LuSi was also studied. The study results will be discussed in this paper, those are: 1) The percentage of lime $Ca(OH)_2$ and curing period needed to stabilize the initia-LuSi, 2) The effect of lime $Ca(OH)_2$ to the constant of granulation rate (k), 3) The effect of lime $Ca(OH)_2$ to the grain size distribution of granular LuSi.

2 Lime $C_a(OH)_2$ for stabilization material of the initial-LuSi

The particles structures of the initial-LuSi can be seen clearly from the Scanning Electron Microscope (SEM) with different size of enlargement given in Fig. 4. The physical and engineering parameters of the initial-LuSi before stabilization are given in Table 1.

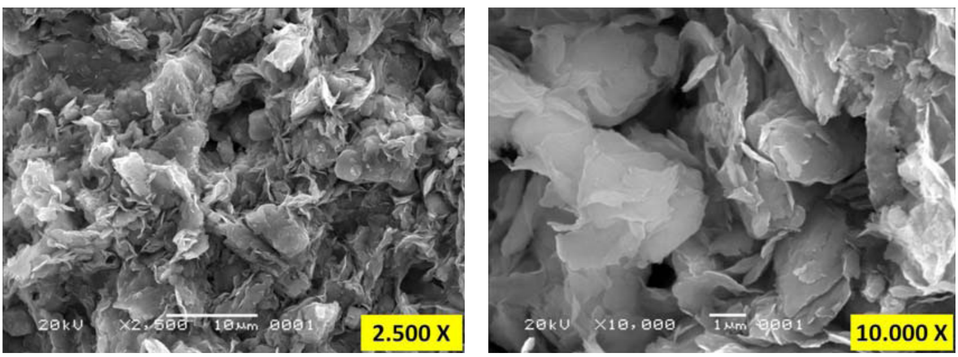


Fig. 4. Scanning Electron Microscope (SEM) of the soil particles structure of initial-LuSi with different size of enlargement (2.500x and 10.000x).

Table 1. Soil Parameters of The Initial-LuSi and Stabilized-LuSi.

LuSi Soil Parameter	Symbol	Unit	Initial-LuSi	Stabilized-LuSi after 20 days of curing
Unit Weight	γ_t	t/m^3	1.704	-
Specific Gravity	G_s	-	2.52	2.68
Liquid Limit	LL	%	81.58	49.52
Index Plastic	IP	%	49.56	9.38
Optimum Water Content	W_{copt}	%	25.27	17.50
Maximum Density	γ_d	t/m^3	1.36	1.39
Cohesion	C	t/m^2	3.5	14.4

To improve its behavior, lime $CaCO_3$ was used as stabilization materials [5]. The percentage of stabilization material is 60% with a curing period of 40 days, the result is very satisfactory. In this study, another type of lime that was lime $Ca(OH)_2$ was chosen as stabilization material. The optimum percentage of $Ca(OH)_2$ was obtained by mixing the initial-LuSi with different percentage of Lime $Ca(OH)_2$ 5%, 10%, and 15%, and then cured in different periods 10, 15, 20, also 30 days. Aafterwards, they were tested in the laboratory to determine the stabilized-LuSi parameters. The results show that 10% of lime $Ca(OH)_2$ and curing 20 days give the maximum result. The physical and engineering soil parameters of LuSi stabilized with 10% $Ca(OH)_2$ and curing 20 days are given in Table 1.

From data given in Table 1, it shows that lime $Ca(OH)_2$ affects all parameters of the initial-LuSi, those are, soil plasticity (LL and PI) decreases and soil cohesion increases. It means that the stabilized-LuSi has better behavior than the initial-LuSi, the stabilized-LuSi also becomes resistant to the water or not melting by water. Its PI value, however, is still higher than 6% so that the stabilized-LuSi has not met the borrow materials requirement. For this purpose, additional effort is carried out in another study that is still in progress.

3 The effect of stabilization material $C_a(OH)_2$ to the constant of granulation rate (k)

To make the stabilized-LuSi to be granular materials, granulation process using the granulator drum was adopted. Length and diameter of the granulator drum used were the same as the one used in the first study [2]. Again, the 'k' parameter was determined because the initial-LuSi was stabilized with lime $Ca(OH)_2$. The procedure to determine the 'k' value of the stabilized-LuSi was the same as the one for the initial-LuSi.

