The Permeability of Portland Cement-Stabilized Clay Shale

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Abstract. Research on the effect of Portland cement on the improvement of problematic soil has been extensively studied in many years and many places. Soil stabilization using cement has improved the strength and durability, enhanced the performance of the problematic soil such as clay shale. However, most studies in the field of Portland cement-stabilized soil have only focused on strength and durability improvement and the information on permeability characteristic has not adequately provided. This study aimed to investigate the effect of Portland cement stabilization on the consistency limits and permeability of the clay shale. The Portland cement content was varied from 2% to 10% by weight of dry soil. The stabilized clayshale specimens were cured for seven days before the testing. Constant head permeability method (method A) of the ASTM D5084 was used to determine the coefficient of permeability. The result shows that both the liquid limits and plastic limits decrease with increased Portland cement content, hence the plasticity index of the soil-PC mixing decrease. The permeability coefficient of the soil mixed with 2% of cement increased about 14 times greater than the untreated soil. Increase in cement content tends to decrease the coefficient of permeability.

1. Introduction

Shales are thinly laminated fine-grained pelite elastic rock composed predominantly of siliciclastic materials by the granulometric composition of mixtures of clays and particles size of powder or silt. The clay shale was originated from 50% to 70% of sedimentation rock on earth crust. Clayshale is formed majorly by clay mineral, claystone, soil, dust or rock with cementation, consolidation and sedimentation processes. This process results in a compact and overconsolidated structure. However, clayshale behaves brittle and low durability [1]. The clayshale is susceptible to weathering and rapidly degrade the geotechnical properties, strength, and durability [2]–[5]. Thus, the behavior generates problems such as unstable fill material, reduction in bearing capacity of shallow and deep foundation, slope stability, piping, and subsidence. The availability, mechanical, chemical properties, and the cost of the Portland Cement (PC) were the advantageous which favored and most used material among the chemical stabilizer. Many researchers have evaluated the properties of PC-soil mixing [6]–[11]. The hydrations reaction of the PC with soil water and pozzolanic reaction were the main factor in the improvement of PC-soil mixture [11]. Previous studies in PC-stabilized soil, generally, focused on strength and durability improvement, but lessen studies investigated the permeability characteristic. The permeability of a soil is its ability to allow water flow under a hydraulic head. To analysis subsurface flow, the permeability is a critical parameter [12].

Measuring and predicting soil permeability properties are still tricky. The porosity, the fabric, the density, and the composite of sediment are the influencing factors of the soil permeability [13].
Measuring the soil permeability was tough, time-consuming, and expensive [14]. There was less published data of measured permeability for mudrocks [13]. The study conducted by Neuzil [12] and Dewhurst et al. [15] measured the permeability of the intact mudrocks samples. The study indicated a notable contribution to a better understanding of the permeability of the mudrock material. Casey et al. [13] tried to predict the permeability of the mudrocks based on its porosity and liquid limit. Reece et al. [16] quantified that small variation in fabrics and composition of the mudstones significantly affected the permeability, although the soil has similar grain-size distributions and porosity. Ewy [17] stated that testing protocols on shale were needed for mechanical testing, which should be designed around the permeability coefficient value of the shale.

Recently, literature has emerged a contradictory finding of the permeability on the stabilized-soil. A study on the permeability of a treated tropical residual soil using lime found that the permeability of the treated soil with 2% lime increased the coefficient of permeability of a brown saprolitic Brazilian soil, whereas contrary as for red lateritic Brazilian soil. Further addition of lime decreased the coefficient of permeability [18]. Alhassan [19] found that the permeability at specified lime content decreased to the lowest value at 6% RHA content, and then the coefficient of permeability slightly increased with further increase in RHA. Study on stabilized soil-cement found that the permeability of the soil decreased as cement content increases [6]. Mousavi and Wang [20] studied the effect of cement-peat ash-silica sand on the permeability of clay. The study found that at an identical void ratio, the coefficient of permeability decreases drastically by the addition of 18% cement. In contrast, Alhasan [19] and Elsharief [21] studied the stabilization of three tropical soil using lime and found the coefficient of permeability increased substantially at optimum lime content. The increased of the permeability properties of the stabilized soil with an increase in the percentage of MgO or lime [22].

It is now well established that the strength and the durability of the soil generally increased with the increasing percentage of the stabilized agent. However, the influence of stabilized agent such as PC on the permeability characteristic has remained discussable. The literature has emerged that offers contradictory findings of the influences of stabilized agent (lime, PC, RHA, etc.) content on the permeability characteristics. A large discrepancy among the research in the permeability of the stabilized soil was because of various soil and mineralogy, testing method, apparatus, and loading condition, etc. The results and recommendation in literature can be adapted as a general guide. The influence factors need to be verified for individual sites. Furthermore, the permeability of the stabilized soil should be carefully assessed in each case. Hence, an objective of this study was to investigate the effect of PC content on the plasticity and permeability characteristics of the clay shale.

