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THE BEHAVIOR OF THE CLAY SHALE STABILIZED BY DRY AND WET CEMENT MIXING METHOD

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ABSTRACT

Cement stabilization has been found to improve the problematic soil effectively. Durability is an important aspect of clay shale stability. Measurement for the durability of stabilized soil has been developed for many years. This paper proposes the investigation of clay shale durability stabilized with cement by dry and sprayed pulverizing and tested by the wetting-drying cycle in the slaking test. The specimen was made according to ASTM standard weight for slaking test. The sample was molded with two types of mold in this study: compacted cylinders (CCS) measuring 1.35 inches in diameter and 1.35 inches in height, and compacted cylinders then broken into 40 ~ 60 g weight fragments (CBF). The cement content was varied from 2 to 10 percent by weight of the dry soil. The results conclude that the CBF specimen shows a higher durability value. In general, the dynamic slake durability index is about 85% lower than the static slake durability index for $I_d \leq 60$. This study has identified that the dry and spray pulverizing mixing methods result in soil stabilization. Dry cement mixing exhibits a higher slake durability index but has a lower unconfined compressive strength than spray mixing.

Key words: Clay shale, durability, slaking, cement stabilization, dry and spray mixing.

1. INTRODUCTION

Toll road project in Java island has been built along 615 km at the north of Java from 2011 to 2018. Road construction was often found over the problematic soil, such as soft soil near the marine area, red residual soil, clay shale at a mountainous area, and expansive clay. The subgrade's durability is the most important consideration during the road pavement's service period. A prior researcher reported a construction problem in the clay shale area (Alatas *et al.* 2015; Muhrozi and Wardani 2011). Shotcrete protection and nailing help to prevent clay shale disintegration caused by the weathering process. On the other hand, weathering reduces the stability's endurance method (see Fig. 1).

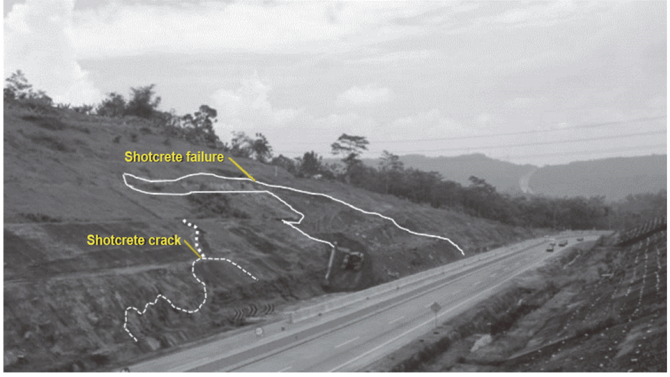

Fig. 1 Shotcrete cracks and failure at Bawen toll road

Cement stabilization significantly improves and effectively increases the durability of soil (Basha *et al.* 2005; Prusinski and Bhattacharja 1999; Yoobanpot *et al.* 2017). Among other calcium-rich-stabilizers such as lime, fly ash, or rice husk ash, only cement has a hydration reaction, resulting in a quick stabilization process (Sariosseiri and Muhunthan 2009). Recently, dry-mixing is the standard method to prepare the specimen for stabilization, while cement slurry is used for the wet-mixing method. Dixon *et al.* (2012) showed that soil stabilizing using cement slurry indicates lower strength than the dry-mixing method. Meanwhile, Pakbaz and Farzi (2015) found that the wet mixing method results in higher soil strength than the dry mixing. Cement-slurry mixing results in an earlier hydration process and a rapid strength gained of the stabilized soil. Limited research provides a comparative study on the wet-mixing method. In addition, researchers have never compared dry and spray pulverizing mixing processes. Furthermore, the specimen shape also plays a role in durability index development. According to the research conducted by Ankara *et al.* (2015) and Agustawijaya (2004), further investigation is needed to assess the durability index for different specimen preparation and stabilizing methods.

This paper investigates the slake durability index of cement stabilized clay shale using dry and spray pulverized mixing methods. The main objective of the research is to investigate the slaking durability of cement-stabilized clay shale with different specimen preparation. The effect of cement on the unconfined compressive strength and permeability of the compacted clay shale is also evaluated in this study. Furthermore, since the available standard for slaking test is for a natural fragment, this paper proposes preparing the specimen to determine the slaking durability. This study evaluated two different preparation meth-

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ods, namely compacted specimen cylinders (CCS) and broken-compacted cylinders (CBF).

2. MATERIALS

2.1 Clay Shale

Clay shale is one type of mudrock. Shale clay is in a harsh condition like the general sedimentary rocks when it is not exposed to the environment and atmosphere. Clay shale is in harsh conditions like most sedimentary rocks. But if it has been weathered, it will look like soil that is easily crushed. Clay shale used in this study has weathered more than 85%. According to the classification by Sadisun *et al.* (2005), this weathering is categorized as extremely high. Block samples (see Fig. 2) were collected from a slope-side of the toll road Semarang-Bawen at km. 441 + 800 in Central Java. The soil sample was dominated by Smectite clay minerals followed by Illite, Kaolinite, and Chlorite as indicated by XRD analysis in Fig. 3. The grain size distribution of the soil sample is shown in Fig. 4. The figure shows that the soil consisted of 6.7% sand and 93.3% silt or clay. The index properties of the soil sample are summarized in Table 1. The Atterberg limits defined the soil as high plasticity (LL > 50, PI > 7) and classified as CH according to the Unified Soil Classification System (USCS).