The granulation process used was random coalescence; this process was able to give more satisfying result and easier to calculate and to apply [6]. The random coalescence introduced by [7] and by [8] explains that coagulation rate among particles with two sizes of i and j have linear proportion with the result of its total concentration, ni x nj; if the population balance is adopted, the granulation process can be written in mathematical model as follows:

$$\frac{dn_i(t)}{dt} = -kn_i(t) + \frac{k}{2N(t)}\sum_{j=1}^{i-1} n_{i-j}(t)n_j(t) \tag{1}$$

i = 1, 2, 3......

Eq. 1 can be solve analytically,

$$n_i(t) = N(0)(-1)^{i+1}\left(\exp\left[-\frac{k\bar{\theta}}{2}\right]-1\right)^{i-1}\exp\left[-k\bar{\theta}\right] \tag{2}$$

where k = constant of granulation rate that affected by temperature (T), water content (W), and inclination angle of granulator drum (S), Θ = mixing period of granulation process in the granulator drum that is function of Di (diameter of granulator drum), L (length of granulator drum), N (rotation speed of granulator drum), and S (inclination angle of granulator drum):

$$\bar{\theta} = \frac{0.23L}{SN^{0.9}Di} \tag{3}$$

In this study, 'k' parameter was determined as follows:

1. Preparing the fine material stabilized-LuSi to be granular ones by using the granulator drum, the parameters chosen were drum inclination angle 2.5°, temperature 25°, water content 38.5%, and drum rotation speed 10rpm. Then, the Cu parameter (uniformity coefficient) of the granular stabilized-LuSi was determined, named as (Cu-exp)1.

2. Preparing another granular stabilized-LuSi as Step-1 with the same parameters chosen in Step-1, except drum rotation speed changed to be 6 rpm, again the Cu parameter of the granular stabilized-LuSi was determined, named as (Cu-exp)2.
3. Choosing any value of 'k' and adopt all parameters in Step-1 to construct grain size distribution curve by a mathematical model. Then, the Cu parameter (uniformity coefficient) from the curve was determined, named as (Cu-sim)1.
4. Make another grain size distribution as Step 3 by using the same 'k' as in Step-3 and the same other parameters as in Step-2. Again, the Cu parameter from the curve was determined, named as (Cu-sim)2.
5. Determine deviation standard between (Cu-exp)1 and (Cu-Sim)1 as (Δ-div)1 and between (Cu-exp)2 and (Cu-Sim)2 as (Δ-div)2, then make average value of (Δ-div)1and (Δ-div)2 as (Δ-div)avg.
6. Repeating Step-3 till Step-5 but with different 'k' value to get another value of (Δ-div)avg.
7. Plotting of the 'k' values chosen with the respected (Δ-div)avg as shown in Fig. 5 to get the 'koptimum' that was the 'k' value with smallest (Δ-div)avg.
8. Get another 'koptimum' by repeating Step-1 till Step-7 but using a different angle of granulator drum, that was 5°.
9. Get another 'koptimum' by repeating Step-1 till Step-7 but using different water temperature, that was 45°.

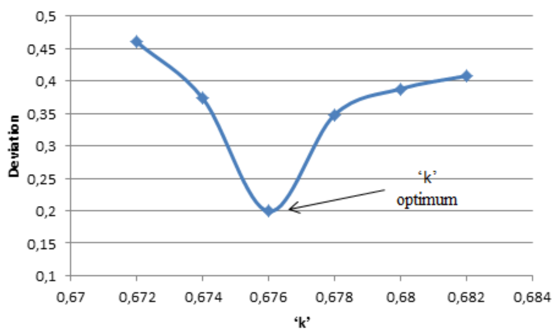


Fig. 5. Deviation curve of C_u (uniformity coefficient) versus 'k' values to determine $'k'_{optimum}$.

