Influence of the Pulverised Method on the Plasticity and Strength Behaviour of Cement Stabilised Clayshale and Sandstone

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Abstract. Clayshale and sandstone are types of sediment that generally have a contrast soil behaviour. Clayshales, however, is less durable due to the hydrosphere and atmospheric exposure, but a sandstone has low strength in loose condition. The present research is to investigate the effectiveness of dry and spray pulverised method on cement-stabilised clayshale and sandstone. The cement content ranged from 2\% to 10\% by the dry weight of soil. The unconfined compression strength test was performed on cement-stabilised soil. The unconfined compression strength test was also performed to evaluate the soil modification due to stabilisation. The results show that cement reduced the liquid limit and increased the plastic limit, which caused a decrement on the plasticity index. As the cement content increased, the unconfined compression strength of clayshale and sandstone also significantly increased. This study has shown that the unconfined compressive strength with the pulverised spray method is higher than that of the dry pulverised method. The secant modulus made using dry pulverised method is higher than the pulverised spray method. The dry pulverised process generates specimens with more brittle behaviour than the spray-pulverised method, based on the study of damage property by using energy dissipation.

1. Introduction
A highway infrastructure should be constructed over a subgrade with sufficient bearing capacity to transmit the traffic load. In Indonesia, some highway projects experienced problems due to their construction-over mudrock deposit, i.e. Cipularang Toll Road in West Java, and Semarang-Bawen Toll Road in Central Java. Mudrock is a general term for sediments consisting of particles of silt and clay [1]. The number of mudrock is estimated to reach two-thirds of all sedimentary rocks in the world [2]. Clayshale would have a high shear strength if the surface were prevented from atmospheric and hydrosphere exposure [3]. However, the strength of the clayshale would decrease drastically when the surface was exposed to the weather. Soil stabilisation using chemical has been widely applied to improve the strength and durability of the problematic soil such as clayshale. Cement stabilisation is a common method of chemical stabilisation due to its availability, applicability, and economy. Cement as a stabilising material almost can be used on all types of soil. However, soils with high organic content and low pH are not suitable to be stabilised using cement. Robbins and Mueller [4] investigated that the soil with an organic content of more than 2\% and a pH of 5.5 or less would not react well with cement due to the medium or high sulphate levels [5].

Cement modified the soil by flocculation and agglomeration process [6]. Athanasopoulou [7] stated that cement bound clay particles and form a larger particles size and resulted in the reduction of the soil plasticity. The research conducted by Kang et al. [8], Lee et al. [9], Sariosseiri and Muhunthan [10]...
showed that the addition of cement could increase the unconfined compressive strength. The higher the ratio of cement-soil in the mixture, then the amount of pores would decrease, and the compressive strength increased [9]. The increase in soil strength at initial conditions was primarily due to the hydration reaction of the cement, while for the long-term, the strength increment was caused by pozzolanic reactions between clay minerals and calcium hydroxide resulting from cement hydration [11]. Soil stabilisation using cement would be more challenging on fine-grained such as clay. The fine-grained soils would be more difficult to be mixed with cement and compacted; moreover, the amount of cement needed for fine-grained soils is higher, so it is less economical [12].

Mainly researches have successfully conducted cement stabilisation by dry mixing with soil. The mixing method in cement stabilisation could influence the reaction product and stabilisation process. Therefore, this research studies the mixing method of cement stabilisation, including dry and spray (wet) pulverised. Further studies are needed to examine the effect of the mixing method on the strength and durability of cement stabilised-soil. Since fewer studies have compared the effect of mixing method on the mechanical properties (e.g. secant modulus, brittleness index, and damage properties) of cement stabilised-soil, thus this study aims to investigate the effect of dry and spray pulverised cement stabilisation on the soil plasticity and the aforementioned mechanical properties. This study provides new insight into spray pulverised as a mixing method in preparing cement stabilised specimens.