Fig. 2 Semarang-Bawen clay shale

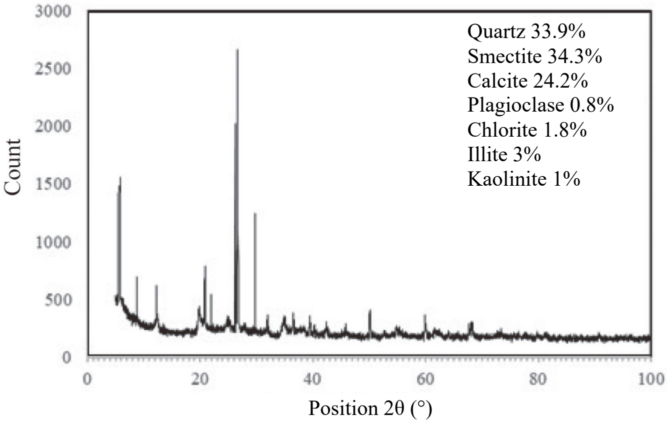


Fig. 3 Clay shale mineralogical composition (Hartono, 2020)

2.2 Cement and Cement Slurry

According to the PCA (Portland Cement Association, 1992), cement can be added up to 11% by weight for compaction tests and wetting-drying tests on sedimentary rock (shell, limestone, red dog, shale, caliche, chert, and chat). Type I cement was used in this study. The available cement in Indonesia is a typical portland cement composite (PCC). The cement met the requirement of Indonesia Standard SNI-15-7064-2004 (SNI 2004). The standard required that the cement should not crystallize and harden before use due to hydration in a humid environment. The cement was stored in a dry and airtight container to prevent early hydration. The cement slurry is a semiliquid mixture of cement and water. This slurry was used in the spraying method. The cement slurry was required to be able to flow through the nozzles of the sprayer. Thus the cement and water ratio was determined by flow cone test as ASTM C939-10 (ASTM 2010a). Figure 5 shows the result of the

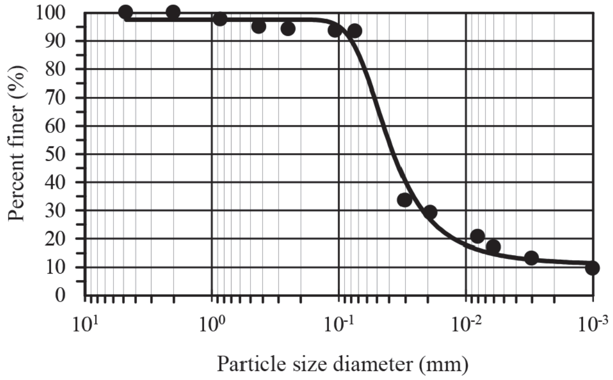


Fig. 4 Grain size distribution of the soil sample

Table 1 Geotechnical properties of clay shale

Soil properties	Quantity
Specific gravity, G_s	2.65
Sand (%)	6.7
Silt/clay (%)	93.3
Liquid limit, LL	57.9
Plastic limit, PL	28.4
Shrinkage limit, SL	10.6
Plasticity index, PI	29.5
Optimum moisture content, OMC (%)	19.0
Maximum dry density, MDD (kN/m^3)	16.3

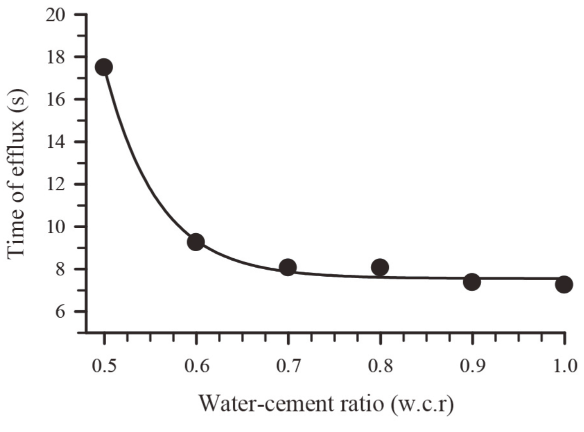


Fig. 5 Determination of the viscosity of cement-water ratio for spray method using flow cone test

flow cone test for cement slurry with various water-cement ratios (w.c.r). Efflux is the time needed for 1725 ml cement slurry to flow through a 0.5-inch discharge tube. Figure 5 indicates that the cement slurry with 0.7 w.c.r is the closest efflux value to water efflux.

3. EXPERIMENT METHOD

3.1 Testing Program

The primary investigation in this research was slaking durability and strength tests. The slaking test was carried out on two types of specimens: compacted specimen cylinders (CCS) and broken-compacted cylinders (CBF). There are two types of soil mixing methods: dry mixing and spray mixing. All specimens were made to the same density, corresponding to the clay shale's optimum moisture content (OMC). Permeability of the stabilized soil was also investigated. The testing program of this study is presented in Table 2.

Table 2 Quantity of specimen for each test

Specimens	Code	Test Type					
		PERM	UCS	Static Test		Dynamic Test	
				CCS	CBF	CCS	CBF
Clay shale	CS	●	●● ■■	●● ■■	●● ■■	●● ■■	●● ■■
98% CS + 2% PC	CS2	●	●● ■■	●● ■■	●● ■■	●● ■■	●● ■■
95% CS + 5% PC	CS5	●	●● ■■	●● ■■	●● ■■	●● ■■	●● ■■
93% CS + 7% PC	CS7	●	●● ■■	●● ■■	●● ■■	●● ■■	●● ■■
90% CS + 10% PC	CS10	●	●● ■■	●● ■■	●● ■■	●● ■■	●● ■■

Notes: PC = Portland cement; CS = clay shale; UCS = unconfined compressive strength; PERM = permeability test; CCS = compacted cylinder specimen; CBF = broken fragment specimen; ● = total number of tested dry mixing specimen; ■ = total number of tested spray mixing specimen

3.2 Specimen Preparation

The dry pulverizing method mixed the soil and cement in dry conditions. An amount of cement was prepared before the mixing and then mixed with soil thoroughly in a batch mixer for about 10 minutes at a slow rate to produce a uniform mixture. The desired water was added gradually to the soil-cement mix to have a homogenous soil-cement slurry. Meanwhile, the spray pulverizing method used cement paste. The total amount of water in the spray mixing was determined at the OMC to control the water content of the specimen. In this method, soil and water were mixed firstly, and then cement paste was sprayed during the mixing. The water-cement ratio for spray method according to the result flow cone test.