2. Materials
The disturbed clay shale samples were collected from cutting slope of the Semarang-Bawen Toll Road at a depth of 1 m – 5 m from the surface. The ASTM D4318 [23] procedure was adopted to determine the Atterberg limits of the samples. The particle size analysis, include sieve analysis and hydrometer testing, was determined by the ASTM D422-63 [24]. The soil classification was according to the Unified Soil Classification System determined using the ASTM D2487 [25] procedure. The maximum dry density (MDD), and the optimum moisture content (OMC) of the untreated clay shale were determined using standard Proctor compaction test, the test based on the ASTM D698 [26]. The density and water content were determined for mixing the stabilized specimens. Figure 1 shows the grain size distribution of the clay shale sample. The soils properties are presented in Table 1. The sample was classified as heavy clays (CH materials) according to the Unified Soil Classification System (USCS). The slake durability index (I_s) was determined using ASTM D4644 [27] procedure. The clayshale has I_s = 1.47%, which was classified as very low durability [28]. The cement was Portland Composite Cement (PCC) which was produced by Holcim Cement Company.
3. Method

3.1. Sample Preparation

The clay shale sample was pulverized and sieved through no. 4 test sieve. The specimens were prepared in five different cement content (PC), which was 2%, 5%, 7%, and 10% by dry weight of the soil. The specimens were compacted statically in rigid steel mold with 35.2 mm in diameter and a height of 70 mm. All the specimens prepared at the MDD and OMC of the untreated soil. For the permeability test, after compacting each specimen was put in a plastic bag and cured for seven days in the room temperature about 28°C.

3.2. The Atterberg limits test

The soil samples were pulverized to pass through the sieve no. 40 (425µm). The testing procedure as outlined in ASTM D4318 [23] for determination of liquid limit (LL) and the plastic limit (PL). Before the test, the soil samples were oven-dried. The tests were carried out on untreated soil and the treated soils with 2%, 5%, 7%, and 10% of cement. The soil-PC mixing procedure for the liquid limit and plastic limit was prepared as recommended by Miura et al. [29]. The soil-PC was mixed thoroughly with water for 10 minutes. Considering the setting time of cement (±120 minutes) and ion exchange in the treated soil, then the soil-cement slurry was kept in a plastic bag for 60 minutes. Afterward, the liquid limit and plastic limit test was performed.

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Figure 1. Grain size distribution.

Table 1. Engineering properties of soil sample

| Properties                        | Value   |
|----------------------------------|---------|
| Specific Gravity                 | 2.65    |
| Liquid Limit                     | 51.04%  |
| Plastic Limit                    | 34.27%  |
| Plasticity Index                 | 16.77%  |
| Percent passing more than no.200 sieve | 93.46%  |
| Optimum Moisture Content (OMC)   | 16.99%  |
| Maximum Dry Density (MDD)        | 16.33 kN/m³ |
3.3. The permeability test
The coefficient of permeability (also referred to as hydraulic conductivity), k, can be defined as the water discharge rate under conditions of laminar flow through a unit cross-sectional area of the soil at 20°C temperature condition and a unit hydraulic gradient [30]. Constant head permeability tests were carried out by a flexible wall permeameter apparatus which referred to ASTM D5084 method A. The apparatus provided the specimen with porous stone at end pieces, enclosed by a flexible membrane sealed at the cap and base and subjected to controlled cell pressures. Two drainage line on the top and two on the base were used to remove air from soil specimens and saturation of the hydraulic system. The main procedures of the permeability test were following (i) confining pressure was applied by a small cell pressure; (ii) saturation process was applied by back-pressure. The degree of saturation was evaluated by measuring the B-value. The specimen was adequately saturated if the B-value was greater than 0.95; (iii) consolidation; (iv) permeation phase. The permeation test was conduction by five trial of head loss. At this step, the backpressure was maintained throughout the permeation phase. The head loss across the permeameter was kept constant. The quantity of inflow, outflow, and changes in the height of specimens was monitored, measured, and recorded. The permeation test was continued until at least four value of permeability coefficient was obtained over an interval of time as follows: (a) the rate was between 0.75 and 1.25 of the ratio of outflow and inflow, and (b) the coefficient of permeability was steady. The steady condition was gained if four or more consecutive permeability coefficient was within the minimum value of 25% and no significant changes in the plot of the permeability coefficient versus time. The calculation of the permeability coefficient as follows;

\[ k = \frac{\Delta Q L}{A h \Delta t} \]  