2. Experimental Method

2.1. Soil and Cement Properties

The clayshale and sandstone were collected from the Semarang-Bawen toll road at km. 441+800. The index properties of the soil samples were presented in Table 1. Based on Atterberg limit test, the clayshale samples show high plasticity since the LL > 50, while the sandstone contained low plasticity fines (LL < 50%). The consistency limits show that clayshale sample has a higher plasticity index than the sandstone samples. The clayshale samples comprised of 93% fines, and 7% sand fraction, while the sandstone samples consisted of 51% sand and 49% fines as shown in Table 1. According to Unified Soil Classification System [13], the clayshale samples could be classified as high-plasticity clay with the symbol of CH, while the sandstone sample was classified as silty-sand with low plasticity clay (SM).

| Table 1. The index properties of the soil samples |
|-----------------------------------------------|
| Properties                         | Clayshales | Sandstone |
|-------------------------------------|------------|-----------|
| Specific gravity, Gs                | 2.65       | 2.58      |
| Sand fraction (%)                   | 7          | 51        |
| Silt/clay fraction (%)              | 93         | 49        |
| Liquid limit, LL (%)               | 58         | 38        |
| Plastic limit, PL (%)              | 28         | 22        |
| Shrinkage limit, SL (%)            | 11         | 17        |
| Plasticity Index, PI (%)           | 30         | 16        |
| Optimum moisture content (%)       | 19         | 25        |
| Maximum dry density (kN/m³)        | 16.3       | 14.8      |

Available commercially Portland cement composite (PCC) was used in this study. The cement was classified as Type I cement and meet the requirement as in SNI 15-7064-2004 [14]. For the spray pulverisation, cement was in slurry form; thus, a flow cone test [15] was carried out to determine the desired amount of water-cement ratio for a suitable cement viscosity. Trial water-cement ratio was designed as 0.5; 0.6; 0.7; 0.8; 0.9; and 1.0 to produce 1725 ml cement paste. The flow cone test result is presented in Table 2. The test concluded that the cement water ratio of 0.7 was suitable to have an efflux value of 8 ± 0.2 s as required in ASTM C939-97 [15]. Efflux is the time needed for grouting material with a volume of 1725 ml to flow out through a discharge tube of 1.27 mm in diameter.
2.2. Specimen Preparation
The specimen was prepared in a cylindrical mould of 35 mm in diameter and 70 mm in height. The soil samples were oven-dried and through sieved No. 40. Amount of dry soil was put in a bowl of the mechanical mixer, and stirred slowly. Dry cement was added to the soil and mixed thoroughly for about 10 minutes until the soil and cement uniform mixed. The desired water at optimum moisture content was added gradually to the soil-cement mixture and stirred until the soil-cement slurry was mellowing. For spray mixing method, cement slurry was prepared with a water-cement ratio of 0.7. The cement slurry was put in the sprayer tube. The air pressure was gradually applied to drive the cement slurry to the sprayer nozzle and mixed with soil in the mechanical mixer. After mixing, for both the dry and spray pulverisation method, the soil-cement mixture was kept in a plastic bag for seven days before used for Atterberg limits test. A part of the soil-cement mixture was fill in compaction cylinder and compacted statically. After completing the compaction, the specimen was extruded from the mould. All specimens were compacted at the maximum dry density of the unstabilised soil. The specimen was weighed and measured its dimension. Finally, the specimen was stored in the wrapped plastic bag for seven days before performing the unconfined compressive strength test. The specimens were stored in a controlled-temperature room about 28°C to prevent moisture change.

2.3. Atterberg Limits Test
After seven days of curing, the soil-cement mixture was prepared for liquid limit and plastic limit test. The tests were conducted following ASTM D4318-17 for liquid limit, plastic limit, and plasticity index [16]. The liquid limit was determined by Casagrande method.

2.4. Unconfined Compressive Strength Test
The unconfined compressive strength test was performed after the specimens were cured for seven days. Three specimens were tested as in ASTM D2166-16 [17]. The unconfined compressive strength (q_u) was equal to the maximum axial stress or the compressive stress at 15% axial strain, whichever was secured first. The stress and strain were recorded to evaluate the failure behaviour through the parameters of secant modulus (E_50), brittleness index (I_b), and damage properties (D_p). The parameter of E_50 and I_b have been widely used in the engineering application to classify the elastic behaviour and specimen brittleness [18]. Damage property is commonly used to define the specimen damage development based on the dissipated energy [19]. The damage variable (D) can be expressed as shown in Equation 1.

\[ D_p = \frac{U_p^d}{U_p} = \frac{U_p - U_p^\sigma}{U_p} \]  \hspace{1cm} (1)

Where \( U_p, U_p^d, U_p^\sigma \) are constitutive energy, dissipated energy, and elastic energy at point P, respectively.