Two identical specimens were prepared as CCS (Fig. 6(a)) and CBF (Fig. 6(b)). The soil-cement mixtures were transferred in a steel cylindrical mold of 34.29 mm × 34.29 mm and pressed statically using a piston to obtain a CCS specimen. The CBF was fragments of the soil-cement mixture compacted in steel mold 69.85 mm diameter and 139.70 mm height, then broken into 40 ~ 60 g weight fragments. All specimens were kept in an air-tight plastic bag and cured for seven days.

(a) CCS specimens (b) CBF specimens

Fig. 6 Test specimens

3.3 Slaking Test

Slaking test was done to assess the resistance of clay shale to weathering process. Static and dynamic slaking tests were selected to compare the effect of the weathering process on clay shale disintegration. The static slaking procedure was modified from the test carried out by Sadisun *et al.* (2005), while the dynamic slaking test was conducted according to ASTM D4644-08 (ASTM 2008) for slake durability shales. For each sample, the test was carried out twice, and the average result was recorded.

3.3.1 Static Slaking Test

The static slaking test was consisted of two main procedures: (1) wetting by immersing the specimens in tap water, (2) and drying the specimens in an oven at 105°C. The specimens consisted of 10 fragments of stabilized clay shale, 450 ~ 550 g weight (see Fig. 6). The test was initiated by drying the specimens in the oven for 16 ~ 24 hours. After drying, the specimens were immersed in water for 16 hours. The water level was kept about 0.5 inches above the specimens. After the wetting process, the specimens were wash-sieved on No.200 sieve size. The remaining fragments were dried to determine grain size distribution using sieve analysis. This procedure was defined as one cycle of wetting-drying. At the end of the cycle, the retained specimens on No.10 sieve size were taken in the bowl for the second cycle of wetting-drying.

The slake index was defined as the percentage of loose specimen mass after the cycle ($W_{d(n)}$) to initial oven-dried mass (B). The slake index ($I_{s(n)}$) was determined by Eq. (1). Then, the slake durability index corresponding cycle ($I_{d(n)}$) was calculated by Eq. (2).

$$I_{s(n)} = \left(\frac{W_{d(n)}}{B}\right) \times 100\% \tag{1}$$

$$I_{d(n)} = 100 - I_{s(n)} \tag{2}$$

where $W_{d(n)}$ = mass of bowl with the retained oven-dried specimen (g),

B = mass of bowl with the initial oven-dried specimen (g).

3.3.2 Dynamic Slaking Test

According to ASTM D4644-08 (ASTM 2008), the dynamic slaking test was conducted for the slake durability of shales. The slake durability device is shown in Fig. 7. The test determines the slake durability index of clay shale after the wetting-drying cycle and abrasion. The specimens consisted of ten fragments of about 450 ~ 550 g weight for each drum. After being mounted on the slaking device, the samples were then immersed in water. The water level was set 0.8 inches below the drum axis. The drum was then rotated with a speed of 20 rpm for 10 minutes. The specimens retained in the drums were removed and dried in the oven for 24 hours. The particle passing through the meshes or smaller than sieve No. 10 were wash-sieved on No. 200 sieve size. Sieving analysis was performed for all the retained particles and remaining fragments. The second cycle was continued by slaking the retained specimen on the No. 10 sieve. Also, each specimen underwent five wetting-drying cycles. The slake durability index is then calculated by Eq. (3).

$$I_d = \frac{W_f - C}{B - C} \times 100\% \tag{3}$$

where I_d = slake durability index (%),
W_f = mass of drum with the retained oven-dried specimen (g),
B = mass of drum with the initial oven-dried specimen (g),
C = mass of drum (g).

3.4 Permeability Test

Soil permeability test was conducted using a flexible wall permeameter based on ASTM D5084 (ASTM 2010b). The compacted soil-cement mixture was used in this test. The specimen size was 38 mm in diameter and 76 mm in height (see Fig 7). The test was conducted by applying confining pressure to the specimen as the beginning. The sample was then saturated until the B-value reaches a higher value than 0.95. The consolidation process started once the specimen reached the desired condition. Permeation test was continued by determining the value of hydraulic gradient; commonly, 1 to 5 can be applied for general field conditions. A constant head test was performed with a constant tailwater (Method A). The tailwater was maintained at the same level along the process once the headwater pressure increased. The hydraulic conductivity (k) was calculated as in Eq. (4). The test was terminated if the k value showed no significant changes, considered at the minimal value of 25%.

$$k = \frac{\Delta Q \cdot L}{A \cdot h \cdot \Delta t} \tag{4}$$

Fig. 7 Slake durability apparatus

where ΔQ = quantity of flow for given time interval Δt, taken as the average of inflow and outflow (m^3),
a = cross-sectional area of the reservoir containing the influent liquid (m^2),
L = length of specimen (m),
A = cross-sectional area of specimen (m^2),
Δt = $t_2 - t_1$ = interval of time (s) over which the flow ΔQ occurs,
t_1 = time at start of permeation trial (hr:min:sec),
t_2 = time at end of permeation trial (hr:min:sec),
h = average head loss across the permeameter/specimen $[(h_1 + h_2)/2]$ (m),
h_1 = head loss across the permeameter/specimen at t_1 (m),
h_2 = head loss across the permeameter/specimen at t_2 (m).

