

CHAPTER III

BASIC THEORY

3.1. Soft Clay

Soft soil is one type of soil that has large fractions of fine particles such as silty and clayey soils, which have high moisture content [24]. According to Unified Soil Classification System (USCS), particle diameter of clay is somewhere between 0.002 mm up to 0.005 mm. Clay consistency varies from very soft to very stiff with the reduction of void ratio (e) and water content along with the increment of stiffness [25]. Soft clay can be found easily, for example in marine area. Marine clay is classified as soft clay. The water content is high and the strength is very low. There is a specific kind of soft clay that has similar characteristics as marine clay, it is lumpur sidoarjo (Lusi). Lusi is a result of mud volcano eruption in Sidoarjo, East Java. Lusi is very soft clay with liquid limit of 58.44%, plastic limit of 30.77%, and shrinkage limit of 22.27%. Lusi has 2.71 specific gravity and contains coarse grain about 15.53%, silt 54.47%, and clay 30% [26]. Since Lusi has some similar properties with marine clay, Lusi is used in the research.

3.2. Ordinary Portland Cement

Cement acts as binder in the mixture. Cement is manufactured through a closely controlled chemical combination of calcium, silicon, aluminum, iron and

Table 1. Main Components of Ordinary Portland Cement [10].

| Name of compound | Oxide composition | Abbreviation |
|-----------------------------|---|-----------------------|
| Tricalcium silicate | $3\text{CaO} \cdot \text{SiO}_2$ | C_3S |
| Dicalcium silicate | $2\text{CaO} \cdot \text{SiO}_2$ | C_2S |
| Tricalcium aluminate | $3\text{CaO} \cdot \text{Al}_2\text{O}_3$ | C_3A |
| Tetracalcium aluminoferrite | $4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$ | C_4AF |

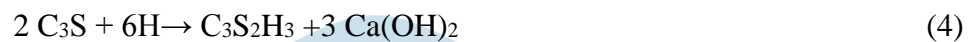
other ingredients [27]. The process when OPC gains its strength from chemical reactions between cement and water is called hydration. Table 1 shows the components of Ordinary Portland Cement (OPC). Tricalcium aluminate, C_3A releases a lot of heat during the early stages of hydration, but has little strength involvement. Gypsum slows down the hydration rate of C_3A . Cement low in C_3A is sulfate resistant cement (SRC). Tricalcium silicate, C_3S hydrates and hardens fast. It is largely responsible for OPC's initial set and early strength gain. Dicalcium silicate, C_2S hydrates and hardens slowly. It is mostly responsible for strength gain after one week. Ferrite, C_4AF is a fluxing agent which reduces the melting temperature of the raw materials in the kiln (from $3,000^\circ \text{F}$ to $2,600^\circ \text{F}$). It hydrates fast, but does not contribute much to the strength of the cement paste [28].

3.3. Water-Cement Reaction

Cement acts as a binder in a mixture. In cement-stabilized soil, cement binds the soil particles with other solids contained. When cement is mixed with water,

hardening reaction will happen. There are 2 types of reactions occur, hydration and pozzolanic reaction. Hydration occurs only between cement and water, while pozzolanic reaction occurs among cement and soil particles such as silica and alumina. Hydration process is shown in eq. (4) and (5) [29].

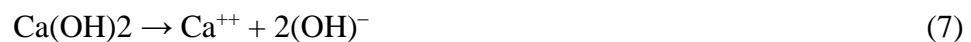
For C₃S hydration:



For C₂S hydration



C₃S and C₂S are the most important components because they are responsible for strength. They require approximately the same amount of water from hydration, but C₃S produces more than twice of Ca(OH)₂ that C₂S hydration produces. From the hydration process, the product Ca(OH)₂ will be triggered to react with soil's substances as what shown in eq. (6) to (10). The reactions are included in pozzolanic reaction unity.



Eq. (6) is the lime hydration that occurs for the first time. Cement has abundant amount of calcium and therefore will react once it is mixed with water. Cation exchange on eq. (7) occurs after lime hydration. Eq (8) and (9) shows the first stage of pozzolanic reaction. Calcium hydroxide together with silicon dioxide that is originated from the

soil, will form C-S-H or calcium silicate hydrate. Moreover, calcium hydroxide will also produce C-A-H or calcium aluminate hydrate in its reaction with aluminum oxide that is also one of the composition of soil.



Eq. (10) is the second stage of pozzolanic reaction. The product is calcium aluminate silicate hydrate or C-A-S-H that has higher strength compared to the previous reactions.