3. Results and discussion

3.1. Effect of Cement on the Plasticity
The results of the Atterberg limit test are shown in Figure 1. For both soil types, the addition of cement reduces the liquid limit and increases the plastic limit. When stabilised with 10% of cement, the liquid limit of clayshale decreases by 15.2%, and the plastic limit increases by 9.3%. The reduction of the liquid limit of the sandstone samples is 7.9%, and the plastic limit increases by 4.9%. The reduction of the plasticity index of the two soil types was about 24.5% and 12.7% for clayshale and sandstone respectively. The reduction of plasticity might be caused by the flocculation and agglomeration process.

| Water-cement ratio | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
|-------------------|-----|-----|-----|-----|-----|-----|
| Average cement efflux (s) | 17.49 | 9.24 | 8.05 | 8.05 | 7.36 | 7.24 |

Table 2. Flow cone test result
that occurs between clay minerals and cement [6]. Athanasopoulou [7] findings show that cement bound the clays particles to each other and form a larger particle of size and resulted in reduction the soil plasticity.

Moreover, Chew et al. [20] stated that the remaining water trapped in the intra-aggregate pore increased the soil moisture, but it’s presence did not affect the soil conditions. Change in liquid limit and plasticity index due to flocculation and agglomeration can be evaluated by plotting the LL and PI on the plasticity chart as shown in Figure 2. Cement addition changed the classification of clayshale from high plasticity soil to low plasticity and the classification of sandstone from medium plasticity soil to low plasticity soil. According to Robbins and Mueller [4] and Epp et al. [5], almost all types of soil can be stabilised with cement, except organic soils, high plasticity soils, and soils that have medium or high sulphate levels.

![Figure 1](image1.png)  
**Figure 1.** Effect of cement addition to liquid limit (a), plastic limit (b), and plasticity index (c).

![Figure 2](image2.png)  
**Figure 2.** The plot of the stabilised soil on the plasticity chart of USCS method [13]

### 3.2. Effect of Cement on the Unconfined Compressive Strength

The variation of unconfined compressive strength of the cement-stabilised soil for both dry and spray pulverised methods are shown in Figure 3a and 3b respectively for clayshale and sandstone. The $q_u$...
presented in Figure 3 was the average value of the three specimens tested. The $q_u$ of the unstabilised soils was about 150 kPa and 98 kPa for clayshale and sandstone respectively. In general, the $q_u$ increases almost linearly with the cement content. However, an addition of 2% cement is less significant to the $q_u$. In chemical stabilisation, a certain amount of cement is required as minimum content to modify the soil properties for short term reaction [8,10]. A higher amount of cement is certainly required to stabilised soil properties for the longterm reaction [11]. The highest $q_u$ is attained at 10% cement addition. The cement stabilised clayshale yield $q_u$ of 900 kPa and 957 kPa for dry and sprayed mixing methods, respectively. The sandstone specimen has $q_u$ of 1148 kPa and 1198 kPa for dry and spray mixing, respectively. The results show that there was an insignificant difference of $q_u$ obtained from dry and spray mixing for both soil type. Generally, the increase in $q_u$ is about 602%-640% and 1171%-1127% for cement stabilised clayshale and sandstone, respectively. This experiment does not show a coherent conclusion on the effect of cement mixing method on the $q_u$ of clayshale and sandstone. For clayshale, figure 3a shows that the spray mixing results in higher $q_u$ than dry mixing for cement content range from 4% to 9%. Whereas for sandstone, dry mixing shows superior to enhance the $q_u$ for cement content range from 2% to 7%, while the spray mixing improves the $q_u$ slightly at cement content of 7%-10%. Cement in slurry form would rapidly react with clays soil since the hydration, and pozzolanic reaction needs a moist circumstance to maintain the reaction [21-23].