3.5 Unconfined Compressive Strength Test

Unconfined compression strength test carried out according to the ASTM D1663 (ASTM 2000). The cylindrical compacted soil-cement was prepared in 38 mm in diameter and 76 mm in height (see Fig. 8). Three specimens were tested to confirm the results. The compression test was performed after seven days of curing. The load was applied continuously on the specimen with a shearing rate of 0.76 mm/min. The unconfined compressive strength of the specimen (q_u) was determined by dividing the maximum load by the cross-sectional area as given in Eq. (5).

$$q_u = \frac{F_{\max}}{A} \tag{5}$$

where $F_{\max}$ is maximum axial load (N), and A is cross section of the specimen (mm^2).

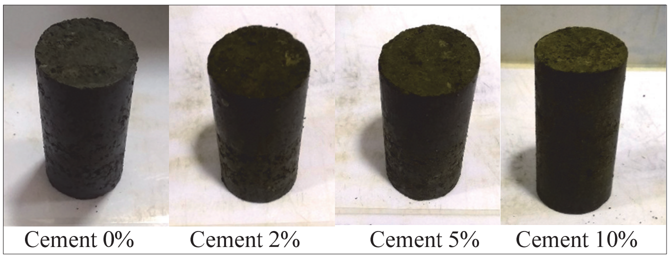


Fig. 8 Specimen for UCS and permeability test

4. RESULTS AND DISCUSSION

4.1 Effect of the Slaking Method on the Slake Durability Index

Two slake durability methods had been done in this study to assess the durability due to weathering process involving the wetting-drying cycle. The slake durability index test results are presented in Table 3. The slake durability index was measured after the first ($I_{d(1)}$), second ($I_{d(2)}$), and fifth ($I_{d(5)}$) wetting-dying cycle. ASTM D4644-08 (ASTM 2008) required the second cycle as the slake durability index ($I_{d(2)}$) for a natural shale or weak rock. However, to evaluate the lasting durability of the stabilized clay shale, it is necessary to measure up to the fifth or more cycles. Some research suggested evaluating high durability rocks with more than three cycles (Cano and Tomás 2016; Fuenkajorn 2011; Yagiz 2010). Hartono *et al.* (2019) assessed slake durability index with more than three cycles for the compacted and stabilized weak rock and recommend $I_{d(5)}$ as the slaking durability index instead of $I_{d(2)}$.

Table 3 Slake durability (I_d) after first, second, and fifth cycle

Testing method / Cement:	$I_{d(1)}$					$I_{d(2)}$					$I_{d(5)}$				
	0%	2%	5%	7%	10%	0%	2%	5%	7%	10%	0%	2%	5%	7%	10%
Static slake – Dry method:															
CCS	2.1%	3.12%	16.9%	49.77%	68.25%	0.37%	2.16%	8.57%	37.93%	58.86%	0.22%	1.81%	3.19%	19.22%	34.08%
CBF	1.51%	7.57%	81.13%	85.34%	91.15%	0.68%	0.8%	60.34%	61.28%	83.35%	0.54%	0.21%	21.27%	33.71%	62.79%
Static slake – Spray method:															
CCS	2.1%	3.2%	12.28%	76.98%	92.19%	0.37%	2.06%	7.18%	51.64%	74.87%	0.22%	1.04%	3.15%	22.15%	42.7%
CBF	1.51%	1.53%	27.86%	85.46%	97.14%	0.68%	0.63%	20.07%	60.85%	93.55%	0.54%	0.17%	25.24%	35.53%	81.46%
Dynamic slake – Dry method:															
CCS	0.77%	2.34%	3.84%	10.7%	20.81%	0.13%	1.86%	1.98%	4.58%	15.45%	0%	1.51%	1.17%	1.19%	8.93%
CBF	1.76%	3.49%	11.81%	50.02%	93.44%	1.35%	2.7%	3.9%	18.69%	81.87%	0.57%	1.58%	1.31%	6.11%	57.29%
Dynamic slake – Spray method:															
CCS	0.77%	2.82%	6.86%	21.98%	29.61%	0.13%	1.45%	2.35%	6.85%	17.9%	0%	0.66%	0.7%	2.29%	6.96%
CBF	1.76%	1.97%	2.08%	5.23%	79.6%	1.35%	1.53%	1.7%	2.97%	54.87%	0.57%	0.77%	0.9%	1.07%	15.26%

The results in Table 3 show that the unstabilized clay shale exhibited a low slaking durability index after the first, second, and fifth cycles if compared to the stabilized clay shale. After the fifth cycle, the compacted clay shale, CCS or CBF, totally degrades, which is indicated by the zero value of $I_{d(5)}$. In general, for the unstabilized and stabilized specimens, the dynamic slaking method resulted in the worst durability index compared to the static slaking test. Figure 9 presents the correlation of the slake durability index between the static and dynamic slaking methods. A bilinear line approaches the correlation. The analysis showed that the dynamic slake durability index was about 85% lower than the static slake durability index for $I_d \leq 60$. However, the dynamic slake durability index was about 30 to 80% lower than the static slake durability index for $I_d > 60$. The Pearson correlation between two slaking methods is presented in Fig. 10. The correlation coefficient (r) was about 0.652, which indicates a strong correlation between the slaking methods.