10. Get another 'koptimum' by repeating Step-1 till Step-7 but using different soil water content, that was 39%.
11. Make regression of all 'koptimum' values obtained from Step-7, Step-8, Step-9, and Step-10 to determine the equation of 'k' for stabilized-LuSi; the result is

$$k_{(stabilized\text{-}LuSi)} = 1{,}137810x\ S^{0{,}444913}\ x\ W^{-0{,}887448}\ x\ T^{0{,}587656} \tag{4}$$

The 'k' equation of the initial-LuSi [2] is

$$k_{(initial\text{-}LuSi)} = 0{,}044275x\ S^{1{,}044230}\ x\ W^{0{,}223160}\ x\ T^{0{,}037178} \tag{5}$$

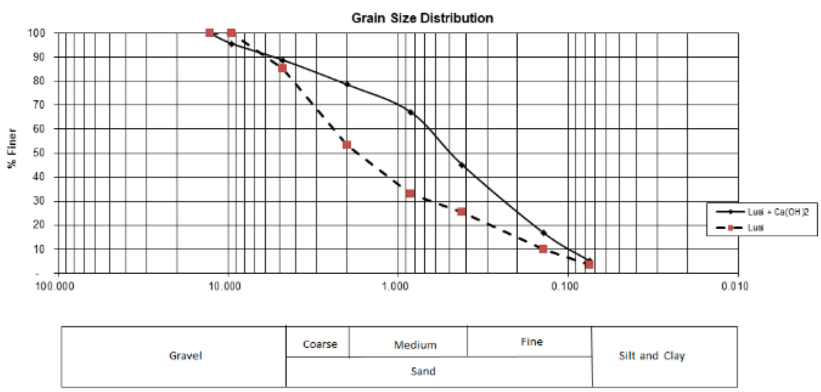
From Eq. 4 and 5 above, it can be seen that the presence of the stabilized material $Ca(OH)_2$ at the initial-LuSi during the granulation process causes:

a. The inclination angle of granulator drum 'S' can be reduced, it shows that 'S' parameter has smaller power.
b. The increment of moisture 'W' can reduce the rate of granulation process, the equation shows that 'W' parameter has negative power.
c. The influence of temperature 'T' is more significant by adding the $Ca(OH)_2$ material, it is shown that 'T' parameter has bigger power.

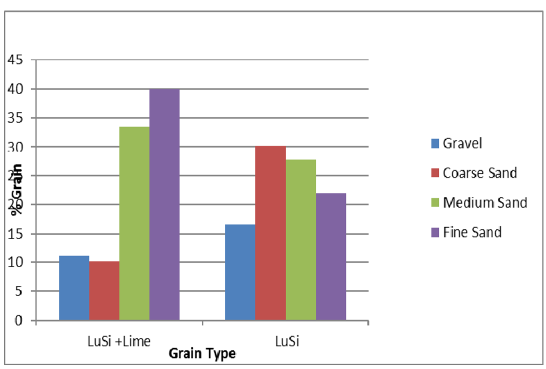
It can be concluded that the presence of stabilized material $Ca(OH)_2$ can produce the granular stabilized-LuSi dryer and more resistance to water, besides, the granulation process becomes shorter due to the $Ca(OH)_2$ has functioned as a binder.

4 The effect of stabilization material $C_a(OH)_2$ to grain size distribution of the granular LuSi.

Although well-graded grain size distribution of the granular initial-LuSi can be obtained as shown in Fig. 3b, the grains are not water resistance; they are melting when submerged into water. Base on that condition, the initial-LuSi was stabilized using 10% lime $Ca(OH)_2$, as study result explain above, before the granulation process.