3.4. Seawater

Seawater has high salinity. Water can be categorized as saltwater if the salinity is greater than 3 g/L [11]. The cations in the water mainly include K^+ and Na^+ , and the anions mainly include Cl^- , SO_4^{2-} , and HCO_3^- . Table. 2 shows the properties of seawater according to Khan [6] where sea water has high turbidity and TDS level along with high chloride and magnesium contents. High turbidity and TDS level can lead to severe

Table 2. Properties of Seawater [6].

| Parameter | Result |
|-----------|------------|
| pH | 6.6 |
| Turbidity | 5.63 NTU |
| TDS | 38500 mg/L |
| Hardness | 7500 mg/L |
| Calcium | 800 mg/L |
| Magnesium | 1576 mg/L |
| Chloride | 2299 mg/L |

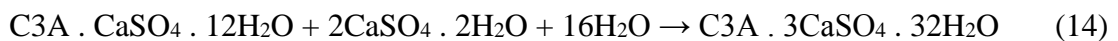
deterioration in cemented material on continuous exposure. Furthermore, magnesium in the form of Sulfates may invite sulfate attack and spalling of cemented material [6].

3.5. Deterioration Caused by Seawater

Deterioration is the process of a cemented material to become progressively weaker or worse. The severity of deterioration can be caused of the reaction between $MgSO_4$ with cement hydrates, and the repetitive crystallization cycles of $MgSO_4 \cdot nH_2O$ by drying-immersion of the hardened pastes that can produce internal stresses in pores leading to the formation of cracks. The reaction of $MgSO_4$ with cement hydrates is shown in eq. (11) and (12).



Magnesium sulfate will replace the existence of calcium and form gypsum, which is a low in hardness and therefore reducing the strength of cemented-soil. Furthermore, the formed gypsum from the above two reactions reacts with calcium aluminate hydrate (C_4AH_{13}) and calcium monosulfoaluminate hydrate (C_4ASH_{12}) to form ettringite as mentioned below:



The formed products are M-S-H as a result of decalcification of C-S-H, gypsum, and ettringite. All of these lead to a decrease of compressive strength and the last two products can cause crack formation [20]. Similar with gypsum, ettringite also has weak

characteristic. The difference is that ettringite gives swelling effect to the cemented material.

3.6. Penetration Test

Micro cone penetration test is conducted to know the strength distribution in the specimen [23]. When specimens are immersed in seawater, the penetration or cone resistance increases sharply from the surface layer [18]. Figure. 9 shows the graph resulted from penetration test. d_n represents the deterioration depth where tip resistance (R) or penetration resistance (F) is close to zero due to deterioration that causes soil to

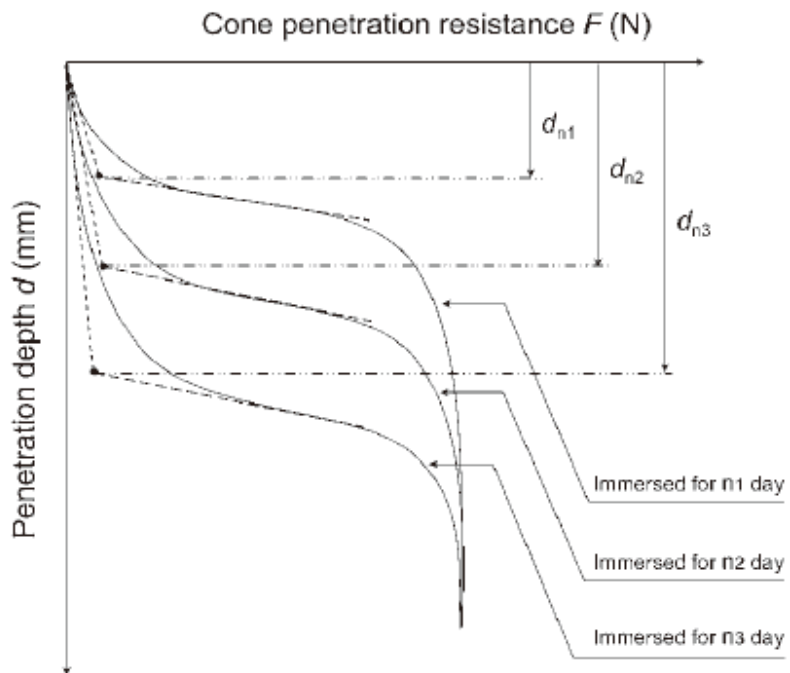


Figure 9. Determination Method of The Deterioration Depth d_n [18].

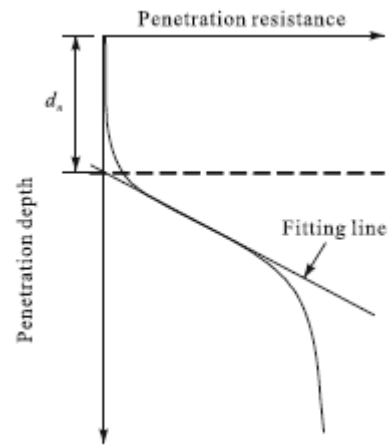


Figure 10. Definition of Deterioration Depth on The Basis of Curves Penetration Resistance [23].