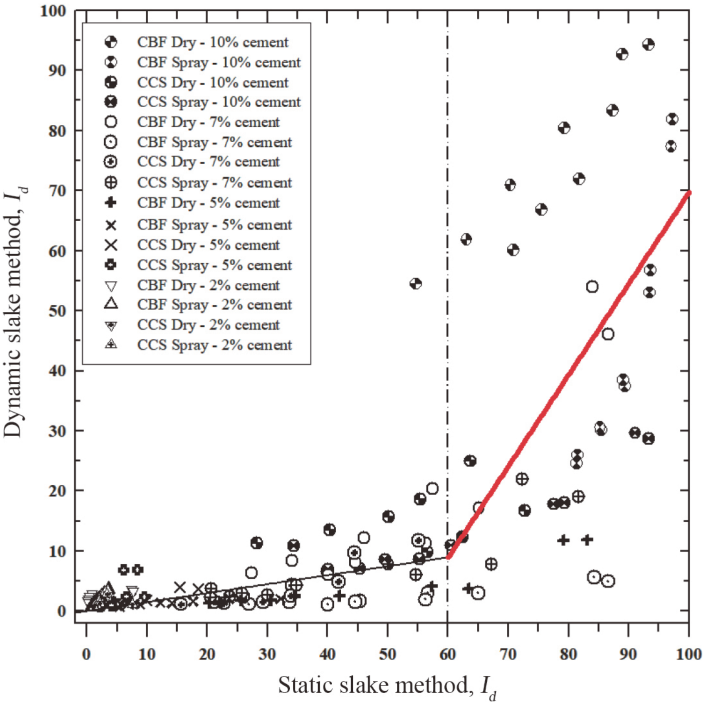


Fig. 9 Slake durability index I_d correlation between static and dynamic method

4.2 Effects of Cement Mixing Method and Specimen Shape on the Slake Durability

The mixing method and specimen shape were evaluated in this study. The mixing method and specimen shape on the slake durability index $I_{d(5)}$, and others can be studied from the correlation analysis as shown in Fig. 10. The correlation between two variables was measured by correlation coefficient (r) that varied from − 1 to 1. A value of ±1 indicates a strong correlation between two variables, whereas the r-value approaching 0 (zero) indicates no correlation (Baecher and Christian 2005). The correlation should be completed by further ANOVA test to evaluate the influenced-variable to slaking durability index. The analysis presented the r and p-values of the models. In the interaction model, if the p-value is less than the significance level ($\alpha = 0.05$), then the model provides a better fit, and the factors are statistically significant. Otherwise, the interaction is less significant (Baecher and Christian 2005).

Figure 9 shows that if the cement content is higher, the durability index of the dynamic method will increase closer to the durability index of the static method. According to the ANOVA result, the dynamic slake durability index, $I_{d(5)\,\mathrm{dynamic}}$, was significantly influenced by the method of cement mixing (drying and spraying). The dry mixing had more effect ($p < 0.0001$, $r = 0.669$) than spraying mixing ($p > 0.05$, $r = 0.267$) on durability under the dynamic slaking test. The specimen shape (CCS and CBF) seemed statistically insignificant to affect the $I_{d(5)\,\mathrm{dynamic}}$ ($p > 0.05$, $r = 0.220$ and 0.230). In contrast, the static slake durability index, $I_{d(5)\,\mathrm{static}}$, was significantly influenced by the cement mixing method and the specimen shape, as shown in Figs. 10(c), 10(e), 10(h), and 10(l), the p-value was smaller than 0.001. In general, the analysis indicated that the cement mixing method was the most influential factor on the slake durability index, which is indicated by the strong correlation.

4.3 Effect of Cement Addition on Unconfined Compressive Strength

The effect of cement content on the unconfined compressive strength (q_u) is shown in Fig. 11(a). The q_u values provided in Fig. 11(a) are the average values of three specimens for each cement mixture. In general, the compressive strength increased with the cement content. The unconfined compressive strength increased