(a)

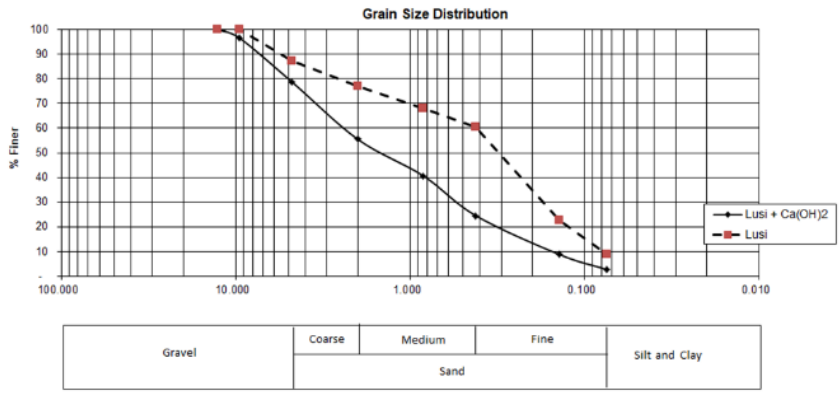


(b)

Fig. 6. (a) Grain size distribution curve of the granular initial-LuSi and granular stabilized-LuSi and (b) percentage of gravel and sand produced at rotation rate of the granulator drum 10 rpm, water content 38.5%, inclination angle of granulator drum 2.5^o, and water temperature 25^{o}C.

The rotation speed of the granulator drum was 10 rpm, inclination angle of granulator drum 2.5^o, and water content 38.5%. The granular stabilized-LuSi produced from granulator drum was then cured for 20 days and dried out at 105°C in the oven for 24 hours. The results are given in Fig. 6 (for water temperature 25^{o}C) and Fig. 7 (for water temperature 45^{o}C).

From Fig. 6a and 7a, it can be seen that water temperature in the granulator drum during the granulation process causes the grain size distribution curve of the granular stabilized-LuSi and the granular initial-LuSi different. When higher water temperature used in the process (from 25°C to 45°C), the grain size distribution curve of the granular stabilized-LuSi located underneath the one of granular initial-LuSi. It means that higher temperature needed during the granulation process for stabilized-LuSi to develop bigger grain size (Fig. 7a). On the other hand, the only low temperature needed to develop a bigger grain size for the granular initial-LuSi (Fig. 6a). The percentage of coarse grain produced at temperature 25°C and 45°C, can be seen in Fig. 6b and 7b, respectively.



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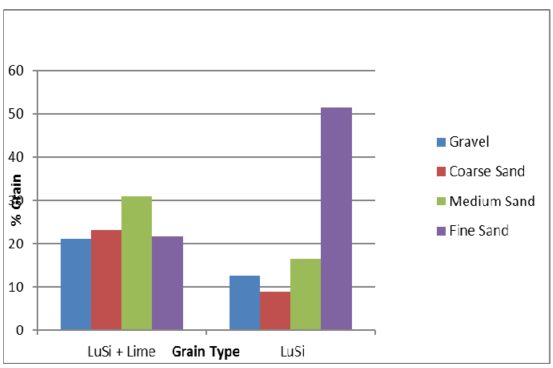

(b)

Fig. 7. (a) Grain size distribution curve of the granular initial-LuSi and granular stabilized-LuSi and (b) percentage of gravel and sand produced at rotation rate of the granulator drum 10 rpm, water content 38.5%, inclination angle of granulator drum 2.5°, and water temperature 45°C.

5 Conclusions

From data analysis given above, it can be concluded that the granular initial-LuSi is not water resistance so that the initial-LuSi has to be stabilized with 20% of $Ca(OH)_2$ before granulation process. The presence of stabilized material $Ca(OH)_2$ at the initial-LuSi during the granulation process affects the equation of the ‘k’ parameter, that is a) for granular initial-LuSi: $k_{(initial\text{-}LuSi)} = 0.044275x\ S^{1.04423}\ x\ W^{0.22316}\ x\ T^{0.037178}$ a) for granular stabilized-LuSi: $k_{(Stabilized\ LuSi)} = 1.13781x\ S^{0.444913}\ x\ W^{-0.887448}\ x\ T^{0.587656,}$ where: (S) is inclination angle of granulator drum, (W) is moisture content, and (T) is water temperature.

Stabilized material $Ca(OH)_2$ can produce the granular stabilized-LuSi dryer and more resistance to water, besides, the granulation process becomes shorter due to the $Ca(OH)_2$ acts as a binder. Grain size distribution curve of granular LuSi is affected by stabilization materials, higher water temperature during the granulation process needed to develop bigger grain size for granular stabilized-LuSi.

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