![Figure 3. Unconfined compressive strength of the cement-stabilised soil (a) clayshale, (b) sandstone](image)

### 3.3. Failure Mode and Damage Properties

The typical final failure mode of the tested specimens is presented in Figure 4. The failure plane of clayshale specimen inclines about 45° to horizontal at the mid of height (see Figure 4a and 4b). This failure pattern indicates a shear failure that occurs in a combination of cohesion and friction, as in Mohr-Coulomb failure theory [24]. In contrast for sandstone specimen, the failure occurs from the top to bottom of the specimen, almost splits the specimen. The slip plane inclines greater than 45° to horizontal (see Figure 4c and 4d). This failure mode indicates that cement-stabilised sandstone exhibits noticeable features of brittle failure. The completed stress-strain curve of the unconfined compressive strength test will show three states: initial-linear state, non-linear, and post-peak failure states. The maximum compressive stress can be at the non-linear phase, which the stress continues until reaching the peak after the initial linear portion. The stress drops suddenly until total failure occurs [24-25].

Energy dissipation occurs when cracks or failure develop on the specimen during the compressive loading. Thus, the specimen collapse can be described by energy dissipation development and expressed with damage property ($D_p$). The specimen damage development can be illustrated in Figure 5. At the initial loading stages (a), the energy is used to compress the specimen pores and cracks [26]. Then, at the elastic condition (b), the amount of dissipated energy will be minimum, hereafter the dissipated
energy then increase when the specimen is in the plastic state (c) due to increased strain [19]. The energy dissipation curve will increase until it reaches \( q_u \). After that, the curve will begin to decrease at the failure stage (d) and tend to be concave until it gradually becomes flat. The energy dissipation tends to be constant when only residual stress (e) is left. Figure 6 to Figure 9 show the stress-strain curve and damage property pattern of the cement-stabilised soils.

**Figure 4.** Failure mode of the specimen after the unconfined compressive strength test (a) unstabilised clayshale, (b) clayshale + 10% cement, (c) unstabilised sandstone, (d) sandstone + 10% cement

**Figure 5.** The phases of specimen damage development under unconfined compressive loading

The \( D_P \) curves of clayshale specimens are illustrated in Figure 6 and Figure 7 for dry and spray pulverised method, respectively. In general, the peak of \( D_P \) curve of the spray pulverised specimen is attained at larger strain than the dry pulverised specimen. The spray pulverised specimen, there are also parts of the curve that tend to be constant before experiencing a significant increase in energy dissipation. The result indicates that the specimen is still in the elastic condition. In spray pulverised specimens with a cement content of 5% and 7%, the transition of specimen state from elastic to plastic occurs very quickly, indicating that the collapse occurred suddenly due to the specimen being too brittle. However, at 10% of cement content, the specimens returned to behave more elastic than before. It is
probably due to the increased number of fibrous bonds between soil and cement formed by pozzolanic product. When the amount of cement addition increased, the volume of small pores in the specimen filled with pozzolanic material also increased [27]. The fibrous bond between those pores has a significant role in bearing loads given to the specimen.

Meanwhile, the stress-strain behaviour and $D_p$ curve of the cement-stabilised sandstone are shown in Figure 8 and Figure 9 for dry and spray mixing, respectively. The Figures show that the behaviour of specimen with a cement addition of 2% and 7% tend to be similar. In specimens with a 5% cement content, the spray pulverised mixing method produces specimens with collapse points at more significant stress. The residual stress of the specimen is also more superior compared to the dry pulverised method.

![Figure 6. Clayshale specimen after stabilised with (a) 2%, (b) 5%, (c) 7%, and (d) 10% of cement content by dry pulverised method.](image)

![Figure 7. Clayshale specimen after stabilised with (a) 2%, (b) 5%, (c) 7%, and (d) 10% of cement content by spray pulverised method.](image)

![Figure 8. Sandstone specimen after stabilised with (a) 2%, (b) 5%, (c) 7%, and (d) 10% of cement content by dry pulverised method.](image)
Figure 9. Sandstone specimen after stabilised with (a) 2%, (b) 5%, (c) 7%, and (d) 10% of cement content by spray pulverised method.

When compared with the dry pulverised specimen, the collapse point (highest $D_p$ value) that occurs in spray pulverised specimen is closer to the peak of the stress-strain curve. Furthermore, the strain conditions at $q_u$ almost three times the dry pulverised specimen. The dry pulverised method produces specimens with more brittle properties. When only small an amount of water available during the initial state of hydration, the geometric of soil-cement bond that formed tend to be more concentrated. In the other hand, if there is more water surrounded the cement particle, dispersive bonds are more expected [22]. Dry pulverised method caused the cement particle to have less water for the reaction because the water itself already mixed with soil and trapped in the pore. This concentrated bond leads to brittle failure on the specimen.