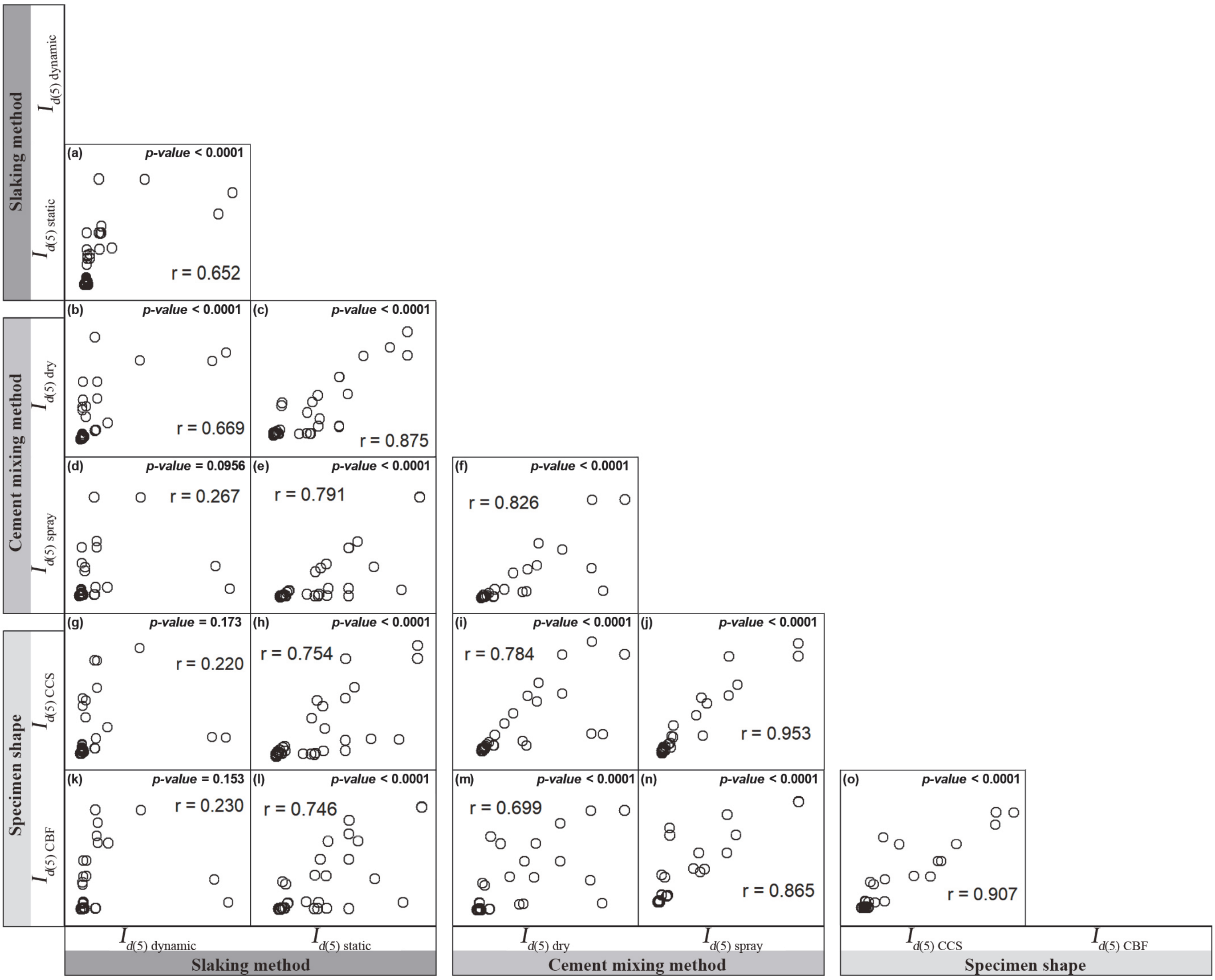
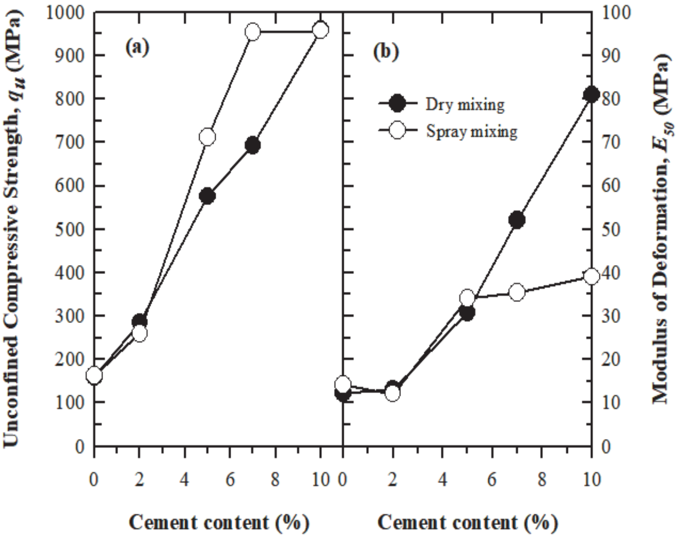


Fig. 10 Correlation analysis on the slake durability index ($I_{d(5)}$)

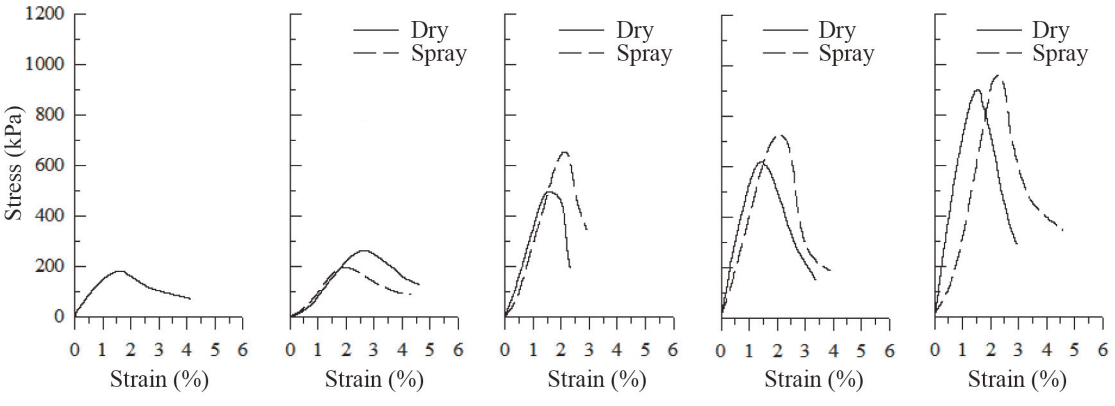


(a) (b)

Fig. 11 Effect of cement content and cement mixing method on the (a) unconfined compressive strength; (b) modulus of deformation

about six times from 160 kPa to 958 kPa by the addition of 10% cement. Figure 10 shows different strengths gained by the dry and spray cement mixing method. The addition of 2% cement to the clay shale resulted in a slight difference between the dry and sprayed mixing methods. Further increase in cement content to 5% and 7% resulted in a difference q_u, in which the spray cement mixing was higher than the dry cement mixing. However, the addition of 10% cement resulted in almost similar q_u for both dry (q_u = 957 kPa) and spray (q_u = 958 kPa) cement mixing.

Deformability of the stabilized soil is defined by a modulus of deformation describing the relationship between the applied load and strain (Fig. 12). Table 4 presents the peak stress, residual stress, and its corresponding strain. The effect of cement content and mixing method on the modulus of deformation (E_{50}) is shown in Fig. 11(b). As the cement content increased, the modulus of deformation increased. However, the addition of 2% cement did not interfere with the E_{50} value of clay shale. In contrast to the q_u characteristics, the dry cement mixing resulted in a higher E_{50} than the spray cement mixing method by adding 5% cement and more. The highest E_{50} is about 81 MPa, which is obtained by the addition of 10% cement. A lower E_{50} obtained by the spray cement mixing was attributable to a larger strain at failure (see Figs. 12(b) and 12(d)).