where:
- \( k \) = permeability coefficient (m/s).
- \( \Delta Q \) = quantity of flow for interval time \( \Delta t \), the inflow and outflow average (m³),
- \( L \) = specimen’s length (m)
- \( \Delta t \) = time interval (=\( t_2 - t_1 \)) over which occurs of the flow \( \Delta Q \) (s),
- \( t_1 \) = time at the start of permeation trial (s),
- \( t_2 \) = time at the end of permeation trial (s),
- \( A \) = specimens cross sectional area (m²),
- \( h \) = head loss of water across the specimen (average value) (=\( h_1 + h_2 \)/2) (m),
- \( h_1 \) = head loss at \( t_1 \) (m),
- \( h_2 \) = head loss at \( t_2 \) (m).

4. Result and Discussion

4.1. The Atterberg Limits
The results obtained from the Atterberg limits test of untreated and treated soils with PC is presented in Figure 2. Both the liquid limit and plastic limit slightly decreases by the addition of PC. The plasticity index reduces 48% from 16.77% to 8.61% by the addition of 10% PC. The plasticity index reduction was due to the decrease in liquid limit and plastic limit. The decrease in plasticity index and the liquid limit is an indicator of improvement [31]. Many works correlated the plasticity index with the engineering properties of soil. A lower plasticity index will enhance the shear strength, compressibility, durability, and workability of the admixed soil [10], [32]. The soil mineralogy is the primary factor that influences the changes in the plasticity properties of the stabilized soil. Cation exchange in cement-soil chemical reaction leads to produce physical change and mineralogy of the stabilized clay [18].
4.2. Permeability of the Clayshale

Figure 3 shows the relationship of the permeability coefficient and PC content. The permeability coefficient was $9.65 \times 10^{-5}$ m/s and $1.40 \times 10^{-4}$ m/s respectively for untreated and 2% PC. The figure shows that the coefficient of permeability increased with the addition of 2-5% cement. The coefficient of permeability of the stabilized soil increases 12 to 14 times by mixing with 2% and 5% cement respectively. However, the addition of higher content of cement results in decreasing the coefficient of permeability. The permeability dropped to $2.9 \times 10^{-4}$ m/s by adding 7% of cement, and the value approximately closed to the untreated soil. This characteristic can be explained that the immediate chemical reaction was the soil agglomeration of the soil by addition of a low cement content e.g. 2-5%. The agglomeration causes a larger interparticle voids. As a consequence, the water rapidly flows in the void and results in substantial increases in the coefficient of permeability. Increase in cement content developed cementation product such as bonding gel which bound the soil particles and hinders the water flow in soil. Therefore, the coefficient of permeability decreases. The result is in agreement with the study conducted by Galvão et al. [18].

![Figure 2. The Atterberg Limits of untreated and treated soils](image1)

**Figure 2.** The Atterberg Limits of untreated and treated soils

![Figure 3. Variation of the permeability coefficient with the cement content.](image2)

**Figure 3.** Variation of the permeability coefficient with the cement content.
Yi et al. [22] found that the hydration product of cement has a significant influence on the permeability of stabilized soil. The particles can fill the soil pores and lead to a decrease in the permeability. Besides, the cracks in stabilized soil were appeared due to the excessive hydration products and lead to increased permeability. The amount of macro-pores in the stabilized soil decreases with the addition of cement and causes a significant reduction in the coefficient of permeability [9]. The improvement of cement-stabilized soil can be divided into three zones which is active, inert, and deterioration zones [7]. In the active zone is the most effective stabilization, the pores are filled with the increased cementitious products. In this condition, the strength reaches the maximum value. At a short period of stabilization, the existence of large pores increases due to the presence of unhydrated cement particles. Solidification due to cementation gel is responsible for the decreasing of the volume of small pores. The large pores will be filled with the cementitious product and increase with the time. The condition of the pores causes strength and permeability development over time. However, unfortunately, the study did not take into account the determination of the micro and macropores of the samples and the mineralogy changes in soil-cement mixture. Notwithstanding the relatively limited sample, this work offers valuable insights into permeability characteristic of the clay shale-PC stabilization.

5. Conclusion

The consistency and the permeability characteristic of the clay shale samples mixed with cement has been successfully tested and discussed. The purpose of the current study was to assess the effect of cement on the plasticity properties and permeability of the treated and untreated soils. The following conclusions can be drawn:

1. The liquid limit, plastic limit, and plasticity index decreased with the cement content. The plasticity index reduces 48% from 16.77% to 8.61% by the addition of 10% PC.
2. The coefficient of permeability increases about 12-14 times by the addition of 2%-4% cement. Further addition of cement, up to 10%, significantly decreases the coefficient of permeability of the stabilized soil.

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