3.4. Effect of cement stabilisation on secant modulus

Elastic modulus is a parameter to identify the strength and durability of a specimen. The elastic modulus in the unconfined compressive strength test is expressed in the value of the secant modulus. The value of secant modulus from the test results is presented in Figure 10. In clayshale and sandstone specimens, the dry pulverised method produces a higher secant modulus. It can be concluded that with the dry pulverised method, the specimens will have more brittle behaviour when compared to spray pulverised specimens.

Figure 10. Correlation between $q_u$ and $E_{50}$ on (a) sandstone specimen and (b) clayshale specimen.
Figure 10 shows the specimens prepared by the dry pulverised method resulted in a lower unconfined compressive strength compared to the spray pulverised method. The difference in compressive strength was 57 kPa in clayshale specimens and 50 kPa in sandstone specimens. Conversely, the value of secant modulus of the specimen prepared by the dry pulverised method is higher than the spray pulverised method. These results indicate that even though it produces a more brittle specimen, the compressive strength of the dry pulverised specimen is not as high as the spray pulverised specimen. Gartner et al. [23] explained the initial stages of hydration in the form of a quick reaction when cement met water. In this phase, hydrolysis occurs on the surface and the release of ions in solution. The hydration reaction is going slow when cement and water in the mixing process produces a hydrate layer on the surface of the C₃S. By using the spray mixing method, the hydration reaction can be optimised by directly mixing cement and water into one solution (cement paste). While in the dry pulverised method, this process is hampered because the water in the mixture is pore water and does not come into direct contact with the cement particles. The spray pulverised method also produce a more homogeneous soil-cement structure due to the more prolonged mixing phase and the presence of water applied to cement [28].

3.5. Brittleness Index

Brittleness index is a parameter that can be used to measure the immediate drop of the stress value after the specimen reaches the maximum stress [10]. The smaller the $I_B$ value, the specimen failure tend to be more ductile [3]. The higher the $I_B$ value, the higher the $E_{50}$ value. Based on the tests conducted by Eskisar et al. [29], cement addition as much as 5% changed the behaviour of the ductile specimen to be brittle and cement addition as much as 10% changed the specimen to be very brittle. The results of $I_B$ value based on the stress-strain curve can be seen in Table 3.

| Cement content (%) | Clayshale | Sandstone |
|--------------------|-----------|-----------|
|                    | Dry Pulverised | Spray Pulverised | Dry Pulverised | Spray Pulverised |
| 0                  | 0.494      | 0.494     | 0.625      | 0.625          |
| 2                  | 0.908      | 0.552     | 0.892      | 0.702          |
| 5                  | 0.880      | 0.836     | 0.879      | 0.686          |
| 7                  | 0.882      | 0.745     | 0.860      | 0.800          |
| 10                 | 0.517      | 0.723     | 0.587      | 0.642          |

4. Conclusion

The present study was designed to determine the effect of dry and spray pulverised mixing method on cement-stabilised clayshale and sandstone. Based on the results of the research that has been done, some funding of this study are as follows:

a. The addition of cement reduces the plasticity index for all specimens. This is because of a decrease in the liquid limit and an increase in the plastic limit. Flocculation and agglomeration are primary causes of the more massive aggregate formation that caused the plasticity index to decrease.

b. The unconfined compressive strength of cement stabilised clayshale with as much as 10% of the dry weight will increase by 640.1%. Addition of cement to sandstone increases unconfined compressive strength by 1126.6%.

c. Spray pulverised method produces higher unconfined compressive strength value than the dry pulverised method. Nevertheless, a higher secant modulus is achieved using the dry pulverised method.

d. The secant modulus will increase after stabilisation using cement. This shows that the addition of cement will increase the compressive strength but make the test object more brittle.

e. The brittleness index for all specimens has increased after cement stabilisation. This is in line with the characteristics of the specimen’s failure that change from ductile to brittle after hydration and pozzolanic products bind clayshale and sandstone particles.
f. According to damage property analysis based on the energy dissipation, the dry pulverised method produces specimens with more brittle behaviour than spray pulverised method.

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