(a) (b) (c) (d) (e)

Fig. 12 Typical stress-strain curves (a) unstabilized soil; (b) 2% cement; (c) 5% cement; (d) 7% cement; (e) 10% cement

Table 4 Stress and strain characteristics and brittleness index

Cement (%)	Mixing method	Peak stress		Ultimate stress		Brittleness index, I_B
		Stress, q_u (kPa)	Strain, ε_u (%)	Stress, q_r (kPa)	Strain, ε_r (%)	
0	–	181.82	1.69	71.49	4.16	0.61
2	Dry	263.70	2.69	127.49	4.64	0.52
	Spray	196.26	1.94	87.87	4.32	0.55
5	Dry	497.10	1.54	192.41	2.33	0.61
	Spray	654.15	2.11	341.47	2.93	0.58
7	Dry	618.16	1.46	147.22	3.39	0.76
	Spray	677.49	1.70	185.10	3.88	0.73
10	Dry	957.08	1.46	287.14	2.94	0.69
	Spray	958.94	2.27	343.15	4.62	0.64

The brittleness index (I_B) is also used to measure ductility to investigate the effect of cement treatment on the mode of failure. The I_B is defined firstly by (Bishop 1971) as the difference between the peak (q_u) and ultimate strengths (q_r), normalized by the peak strength ($I_B = (q_u - q_r)/q_u$). The index ranges from 0 to 1, where $I_B = 1$ indicates brittle and $I_B = 0$ occurs in ductile behavior. The I_B of the compacted specimen is 0.61, which tends to behave like a brittle failure. In general, the I_B of the cement-stabilized clay shale ranges from 0.52 to 0.76 for dry mixing and 0.55 to 0.73 for the spray mixing method, as presented in Table 4. Table 4 and Fig. 11(b) show that the brittleness index and the deformation modulus of dry mixing are higher than that of spray mixing if the cement content is 5% or more. Spray mixing with at least 5% cement has higher compressive strength (q_u) than dry mixing. Thus, spray mixing above 5% increases strength and ductility. On the other hand, spray mixing has lower compressive strength and is more brittle than dry mixing at 2% cement content. A higher I_B and E_{50}, more brittle behavior will be observed.

4.4 Effect of Cement Addition on the Coefficient of Permeability

Table 5 shows the variation of the coefficient of permeability (k) with the cement content. The k value of the unstabilized clay shale was 9.7×10^{-5} m/s. In general, the stabilized clay shale had a higher k value than the unstabilized clay shale. The highest k value was obtained by adding 2% cement, which was 1.40×10^{-3} m/s. This result indicates that the clay shale was more permeable by the addition of 2% cement.

Table 5 Coefficient of permeability of stabilized soil

Cement content (%)	Coefficient of permeability, k (m/s)
0	9.70×10^{-5}
2	1.40×10^{-3}
5	1.27×10^{-3}
7	2.90×10^{-4}
10	9.00×10^{-5}

Further increase in cement content resulted in a decrease in the coefficient of permeability. The k value decreased significantly to 1.27×10^{-3} and 2.90×10^{-4} by adding 5% and 7% cement, respectively. The decrease in the coefficient of permeability continued for 10% cement mixing, in which the k value was closer to the unstabilized clay shale. At this condition, the stabilized clay shale behaves impermeable. Therefore, this study showed a certain amount of cement to increase the permeability of clay shale.

4.5 Discussion

It should be noted that in the dynamic slaking test, abrasion takes place while rotating the drum. During rotation, the specimens collided, and some of the fragments were broken into small pieces that passed through the drum's 2 mm wire mesh. As a result, the specimen with the dynamic slaking test experienced disintegration caused by sliding inside the drum during rotating. Moreover, the shear stress acting on the specimen due to sliding was more destructive and contribute more to the particle deterioration (Erguler and Shakoor 2009). The static slaking induced swelling-shrinking process. A small crack triggered the disintegration at the beginning of drying. Slaking reduced the contact bond of particles; the specimens deformed, and cracks appeared. The deformation extended at the final stage of slaking cycles, causing extensive disintegration. This mechanism was confirmed by Fukumoto and Ohtsuka (2019). The results indicated that the selection of slaking method is essential to evaluate the degree of disintegration of stabilized soil. During the wetting process, the water penetrated to the subsurface of soil particles. The permeability controlled the water penetration. The addition of the cement will modify the texture of clay shale, which induces the coefficient of permeability (see Table 5). Yi *et al.* (2014) explained that the product of cement during the hydration stage would fill soil pores and flocculated. Thus, the macropore in the stabilized clay shale decreased as the cement increased and reduced the permeability. A lower permeability (Table 5) and a higher strength (Fig. 10) due to cement mixing resulted in higher durability of clay shale.

Table 3 shows that the $I_{d(5)}$ of the CBF specimens was always higher than the CCS specimens. The surface of the CBF specimens is more angular and rougher than that of the CCS specimens (see Figs. 6(a) and 6(b)). Kolay and Kayabali (2006) stated that surface roughness correlated with the angular surface would increase the abrasion rate while the specimen collided with the inner part of the drum. Agustawijaya (2004) added, while being rotated, an irregular specimen with angular surface bumps to each other, leading to the disintegration of the angular surface and break away from the main fragments. The shape of broken fragments is usually similar to small grains which pass the drum mesh. The angular surfaces removed from CBF specimens after broken into fragments will make the specimen more spherical and reduce the specimen surface contact with water. These results are also supported by Aksoy *et al.* (2019). The I_d value will be easier to determine by using a spherical specimen or at least the irregular specimen of which the angular or squared part is already removed. The angular parts of a specimen that collide with each other are easier to broke into smaller pieces. In this study, the specimen shape has only a significant effect on the dry mixing method.