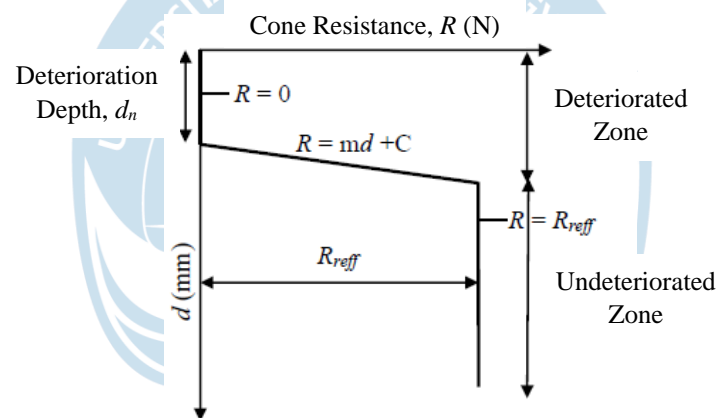


Figure 11. Laboratory Penetration Test Data Simplification [30]

have very low strength. By the time the F increases, the area is no more a deterioration depth. Until the resistance (F) reaches the maximum value that it becomes constant. Figure. 10 shows the penetration test result approach. Furthermore, [30] also stated about the fitting line as shown in Figure. 11. Fitting line is a line that represent the actual data from laboratory. Fitting line can be obtained from equation (15) where R is cone resistance, R_{ref} is reference cone resistance, d is penetration depth (mm), and α, β, γ are fitting constants. Junjie [23] did the penetration test by the rate of 1.0 mm/min

$$R = R_{ref} - \frac{R_{ref}}{(1+(\alpha d)^\beta)^\gamma} \quad (15)$$

and load range of 500N. Hara, [18] used a 6 mm cone diameter with 60° tip angle, by the penetration rate of 3 mm/min.

3.6.1. Immersion Variation

Curing time of specimens inside the seawater affects the deterioration depth. From Figure. 11, it can be concluded that penetration resistance is scarcely enhanced with the increase of penetration depth. Moreover, at the same cement content, the longer the curing time, the larger the value of the deterioration depth.

3.6.2. Cement Content Variation

Cement content is one of the influencer on determining deterioration depth. At the same period of curing or immersion time, the dn of specimens

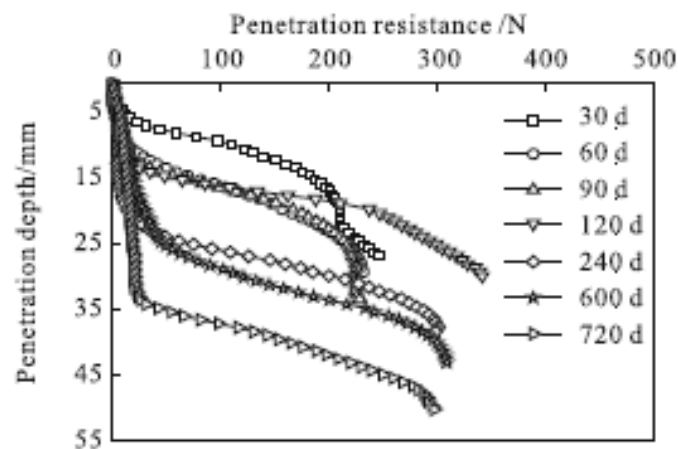


Figure 12. Results of Micro-Cone Penetration Test on The Samples with The Cement Ratio of 7% [23].

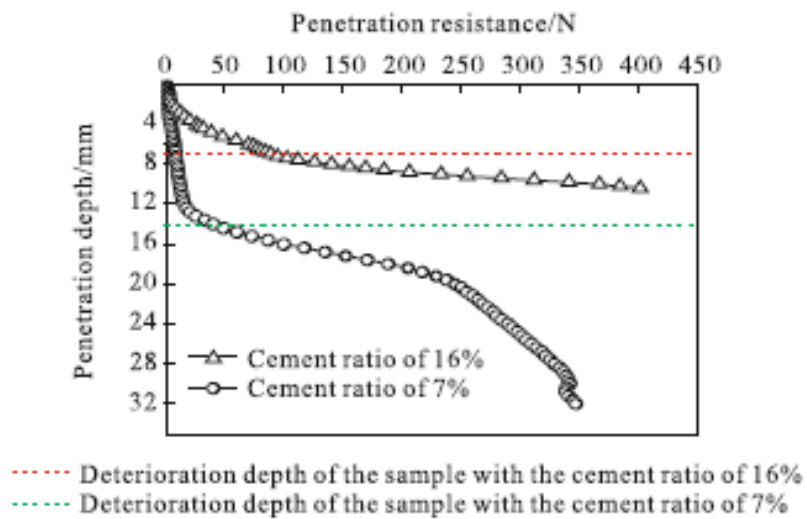


Figure 13. Results of Micro-Cone Penetration Test on The Samples With The Curing Time of 120d [23].

with higher water content is smaller than the ones with low cement content. Therefore, the increase of cement content not only improves the soil strength, but also lessen the deterioration degree due to the corrosive environment.