The dry cement mixing method is preferred to produce a higher dynamic slake durability index of the stabilized clay shale (see also result in Table 3). In contrast, the spray mixing method shows an effective treatment on the static slake durability index for both CCS and CBF specimens (Figs. 10(i) and 10(n)). Spray mixing resulted in an early hydration reaction in soil-cement slurry and produced an early strength gain than the dry cement mixing. The chemical reaction continued to increase the strength with time and resulted in a higher strength than the dry cement mixing, as shown in Fig. 11(a). The finding is affirmed by Pakbaz and Farzi (2015), and Dixon *et al.* (2012). Yagiz (2010) mentioned a strong relationship between slake durability index, unconfined compressive strength, and modulus of deformation of the rock specimen. A higher compressive strength caused the specimen to retain its integrity from the wetting and drying cycles. This condition is shown by spray cement mixing, which had a high static slaking durability index. A stiffer soil structure can resist its stability during colliding, tumbling, and abrasion in the drum. As shown in Fig. 11(b), the E_{50} value of the dry cement mixing was higher than that of the spray cement mixing. This condition is the reason that dry cement mixing behaves more durable than spray mixing. According to the law of energy conservation, the stress-strain curve (Fig. 12) obtained from the unconfined compressive strength test can be treated as a process of elastic energy accumulated or absorption and release or dissipation (Jiang *et al.* 2019; Tan *et al.* 2019).

Even though dry cement mixing shows a higher I_B than the spray mixing method, dry cement mixing has a lower energy dissipation than spray cement mixing. Hartono *et al.* (2020) used the damage properties (D_P) curve to explain the stress-strain characteristics. In general, the spray mixing specimen attained the peak D_P curve at a higher strain than the dry pulverized specimen. Other sections of the curve in the spray mixing specimen tend to be steady before experiencing a considerable increase in energy dissipation. At this stage, the specimen was still in elastic mode. The transition from elastic to plastic states occurred very quickly in spray mixing specimens with a cement content of 7%, indicating that the collapse occurred suddenly due to the specimen being too brittle (Hartono *et al.* 2020). However, increasing the cement content to 10% cement results in a lower brittleness index than the 7% cement content (Table 4). Ma *et al.* (2018) explained that energy dissipation reflects the evolution of the internal crack, which leads to the weakening of rock due to dynamic freeze-thaw cycles. It is a possible reason that spray cement mixing exhibits a lower slake durability index.

Previous studies do not show a coherent conclusion on the effect of cement or a chemical on the coefficient of permeability. Wang and Tanttu (2018) concluded that the effect of the chemical on the coefficient of permeability is modest, and no significant change in the permeability. A reduction in the coefficient of permeability with an increase in cement content was concluded by Bahar *et al.* (2004). In contrast, Nalbantoglu and Tuncer (2001) showed an increase in hydraulic conductivity, increasing the percentage of chemicals added to the soils. In this study, the increase in the coefficient of permeability with 2% cement is caused by the agglomeration of the soil due to cement modification. The agglomeration produces macropores. As a result, it is easier for water to flow into soil particles, thus reducing the slaking durability. Horpibulsuk *et al.* (2010) found that an inadequate amount of cement addition was not enough to produce cementitious material. Thus, the pores will not flocculate due to the insignificant cement content compared to the soil mass. When the percentage of cement added increases, the macropores in the specimen could be filled by cementitious product from hydration and pozzolanic reaction. Thus, the permeability of stabilized soil decreased (Sasanian and Newson 2014). Furthermore, Yi *et al.* (2014) show that the cementitious product could also cause cracks on the specimen due to the excessive hydration and pozzolanic reaction. It can reduce the slake durability of stabilized clay shale.

The method of stabilization with soil mixing that is mostly used in Indonesia is dry mixing. This study suggests that the soil strength with the spray mixing method is better than dry mixing at cement content above 5%. The spray method is also more environmentally friendly because it produces less air pollution than the dry method. As expected, these findings will contribute for improving the stabilization design or methods.

5. CONCLUSIONS

The current research has investigated the effect of the dry and spray mixing method on slake durability of the cement stabilized clay shale. Two methods for the determination slake durability test has been introduced. The method used two shapes of compacted specimens, namely CCS and CBF. Based on the results and discussion of the study, unstabilized clay shale exhibits a lower slaking durability index after the first, second, and fifth cycles compared to the stabilized clay shale. After the fifth cycle, the compacted clay shale, CCS or CBF, totally degrades, indicated by the zero value of $I_{d(5)}$. Moreover, CBF specimen showed a higher durability value. In general, the dynamic slake durability index is about 85% lower than the static slake durability index for $I_d \leq 60\%$. But the dynamic slake durability index is about 30 to 80% lower than the static slake durability index for $I_d > 60\%$. This study has identified that higher cement content increasing durability. The spray mixing method and specimen shape better affect the static durability index of clay shale. Meanwhile, dry cement mixing specimen with a higher slake durability index in the dynamic test has a lower unconfined compressive strength than spray mixing. This study shows that the soil strength and ductility of the spray mixing method are better than dry mixing at cement content above 5%. Increasing the permeability coefficient with 2% cement made it easier for water to flow to the soil particles, thus reducing the strength and durability.

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DATA AVAILABILITY

This study does not generate new data and/or new computer codes.

CONFLICT OF INTEREST STATEMENT

The authors state that there are no financial interests or personal relationships that might influence the work reported in this paper.

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